Capture of Electrons and Ionization by Protons in Hydrogen

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The effective cross section of single electron capture and ionization in hydrogen by means of protons of energy in the region of 12.3 to 36.7 kev was measured by means of an improved method of collecting slow particles on the electrode of a plane parallel condenser. The results obtained are compared with data obtained by other workers as well as with theoretical calculations. When protons pass through hydrogen, negative hydrogen ions are found in the proton beam. It is shown that at low gas pressures the appearance of negative hydrogen ions is connected with the process of double electron capture from hydrogen by the protons. Preliminary measurements of the effective cross section for this process with protons of energy 13, 21 and 31.4 kev show that this phenomenon cannot distort the measurements on the effective cross section of single electron capture as we have measured it.

INTRODUCTION

A considerable amount of work has been devoted to the study of elemental processes that take place during the collision of positive ions with gas particles. This work is reviewed in a monograph by Massey and Burhop[1]. Among other inelastic processes, there were studied single electron capture and ionization by positive ions passing through a gas. Several researches are devoted to the study of these processes in the passage of protons through hydrogen[2-5]. An acquaintance with these works shows that the effective cross section of single electron capture varies markedly from author to author; as to the effective cross section for ionization, it was measured only by one author[4].

The differences in the results of the various authors is connected with certain errors in their experimental methods that distort their results.

When fast, singly charged ions pass through a gas, the following elemental processes are possible:

$$A^+ + B \rightarrow A + B^+ \text{ (capture of a single electron)}; \quad (1)$$

$$A^+ + B \rightarrow A^- + B^{++} \text{ (capture of two electrons)}; \quad (2)^*$$

$$A^+ + B \rightarrow A^{k+} + (k-1)e + B \;\; (2 < k < Z_A) \quad (3)$$
(loss of electrons);

$$A^+ + B \rightarrow A^+ + B^{k+} + ke \;\; (1 < k < Z_B) \quad (4)$$
(ionization).

As a result of these processes in the beam, some of the singly charged ions are converted to multiple charged ions, neutral atoms or negative ions. In addition, there appear in the gas through which the beam passes a variety of slow particles, such as positive ions and electrons.

Upon the passage of protons through hydrogen one gets specifically the following reactions:

$$H_1^+ + H_2 \rightarrow H_1 + H_2^+ \text{ (capture of one electron)}; \quad (5)$$

$$H_1^+ + H_2 \rightarrow H_1^- + H_1^+ + H_1^+ \text{ (capture of two electrons)}; \quad (6)$$

$$H_1^+ + H_2 \rightarrow H_1^+ + H_2^+ + e \quad \text{(single ionization)}; \quad (7)$$

$$H_1^+ + H_2 \rightarrow H_1^+ + H_1^+ + H_1^+ + 2e \text{ (double ionization)}. \quad (8)$$

The effective cross sections of the above reactions can be studied either by analyzing the nature of the fast particles in the beam that passes through the gas, or by analyzing the slow ions and electrons that appear in the gas upon passage through it of a beam of fast ions.

Realizing the importance of these measurements, we undertook to repeat the experiments with the aim of removing, as far as possible, the errors peculiar to the method of slow particle collection.

* Process (2) can take place only when atom A has a positive electron affinity.

[1] H. S. W. Massey and E. H. S. Burhop, *Electronic and Ionic Impact Phenomena*, Ch. VIII, Oxford University Press, 1952

[2] H. Bartels, Ann. Physik **13**, 373 (1932)

[3] H. Meyer, Ann. Physik **30**, 635 (1937)

[4] J. P. Keen, Phil. Mag. **40**, 369 (1949)

[5] W. Sherwin, Phys. Rev. **57**, 814 (1940)

