RESONANCE CHARGE EXCHANGE OF PROTONS AND DEUTERONS AT LOW ENERGIES

V. A. BELYAEV, B. G. BREZHNEV, and E. M. ERASTOV

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The method of overtaking beams has been used to measure the cross sections for resonance charge exchange of protons in hydrogen atoms and deuterons in deuterium atoms in the energy range 5—100 eV. A comparison has been made with previously published experimental and theoretical values.

1. INTRODUCTION

FOR a correct understanding of a large number of processes occurring in gas discharges, the upper atmosphere, high temperature plasmas, and a whole series of other physical phenomena, it is necessary to have information on the cross sections for ion-atom collisions occurring at low energies (1—100 eV). Although a good many studies have been devoted to the theoretical discussion of this question, a general theory giving true quantitative results has not yet been produced. The experimental methods existing at the present time are not very suitable for obtaining information of this type, both because of the difficulty in producing monochromatic beams of low energy particles with sufficient intensity, and also because of the difficulties necessarily encountered in passing these beams through equipment and detecting them. In addition, the complexity of taking into account all of the parasitic processes occurring in the collision chamber (scattering of the primary beam by the target, energy change of the primary ion beam particles in the region of the collision by the electrostatic field of the electrodes which collect the reaction products) can result in appearance of large systematic errors in these methods. It therefore becomes important to develop new experimental methods of studying ion-atom collisions at low energies, free from the difficulties cited. One of these methods is the method of overtaking beams.[1]

In this method, two monochromatic particle beams intersect at an angle close to or equal to zero. As the result, a low relative velocity of the colliding particles (and consequently also a low energy of their collision) can be obtained at rather high energies, convenient for experiment, of the beam particles in the laboratory system, with the possibility of making measurements even at collision energies below the energy spread in the beams.

This method provides the possibility of obtaining the data necessary both for solution of practical problems and also for further development of the theory of ion-atom collisions at low energies and, in particular, for verification of the existing results obtained in those parts of the theory which have already been well developed (for example, resonance charge exchange[2-5]).

In the present work we have used the method of overtaking beams to measure the cross sections for resonance charge exchange of protons in hydrogen atoms:

$$H^+ + H \rightarrow H + H^+$$

and of deuterons in deuterium atoms:

$$D^+ + D \rightarrow D + D^+$$

in the energy range 5—100 eV.

2. DETERMINATION OF THE CROSS SECTION FOR THE CHARGE-EXCHANGE PROCESS

Let a beam of atoms with velocity v_1 and density n intersect at an angle φ a beam of ions with velocity v_2 and current i_2 so that in the intersection the ion beam passes completely inside the atomic beam. As the result of charge exchange, a fraction of the atoms of the first beam are converted to ions. The value of the current i of these newly formed ions (the "effect current") will be

$$i = i_2(1 - e^{-n\sigma v t}). \qquad (1)$$

Here σ is the cross section for charge exchange for a relative velocity $v = (v_1^2 + v_2^2 - 2v_1v_2\cos\varphi)^{1/2}$; t is the duration of the interaction, which is given by L/v_2, where L is the distance traversed by the ion beam inside the atomic beam. In the case when the duration of the mean free path $(nv\sigma)^{-1}$ considerably exceeds the time during which the ion is in the interaction region (this condition is always satisfied in the experiments described), expression (1) can be written in the form

$$i = i_2 n\sigma L(v/v_2).$$

Hence, taking into account that $n \sim i_1/sv_1$ (where i_1 is the intensity of the atomic beam and s is the cross section of the atomic beam in the region of the collision) and expressing the velocities in terms of the corresponding energy values, we obtain for the resonance charge-exchange cross section the following expression:

$$\sigma(T) = K\frac{s}{L\sqrt{M}}\frac{i}{i_1 i_2}\sqrt{\frac{T_1T_2}{T}}, \qquad (2)$$

where M is the mass of the colliding particles, T_1 is the energy of the atoms, T_2 is the energy of the ions, T is the energy of the ions in a frame of reference traveling with the particles of the atomic beam (the "collision energy"), and K is a numerical coefficient.

Expression (2) provides the possibility, for known parameters of the interacting beams and effect current, of calculating the cross section for a collision energy $T = T_1 + T_2 - 2\sqrt{T_1T_2}\cos\varphi$. In practice the interacting beams will always have a certain energy spread and angular divergence, as the result of which the measured effect current will have contributions from interactions occurring for a certain set of values of T, which leads to an uncertainty in the value obtained for $\sigma(T)$.