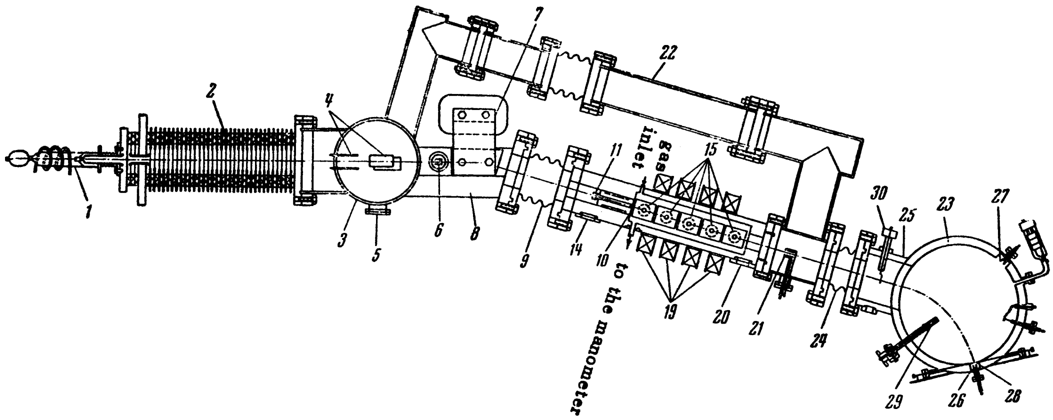

FIG. 1

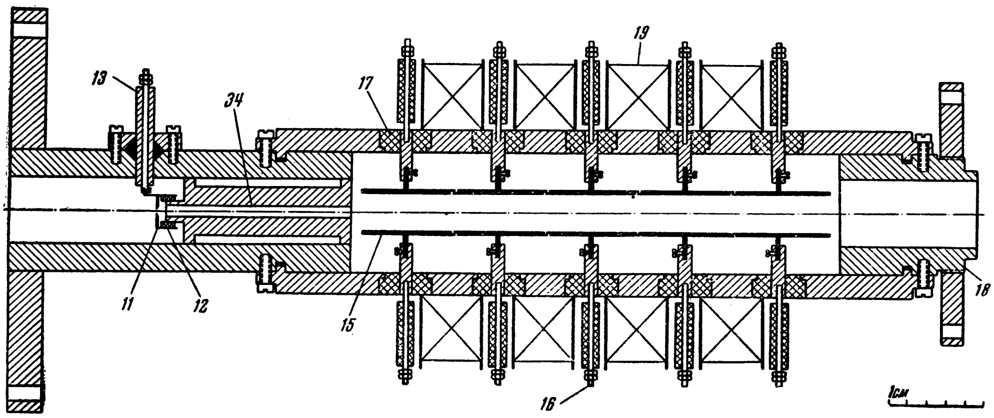

FIG. 2

The method of our measurements is similar to the experiments of Bredov and Fedorenko with some additions that yield somewhat better precision.

During the course of our experiments on single electron capture and ionization with protons in hydrogen, we were the first to observe the phenomenon of double electron capture by protons in a single collision with a hydrogen molecule, and to obtain a tentative value for the effective cross section of this process.

DESCRIPTION OF THE APPARATUS

Figure 1 is a schematic drawing of our experimental equipment.

As a proton source we used a high frequency ion source *1* of the type employed by Tonemann[7]. Having passed through the focusing and accelerating electrodes *2*, the beam of hydrogen ions entered the chamber that connected the equipment to the vacuum system. In this chamber *3* were found a pair of crossed plane condensers *4* that constituted the electrostatic corrector for the beam direction. The focusing of the beam was observed through the window *5*. In order to measure the ionic beam current we used a Faraday cylinder so mounted that it could be removed from the path of the beam.

In order to remove protons from the ion beam, we used a mass monochromator *7* with a beam rotation of 15°. The magnetic field of the mass monochromator was enough to give a 60 kev proton beam. The mass monochromator was connected to the collision chamber *10* by means of a flexible connection *9*. This allowed the proper orientation of the collision chamber with the beam.

A cross sectional drawing of the collision chamber is shown in Fig. 2. The proton beam enters the collision chamber through the diaphragm *11* which is insulated from the body of the instrument by means of ring *12*. Input *13* was used to

[6] M. M. Bredov and N. V. Fedorenko, Zh. Tekhn. Fiz. 20, 1464 (1950)

[7] P. S. Tonemann, J. Moffatt, D. Roaf and J. H. Sanders, Proc. Phys. Soc. (London) 61, 483 (1948)

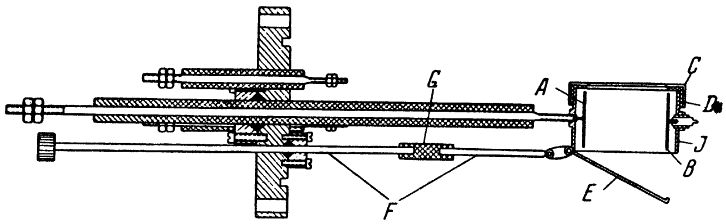

FIG. 3

apply voltage to the diaphragm. The beam then entered the measuring space of the chamber through a tube *34* which was 5 mm in diameter and 100 mm long. The passage of the beam through the entrance diaphragm could be observed through window *14*. The measuring space consisted of five plane condensers *15* with electrodes 50 by 50 mm^2 in area and a separation of 20 mm. Voltage to the condensers was applied through electrodes *16* that were insulated from the body of the chamber by means of polystyrene washers. The main body of the chamber consisted of a copper block *18* of rectangular cross section. A space for the various electrodes was milled out inside this block.

Four coils *19*, wound around the chamber, were used to introduce a longitudinal magnetic field. By means of these coils a magnetic field of the order of 300 oersteds could be introduced into the chamber. The proton beam emerged from the measuring chamber through a canal 35 mm in diameter and 74 mm long. A viewing window *20* was used to observe the beam as it emerged from the collision chamber. Hydrogen was allowed into the chamber through a palladium filter from a steel tank that held the gas at a pressure of 5 atmospheres. The pressure inside the chamber was measured with a McLeod gauge. A mercury vapor trap was installed between the McLeod gauge and the chamber.

The proton beam current was measured with a Faraday cylinder *21* shown in Fig. 3. Two electrodes *A* and *B* inside the Faraday cylinder *J* served to introduce a transverse electric field that prevented secondary electron emission from the cylinder. The entrance to the cylinder was covered with a circular diaphragm *C* that had an opening of diameter 17 mm, and that was insulated from the body of the cylinder with a polystyrene ring *D*. This diaphragm was intended to limit the degree of dispersion of the proton beam. The cylinder had a movable bottom *E*, connected to rod *F* that was insulated from the ground with a polystyrene connector *G*. The collision chamber was connected to the vacuum system by means of a brass tube *22*, 140 mm in diameter. After the collision chamber, the proton beam entered the space of the magnetic analyzer *23* that was between the poles of an electromagnet. The magnetic analyzer was oriented in the direction of the beam by means of the flexible connection *24*.

The analyzing chamber was a brass ring of outer diameter 290 mm, inner diameter 220 mm and height 20 mm. The covers consisted of iron discs 290 mm in diameter and 30 mm thick. An iron pipe *25* connected the analyzer to the rest of the equipment. This pipe was made of iron in order to minimize the spreading of the beam as it enters the chamber. Inside the analyzer were two Faraday chambers *26* and *27*, so arranged as to intercept protons and negative hydrogen ions that were deflected through an angle of 60°. A regulating slit *28* was placed in front of cylinder *26* that served to measure the proton component of the beam. No special precautions were taken to avoid secondary emission from the Faraday cylinders in the analyzer since they were in the presence of a magnetic field.

A ballistic coil *29* was used to measure the magnetic field inside the analyzing chamber. After its assembly, the analyzing chamber was placed between the poles of an electromagnet. The diameter of the poles was 290 mm. The distance between the pole faces was 80 mm, leaving ample room for the analyzer. The field inside the analyzer could be as high as 6000 oersteds.

The current in the measuring electrode was measured with a mirror galvanometer of sensitivity 1.8×10^{-10} amperes per division. The beam current was measured with a shadow galvanometer of sensitivity 6.9×10^{-9} amperes per division. The current in the Faraday cylinders inside the analyzing chamber was measured with a constant deflection string electrometer. By switching in different values of resistances, the sensitivity of the electrometer could be changed. We used resistances with values of 1.4×10^{11} and 3.1×10^{9} ohms.

The energy of the protons was determined by the various potentials applied to them. These included the emission potential, the focusing potential and the accelerating potential. The first two were measured with an electrostatic voltmeter, while the last was measured with a system of graded resistors.

EXPERIMENTAL METHOD

Although in principle it should be easy to measure the cross section of single electron capture and ionization by the method of slow particle analysis, in practice, reliable results are to be expected only when the following conditions are satisfied:

a) The probability of all processes that occur during the collisions of protons with hydrogen molecules and that result in the appearance of slow charged particles must be small compared to the probability of single electron capture and ionization.

b) One must prevent the appearance in the measuring chamber of secondary electrons originating in the various parts of the instrument.

c) One must prevent the exchange of slow particles between the measuring space and the Faraday cylinders. This can be accomplished with a longitudinal electric field.

d) The spreading of the proton beam in the measuring chamber must be negligible.

e) One must prevent the emission of electrons from the measuring electrodes due to the impact of positive ions (cold emission) and photons (photoeffect).

f) The slow particles in the measuring chamber should be the result of a single stage process.

g) In measuring the proton beam current, one must account for the neutralization of some of the protons in the measuring chamber.

Preliminary experiments were performed in order to determine to what extent the above conditions were satisfied. As was mentioned in the introduction, in the interaction of protons with hydrogen molecules, double electron capture and double ionization may result, in addition to single electron capture and single ionization.[as a result of which there arise slow molecular ions of hydrogen and slow electrons {see Eqs. (5) and (7)}].

As a result of two electron capture slow protons appear in the measuring chamber while fast negative hydrogen ions appear in the beam. Two stage ionization gives rise to both slow electrons and slow protons in the measuring chamber [see Eqs. (6) and (8)].

With the aid of a mass spectroscopic analysis of the slow particles that appear in hydrogen when a proton beam passes through it, one can estimate the probability of the process of single electron capture and single ionization relative to the probability of the process of double electron capture and double ionization.

Such a mass spectroscopic analysis was performed by Keen[4]. The mass spectrum showed one peak of mass 2 (H_2^+ ions) and another smaller peak at mass 1 (protons). The intensity of the proton peak was only a few percent of the mass 2 peak. When fast He^+ ions were passed through hydrogen the mass spectrum showed a peak only at mass 2.

The results of mass spectroscopic analysis of the slow particles show that the probability of processes (6) and (8), that are related to the presence of slow protons, is small compared to the probability of processes (5) and (7).

Since the process of double electron capture by protons is connected with the appearance of fast negative hydrogen ions in the proton beam, it is possible to estimate the probability of this process by analyzing the beam after it passed through the collision chamber. Since our equipment included a magnetic analyzer after the collision chamber, it was possible for us to make this analysis. The results of this analysis confirm the conclusion, based on mass spectroscopic data, that the probability of double electron capture by protons is low.