As we have shown previously,[6] in the study of collisions occurring between atoms and ions of the same material it is desirable to use spatially superposed beams traveling in the same direction. Here, if the greatest possible collision angle is α, then for strictly monochromatic beams the possible values

$$T(\varphi) = |\sqrt{T_1} - \sqrt{T_2}|^2 + \varphi^2\sqrt{T_1T_2}$$

(for $\varphi \ll 1$) will lie in the interval $T(0) \leq T(\varphi) \leq T(\alpha)$. Taking as an average value

$$T = \frac{T(0)+T(\alpha)}{2} = |\sqrt{T_1} - \sqrt{T_2}|^2 + \frac{\alpha^2}{2}\sqrt{T_1T_2}, \qquad (3)$$

and assuming an energy spread $\pm(\Delta T_1/T_1)$ and $\pm(\Delta T_2/T_2)$ in the atomic and ion beams, respectively, we obtain the following expression for determination of the possible values of collision energy:

$$\pm\frac{\Delta T}{T} = \sqrt{\frac{T_1}{T}}\left(\frac{\Delta T_1}{T_1}\right) + \sqrt{\frac{T_2}{T}}\left(\frac{\Delta T_2}{T_2}\right) + \frac{\alpha^2\sqrt{T_1T_2}}{2T}. \qquad (4)$$

From this expression we can see the advisability of using particle beams of the smallest possible energy, since an increase in particle energy in the beams will require increased monochromaticity and smaller divergence angle of the interacting beams to obtain given values of T and ΔT. Thus, in the case $T_1 \approx T_2 \approx 1000$ eV, to obtain T = 10 eV with an accuracy of 20% the monochromaticity of the beams must be ±0.5% for a total angular divergence of each beam $\alpha \approx 2.5°$, if both of these factors contribute equally to the uncertainty. In the same case, when $T_1 \approx T_2 \approx 10\,000$ eV, a beam monochromaticity of ±0.16%, for $\alpha \approx 0.8°$, is required to obtain T = 10 eV with the same accuracy. However, marked decrease in the energies of the interacting beams can lead to difficulties inherent in the generally used methods of studying ion-atom collisions at low energies. Therefore the severe requirements for monochromaticity and angular divergence of the interacting beams are necessary in the method described.

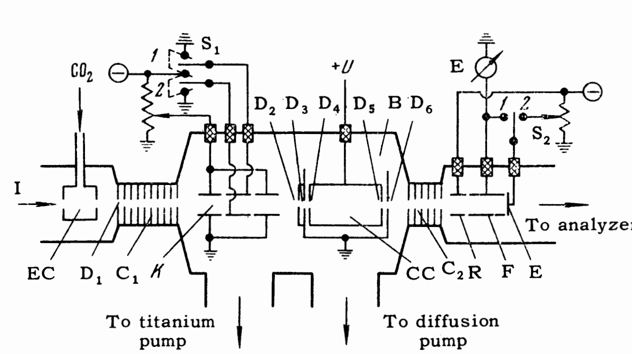

FIG. 1. Diagram of the experimental apparatus: I – primary ion beam, EC – charge-exchange chamber, D_1–D_6 – circular diaphragms, C_1, C_2 – vacuum impedences, K – clearing analyzer, CC – collision chamber, B – high vacuum vessel, F – Faraday cup, 3 – movable bottom of Faraday cup, R – reflector, S_1, S_2 – switches, E – electrometer.

3. EXPERIMENTAL SETUP

In the present work the interacting beams were produced by an ion source of the oscillating type, operating in a longitudinal magnetic field. The anode of the source was maintained at a potential of +1 kV with respect to the system. Ions extracted from the source and shaped into an ion beam by means of a two-lens system were directed into a monochromator magnet which provided second-order spatial focusing at a bending angles of 90°. The energy dispersion of the monochromator (for equal masses) was 0.2% per mm. A diaphragm D_2 2 mm in diameter (see Fig. 1) was placed at the focus of the monochromator. This gave the possibility of separating from the total ion flux, which had a large energy spread produced by the discharge voltage of the source, a monochromatic proton (deuteron) beam with energy $T_1 \approx 1000 \pm 2$ eV and a current $i_2 \sim 10^{-7}$ A.