A potential of 70 volts was applied between the inlet diaphragm and the body of the collision chamber in order to remove the possibility of the appearance of secondary electrons in the measuring space. This voltage on the diaphragm does not introduce an electric field into the measuring space because the two are separated by a long tube. This was confirmed by special measurements that showed that the positive voltage applied to the entrance diaphragm does not change the current even in the measuring electrode that is nearest to the diaphragm.

If the protons are allowed to strike the walls of the entrance canal then the secondary electrons may enter the measuring space and distort the results. That this is possible is shown in Fig. 4 which shows the ratio of the positive or negative current in the measuring electrode I_{eff} to the proton beam current I_0 as a function of the diameter of the entrance diaphragm.

The unequal distribution of negative current in the different measuring electrodes (the number of the electrode goes up as its distance from the entrance canal increases), as was observed for the case of entrance diameter of 3 mm and gas pressure of 8×10^{-6} mm Hg, shows that secondary electrons from the walls of the entrance canal do not penetrate into the measuring chamber. As the diameter of the diaphragm is decreased to 1 mm the

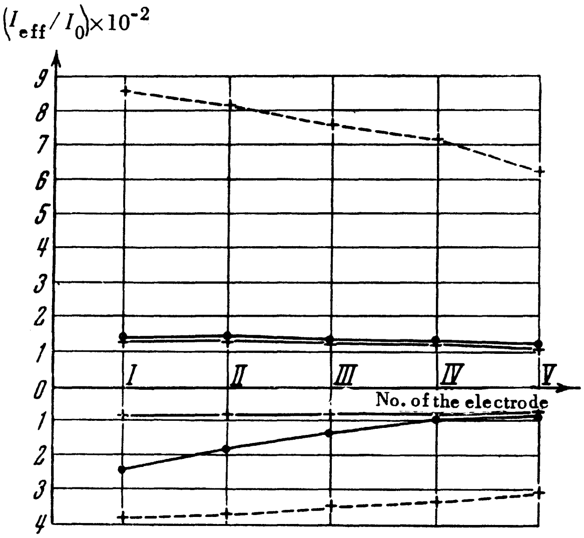

FIG. 4. Gas pressure in the chamber: solid line curves 8×10^{-6} mm Hg (background), dashed curves 6.5×10^{-4} mm Hg. Diameter of the diaphragm: ● = 3 mm, × = 1 mm.

phenomenon disappears. We therefore used a diaphragm of 1 mm diameter in our experiments. The slight decrease in the positive and negative currents that occurred at the pressure of 6.5×10^{-4} mm Hg as one passed from electrode one to five was due to the decrease in the number of protons in the beam because of neutralization.

We took measures to prevent the entrance of secondary electrons from the Faraday cylinder into the measuring space. To suppress secondary electron emission from the walls of the Faraday cylinder a transverse electric field was applied between electrodes A and B in Fig. 3. It was shown that when the potential difference between electrodes A and B is 150 volts, secondary electron emission from the Faraday cylinder is completely suppressed.

In order to suppress secondary electron emission from the diaphragm of the Faraday cylinder a positive potential was applied to it. To determine the magnitude of the potential necessary to suppress the secondary emission from the diaphragm of the Faraday cylinder, we measured the effect of positive voltage (on the diaphragm) on the negative current in the measuring electrodes. Figure 5 shows this effect on the fifth electrode, the one nearest to the Faraday cylinder. Similar curves were obtained for the other electrodes. The transverse electric field during these measurements was 160 volts. As Fig. 5 shows, complete suppression of secondary emission from the diaphragm of the Faraday cylinder obtains when the voltage applied to it is plus ten volts.

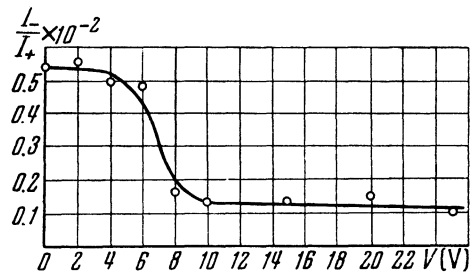

FIG. 5

The presence of a transverse potential difference in the Faraday cylinder can result in a longitudinal field that will encourage the exchange of slow particles between the Faraday cylinder and the measuring space.

The measurements shown in Fig. 6 show that the effect does not take place. Figure 6 shows the dependence of the positive current in the fifth electrode on the transverse potential difference in the Faraday chamber. The measurements show that the current in the electrode nearest to the Faraday cylinder does not depend on the transverse potential difference up to a voltage of 400 volts. During these measurements, the voltage on the diaphragm of the Faraday chamber was plus 10 volts. It is quite certain that there is no exchange of particles between the Faraday cylinder and the measuring space, since the two are separated by a long canal.

Figure 7 shows the current through the diaphragm of the Faraday cylinder as a function of the transverse potential across electrodes A and B (see Fig. 3) and plus ten volts applied to the diaphragm. The negative current through the diaphragm is due to the incidence upon it of part of the secondary electrons from the walls of the Faraday cylinder. When the transverse potential difference is of the order of 400 volts the current through the diaphragm becomes positive, because it collects some of the protons from the spreading proton beam. The small value of this current indicates the slight spreading of the proton beam in our experiments.

Control experiments on the spreading of the proton beam in the presence of positive current in the circular diaphragm of the Faraday cylinder indicate that the effect is so small that it may be neglected.

To avoid the possibility of secondary electron emission from the walls of the measuring electrodes we used a longitudinal magnetic field obtained from coils around the collision chamber. The magnetic field was made strong enough to return all secondary electrons back to the electrodes and yet not so strong as to prevent

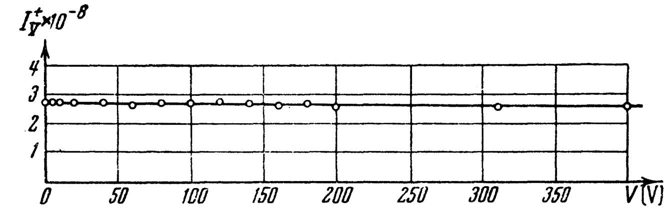

FIG. 6

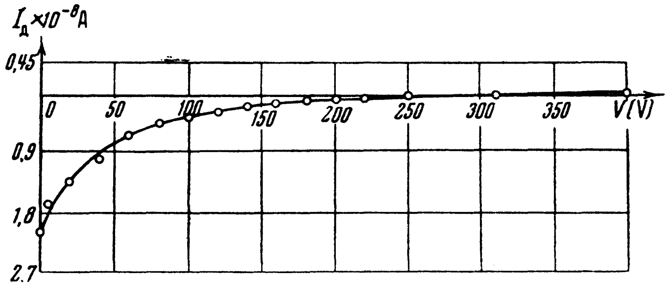

FIG. 7

positive ions from reaching the electrodes. The magnitudes of the positive and negative currents in the measuring electrodes in the presence of magnetic field can be expressed as follows:

$$i_+ = i_1 + i_2 + i_3, \tag{9a}$$

$$i_- = i_2 + i_3, \tag{9b}$$

where i_1 is the ionic current that results when the protons capture electrons from gas molecules, i_2 is the ionic or electronic current that results from the ionization of gas molecules by protons and i_3 is the current of secondary emission from the measuring condenser.

In the presence of a magnetic field, the positive and negative currents are given by:

$$i_+^H = i_1 + i_2, \tag{10a}$$

$$i_-^H = 0. \tag{10b}$$

From Eqs. (9a), (9b) and (10a) we obtain the following relations for i_1 and i_2:

$$i_1 = i_+ - i_- \tag{11a}$$

$$i_2 = i_+^H - (i_+ - i_-). \tag{11b}$$

By measuring the positive and negative current in the absence of a magnetic field and the positive current in the presence of a magnetic field, we can determine the ionic and electronic currents that arise from electron capture and ionization, without the distortion due to secondary emission.

The current-voltage characteristics of the measuring electrodes, with and without a longitudinal magnetic field of 70 oersteds, show that in both cases the current is saturated at a voltage of ±25 v.

Figures 8 and 9 show the dependence of the positive and negative currents in the measuring electrodes upon the pressure of hydrogen in the collision chamber and upon the strength of the beam current. As is seen from the graphs, the dependence is linear up to pressures of 3.5×10^{-4} mm Hg and beam currents of 0.5 micro-amperes. This indicates that the slow particles found in the gas are the result of single stage processes.

Having convinced ourselves that it is possible to eliminate the sources of systematic error, we began the measurements of the effective cross section.

The actual measurements of the positive and negative currents were made on electrode *IV*. Electrodes *III* and *V* were included as checks. Electrodes *I* and *II* were grounded.

The following potentials were used during our measurements: on the entrance diaphragm, + 70 v; on the diaphragm of the Faraday cylinder, + 10v; between the electrodes *A* and *B* of the Faraday cylinder, 400 v; and on electrodes *III*, *IV* and *V*, ± 25 v.

Keeping the energy of the proton beam constant, we first measured the positive and negative currents with the gas in the collision chamber at the terminal pressure of 6 to 8×10^{-6} mm Hg. Then the palladium filter was warmed until the hydrogen current was such that the pressure in the chamber was in the vicinity of 3 to 4×10^{-4} mm Hg. At this

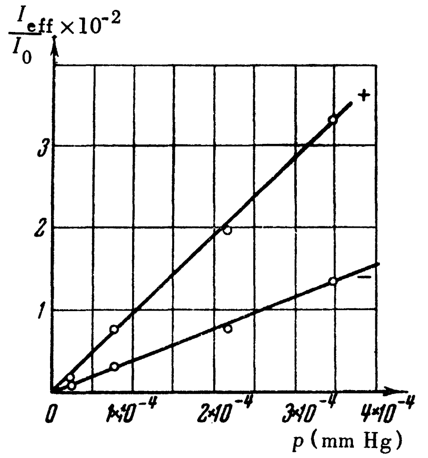

FIG. 8

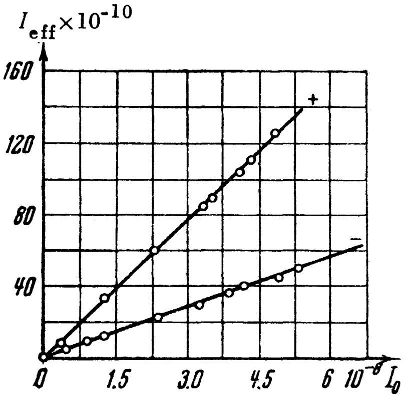

FIG. 9

pressure we again measured the positive and negative currents. During this measurement the pressure was measured at least twice The hydrogen stream was then shut off and again we measured positive and negative current at the residual pressure in the chamber. The values of the positive and negative currents, obtained at the residual pressures before and after hydrogen was introduced, were averaged, and this average value (the background) was subtracted from the corresponding values obtained while hydrogen was present.