Particles passing through the diaphragm D_2 entered the collision chamber CC, which was made in the form of a cylinder whose side surface consisted of fine wires arranged parallel to the generatrix to improve pumping. At the ends of the cylinder and coaxially with it were placed circular apertures D_4 and D_5. The dimensions of these apertures, as well as those of D_3 and D_6, provided unobstructed passage for particles transmitted by diaphragm D_2. The angular divergence of the beam entering the collision chamber was determined by diaphragms D_1 and D_2 and was $\alpha = 1°20'$.

In front of D_1 was placed a charge-exchange chamber EC filled with CO_2. A fraction of the ions (~10%) were neutralized in the charge-exchange chamber. The small difference in the ionization potentials of CO_2 and H (or D) (~0.2 eV) enabled us to assume that the ion and atomic beams entering the collision chamber had practically the same energy and degree of monochromaticity. On neutralization of the ions in the charge-exchange chamber, part of them could capture an electron into a metastable level (2s). To convert the metastable atoms to the ground state, they were passed through an electrostatic field produced by the electrodes K placed directly in front of the collision chamber. The value of the field was chosen in accordance with the results obtained by Sellin.[7] The electrodes were divided into three sections, the field in the center section being opposite to that in the edge sections (S_1 in position 1). The ratio of the fields in the sections was chosen so that the ion beam, after passing through the electrodes, returned to the extension of its previous trajectory.

The collision chamber was isolated from the system and held at a potential +U, which slowed the ions to an energy $T_2 = T_1 - U$. By this means we, first, provided the difference in energies of the ions and atoms necessary to obtain the required collision energy T and, second, fixed the length for interaction since, on traversing the collision chamber, ions which have not undergone the reaction acquire again an energy T_1. Those ions which were formed in the collision chamber from atoms (and had therefore an energy T_1 in the collision chamber) were accelerated on leaving the chamber to an energy $T_1 + U$. This gave the possibility of separating them subsequently from the total particle flux and recording them.

To obtain the length of interaction, we used an electrolytic bath to obtain the potential distribution along the collision chamber axis (Fig. 2a). The analyzer to which the total flux of particles leaving the collision chamber was directed was arranged to separate only those ions whose energy was $(T_1 + U) \pm \Delta T_1$. Therefore we took for the length of interaction the dimension L shown in Fig. 2b. The value of ΔL depended on the value of U and in the present experiments did not exceed 1% of L.

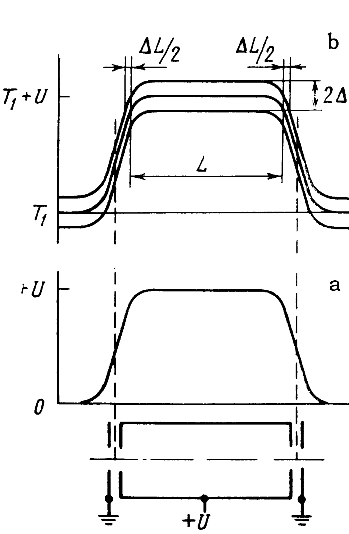

FIG. 2. Potential distribution along collision chamber axis (a) and ion energy at the input to the energy analyzer as a function of the place of formation of the ion from an atom (b).

The weakly focusing electrostatic lens formed by diaphragms D_2, D_3, and D_4 at the entrance to the collision chamber guaranteed passage of the ions inside the atomic beam during the entire length of interaction.

Ions with energy T_1 could be formed in the collision chamber not only as the result of resonance charge exchange but also as the result of other processes, which thus produced a parasitic current i_0. The main contribution to this current was from stripping of atoms in the residual gas. To reduce i_0 the collision chamber was placed in a high-vacuum enclosure B evacuated by two pumps: an oil diffusion pump with an extended nitrogen trap and a titanium pump. The vacuum impedences C_1 and C_2 which consisted of a set of diaphragms and which separated the high vacuum region from the remaining apparatus enabled us to maintain a vacuum of at least 2×10^{-9} mm Hg in the region of the collision chamber during the experiment.

The ions formed in the collision chamber $(i + i_0)$ were separated from the total particle flux leaving the collision chamber by means of a two-step energy analyzer described by us previously[6] and consisting of a sector magnet with spatial focusing (first step) and cylindrical electrostatic analyzer (second step). The ions separated by the analyzer were recorded by a detector similar to that described by Afrosimov et al.[8] and consisting of a scintillation counter recording secondary electrons knocked out of a metal plate by the ions and accelerated to 15 keV. Before each measurement the detector was calibrated by means of an Edelman-Lutz string galvanometer.