The magnitudes of the positive and negative currents were taken as the average of ten readings. The proton beam current was constantly monitored in order to eliminate the effects of proton beam fluctuations on the results of our measurements.

The current measurements were made both with and without a magnetic field in the measuring chamber. The effective cross section of single electron capture and ionization, σ_{10} and σ_i, were calculated from the values of i_1 and i_2, which in turn were calculated [with the help of Eq. (11)] from the measured values of positive and negative current.

In calculating the values of σ_{10} and σ_i, we introduced a correction to account for the decrease of the proton beam due to neutralization of protons as the beam passes from the measuring condensers to the Faraday cylinder.

The calculations of σ_{10} and σ_i, including the correction, were made from the following equations:

$$\sigma_{10} = \left(\frac{i_+}{I_0} - \frac{i_-}{I_0}\right) T \left[9.65 \cdot 10^{18} pL \times \left\{1 + \frac{l_{эфф}}{L}\left(\frac{i_+}{I_0} - \frac{i_-}{I_0}\right)\right\}\right]^{-1}; \qquad (12a)$$

$$\sigma_i = \left\{\frac{i_+^H}{I_0} - \left(\frac{i_+}{I_0} - \frac{i_-}{I_0}\right)\right\} T \left[9.65 \cdot 10^{18} pL \times \left\{1 + \frac{l_{eff}}{L}\left(\frac{i_+}{I_0} - \frac{i_-}{I_0}\right)\right\}\right]^{-1}, \qquad (12b)$$

where l_{eff} is the effective length of the collision chamber, L the length of the measuring electrode, p is in mm Hg, T is in absolute degrees and I_0 is the initial value of the beam current.

The errors of a single determination of σ_{10} and σ_i are 12 and 18% respectively. A considerable part of the error (8%) is due to the inaccuracy of the pressure determination with the McLeod gauge. Errors in the energy determination of the protons account for another 3%.

We did not make a great effort to reduce the random error in these measurements since our aim was to develop a method that eliminated the systematic errors that at times may distort the results two or three fold (see the discussion of Sherwin's measurements[5] in the paper by Bredov and Fedorenko[6]).

TABLE I

Energy of Protons in kev	$\sigma_{10} \times 10^{16}$ in cm^2	$\sigma_i \times 10^{16}$ in cm^2
12.3	8.1	1.4
16.6	6.5	1.5
20.8	5.2	1.6
25.4	4.5	1.7
29.7	3.6	1.8
33.0	3.1	2.0
36.7	2.6	2.2

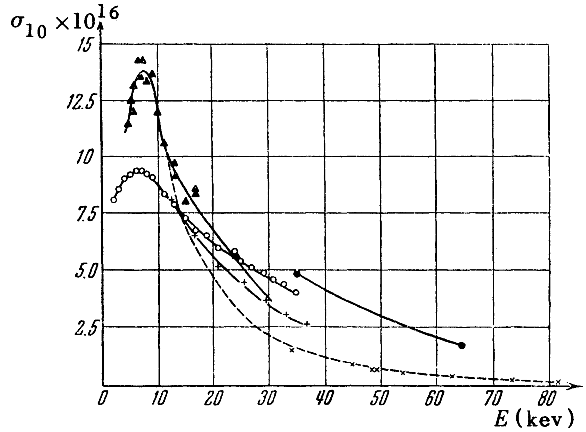

FIG. 10. σ_{10} as a function at proton energy according to: ▲-Bartels[2]; ○-Keen[4]; ● -Meyer[3]; ±-Our results; × -Ribe[8]; Dashed curve = theoretical results of Jackson and Shiff[9].

RESULTS OF THE MEASUREMENTS

Using the method described above we measured the effective cross section of single electron capture and ionization by protons in hydrogen. The energy of the protons varied from 12.3 to 36.7 kev.

The results of our measurements are shown in Table I.

In Fig. 10 we plot the effective cross section σ_{10} as a function of proton energy from our data, and also similar curves as obtained by Bartels[2], Meyer[3], Keen[4] and Ribe[8].

As is seen from the graphs, the results obtained by different authors are in very poor agreement. Even those results obtained by the same method differ considerably. Thus the points obtained by Meyer do not lie on the extension of Bartel's curve into the high energy region even though the two used the same experimental method. Bartels and Keen established the maximum value of the cross section σ_{10} at 7 kev, but the magnitude of σ_{10} as measured by Bartels is always greater than that obtained by Keen for all the measured values of proton energies. The magnitude of σ_{10} in reference 8 is considerably less than in all the other works. This may be explained by the distorting influence of double collisions of protons with hydrogen molecules.

Our results agree best with those of Keen, whose experiments were also based on the method of slow particle collection. Our values of σ_{10} are almost invariably lower than those of Keen in all regions of proton energies that were used.

Theoretical calculations of the effective cross section of electron capture by protons in hydrogen* were made in references 9 and 10.

Both calculations considered the capture of electrons in the principal state 1s as well as the excited states 2s, 2p, etc. The results obtained by the two authors were similar. In view of the fact that the Born approximation was used in the above calculations, the results can be correct only for energies above 25 kev (when the energy is 25 kev the proton velocity is the same as the velocity of the electrons in hydrogen). Nevertheless, the authors in reference 9 compare their theoretical results with the experimental values in reference 8 and conclude that there is good agreement between theory and experiment up to 33 kev (the lowest proton energy used in reference 8). A glance at Fig. 10, that plots the theoretical results alongside the experimental shows that, with the exception of the work by Ribe, the agreement between theory an experiment is very poor. Considering the fact that the theoretical calculations neglected the effect of the hydrogen bond and also that the Born approximation is not good in the vicinity of 25 kev, we believe that the divergence of our data and Keen's from the theoretically predicted values is a better representation of the true state than the agreement found between the theory and the results of Ribe [8].

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[8] F. L. Ribe, Phys. Rev. **83**, 1217 (1951)

* These authors calculated the effective cross section of electron capture by collision of protons with atomic hydrogen.

[9] J. D. Jackson and H. Shiff, Phys. Rev. **89**, 359 (1953)

[10] D. R. Bates and A. Dalgarno, Proc. Phys. Soc. (London) **A65**, 919 (1952); **A66**, 972 (1953)

Our results on the effective cross section of ionization of hydrogen by protons can be compared only with the results of Keen, since no other work in this energy region is known to us.

Figure 11 shows the magnitude of σ_i as a function of energy obtained by us and by Keen[4]. The graphs show a constant difference between the two results, those obtained by the present authors always higher at all proton energies. This can be explained by the fact that in Keen's set up there was always a longitudinal field between the Faraday cylinder and the measuring space. This field produced a force that tended to pull electrons from the measuring space. This effect decreased the value of the measured cross section of ionization. If our interpretation is right, then the values of σ_{10} obtained by us and by Keen must differ, and the difference should increase with increase in proton energy. This is indeed so, as may be seen in Fig. 10.

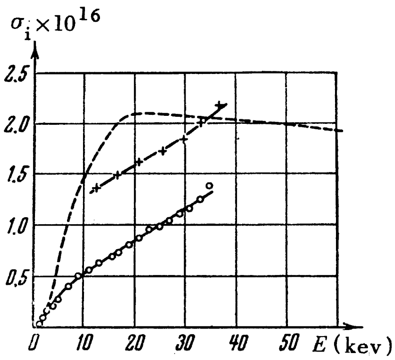

FIG. 11. σ_i as a function of proton energy according to: ○ - Keen[4]; + - Our results; Dashed curve = theoretical results by Bates and Griffing[11].

A theoretical calculation of the effective cross section of the ionization of hydrogen atoms by means of protons was made by Bates and Griffing[11]. These calculations also used the Born approximation. The results of the calculations are shown in Fig. 11 as a broken line. Again there is a considerable difference between the theoretical values and the experimental results. Not only are the theoretical values almost at all energy levels higher than the experimental results, but they go through a maximum in the region of 2 to 36 kev whereas the experimental results rise monotonically throughout this energy interval. The difference between the theoretical and experimental values of σ_i can be explained in the same manner as the corresponding differences in σ_{10}.

RESULTS ON STUDIES OF THE CAPTURE OF TWO ELECTRONS BY PROTONS FROM HYDROGEN

Because of the stability of negative hydrogen ions, it is possible for a proton to capture two electrons from a molecule of hydrogen [see process (6)].

To calculate the possibility of the formation of negative hydrogen ions in a beam passing through matter, the following differential equations apply:

$$dN_+ / d(nx) = -(\sigma_{10} + \sigma_{1-1}) N_+ + \sigma_{01} N_0 + \sigma_{-11} N_-; \tag{13a}$$

$$dN_0 / d(nx) = \sigma_{10} N_+ - (\sigma_{01} + \sigma_{0-1}) N_0 + \sigma_{-10} N_-; \tag{13b}$$

$$dN_- / d(nx) = \sigma_{1-1} N_+ + \sigma_{0-1} N_0 - (\sigma_{-11} + \sigma_{-10}) N_-, \tag{13c}$$

where N_+, N_0 and N_- represent the number of protons, hydrogen atoms and negative hydrogen ions in the beam, respectively, and σ_{ik} the cross section for the transition from one particle to the other [for example σ_{1-1} is the cross section for process (6), σ_{10} the cross section for process (5) and so on].

To determine the cross section of the capture by protons of two electrons σ_{1-1}, we can use the differential equation (13c) which, under the initial conditions $N_+ = N_+^*$, $N_0 = 0$ and $N_- = 0$ (meaning that the initial beam consists of protons only) takes the form

$$\left[\frac{dN_-}{d(nx)}\right]_{nx=0} = \sigma_{1-1} N_+^* ,$$

from which

$$\sigma_{1-1} = \frac{1}{N_+^*} \left[\frac{dN_-}{d(nx)}\right]_{nx=0} \tag{14}$$

If we substitute the corresponding currents in Eq. (14) for the number of particles and use the pressure p as a measure of n, we have the following relation for σ_{1-1}:

$$\sigma_{1-1} = 1.08 \cdot 10^{-19} \frac{T}{L} \left[d\left(\frac{I_-}{I_+^*}\right) \Big/ dp \right]_{p=0} , \tag{15}$$

[11] D. R. Bates and S. Griffing, Proc. Phys. Soc. (London) **A66**, 961 (1953)

where L is the length of the gas interval, I_- is the current of negative ions and I_+^* is the current of the entering proton beam.

In principle, the determination of σ_{1-1} from Eq. (15) depends on the determination of the dependence of the ratio I_- / I_+^* on the gas pressure. The magnitude of $\frac{d}{dp}\left(\frac{I_-}{I_+^*}\right)$ is determined from the linear portion of this curve. The presence of the linear portion depends on the formation of negative ions of hydrogen by single collisions of the type described in Eq. (6).

Because ouf equipment contained magnetic analyzer after the collision chamber, we were able to analyze the beam after its passage through the gas and thus determine the cross section σ_{1-1}.

The following method was used to measure σ_{1-1}. The proton beam passed the outlet diaphragm of the collision chamber into the magnetic analyzer where it was deflected through an angle of 60°, thus entering the Faraday cylinder marked *26* in Fig. 1. The negative hydrogen ions in the beam, which arose because of capture of electrons by protons, were deflected in the magnetic field through an angle of 60° in the opposite direction and fell into Faraday cylinder *27*. In this manner we could measure the ratio of the negative ion current to the proton current I_- / I_+.

A simple calculation showed that the measured value of I_- / I_+ did not differ from $(I_- / I_+)_0$, its value before entering the analyzer, by more than 3%.

Equation (15) contains the ration I_- / I_+^*, where I_+^* is the proton beam current before it enters the gas space. Because some protons are neutralized in the passage from the entrance diaphragm to the analyzer, the magnitude I_- / I_+ is somewhat different from the magnitude I_- / I_+^*. Even at the highest pressure on the linear portion of the curve in Fig. 12, this difference is less than 10%. Since the errors in pressure measurements in this range are considerably greater, we made no corrections for this effect.

Figure 12 is a graph of the tatio I_- / I_+ as a function of hydrogen pressure for protons of energy 21 kev. In constructing the curve, we subtracted the value of the background ratio $(I_- / I_+)_{\text{background}}$ from the measured value of I_- / I_+. The background is the value I_- / I_+ measured at the residual pressure, which was of the order of 6 to 8 $\times 10^{-6}$ mm Hg.

As can be seen from Fig. 12, I_- / I_+ varies linearly with pressure at low pressures. As the pressure goes up, the curve deviates from linearity

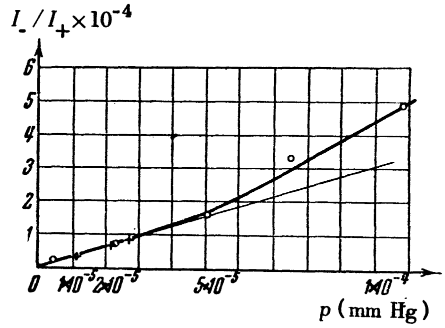

FIG. 12

because of the increased probability of two consecutive collisions between the particles in the beam and the gas molecules.

The magnitude of the differential $d(I_- / I_+) / dp$ can be obtained from the linear portion of the curve, and the value of σ_{1-1} can then be determined with the help of Eq. (15).

Using this method, we determined the effective cross section with three proton energies. The results are shown in Table II.

TABLE II

Energy of Protons in kev	$\sigma_{1-1} \times 10^{18}$ in cm^2
13.0	2.7
21.0	2.3
31.4	1.1

The error of a single determination is about 50%, due largely to the inaccuracy of the pressure determination in the linear region of the graph $(I_- / I_+) = f(p)$.

The data shown in Table II indicates that the effective cross section of double electron capture by protons is much smaller than the cross section for single electron capture. From this we conclude that the effective cross section σ_{10} for single electron capture by protons as measured by us is not materially distorted by the presence of the process of double electron capture.

The observation of negative hydrogen ions arising from the process of double electron capture by protons upon collision with hydrogen molecules has not previously been observed by others. We undertook a preliminary study of thisphenomenon in order to determine its effect on the determination of the cross section of single electron capture. However, the proton capture of two electrons resulting in the formation of negative hydrogen ions is in itself of interest. We intend to improve our experimental method and continue the study of double electron capture by protons and the resulting negative ions, using a variety of positive ions with positive electron affinities.

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