4. MEASUREMENTS

The intensities of the interacting beams were measured by a Faraday cup F (Fig. 1) whose bottom 3 could be removed to provide free passage of all particles from the collision chamber to the entrance of the analyzer. The bottom of the cup was insulated and had a separate lead. This made it possible to measure both ion current i_2 (S_2 in position 1) and the current of secondary electrons produced in the bottom of the cup by ions (i_2^-) and by atoms (i_1^-) (S_2 in position 2), the ion beam being removed by the analyzer K during the measurements of i_1^- (S_1 in position 2). The negative potential of the reflector R provided complete suppression of secondary electrons in the cavity of the Faraday cup. The intensity of the atomic beam was calculated from the formula $i_1 = i_2 i_1^-/i_2^- \chi$, where χ is the ratio of the coefficients of secondary electron emission arising from incidence of atoms and ions with energy T_1 on the bottom of the cup (see Appendix).

To compute the values of the cross section for each separate value of T we measured the effect current i. With the analyzer set to the energy of the effect ions (T_1 + U) the detector, in addition to the effect current, measured the parasitic current

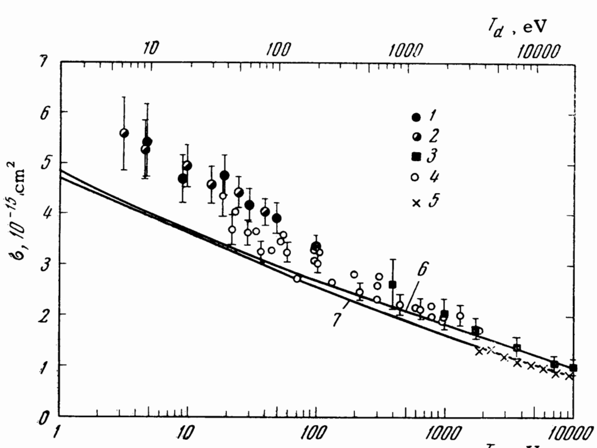

FIG. 3. Cross sections for resonance charge exchange of protons in hydrogen atoms (1, 3–7) and deuterons in deuterium atoms (2) as a function of the collision energy: 1, 2 – present work, 3 – [10]; 4 – [11]; 5 – [12]; curves – theoretical: 6 – according to [4], 7 – according to [3]. The values of proton energy T_p and deuteron energy T_d, which coincide on the plot, correspond to the same relative velocities of the particles in H^+–H and D^+–D collisions.

i_0 and also a certain instrumental background i_b, i.e., the current measured was $I_1 = i + i_0 + i_b$. In the case when the ion beam (i_2) was deflected by the field of the analyzer K (S_1 in position 2), the entire ion current leaving the collision chamber was the result of stripping of atoms in the residual gas, and the detector measured a current $I_2 = i_0 + i_b$.

The value of the effect current was determined as the difference $i = I_1 - I_2$ and in the measurements performed was 10^{-17}—10^{-16} A. Although this current could be due both to resonance charge exchange and also to ionization of atoms by the ion beam, nevertheless, because of the difference in the values of the cross section for these processes by several orders of magnitude in the energy region being studied (see, for example, Bates and Dalgarno[9]), ionization was not taken into account in the calculations.

5. RESULTS

The results of measurements made in the energy interval 5—100 eV are given in Fig. 3. The cross sections were calculated according to formula (2), the uncertainty in the cross sections shown in the figure resulting mainly from the statistical error in measurement of the effect current and the presence of energy and angular spreads in the interacting beams, according to Eq. (4).

Since the interacting particles in D^+-D collisions differ from those in H^+-H collisions only in their masses, it is natural to assume that the cross sections for resonance charge exchange in these two cases are equal at collision energies corresponding to the same interaction time and, consequently, to the same relative velocities of the colliding particles. However, Fite and co-workers,[13] in measurements of resonance charge exchange for protons and neutrons in the energy region 200—1000 eV, obtained a result not in agreement with this assumption. Therefore in the energy region studied in the present work we measured the cross sections for resonance charge exchange both for protons and for deuterons. As can be seen from Fig. 3, the measurements gave complete agreement of the cross sections for the same relative velocities of the particles in D^+-D and H^+-H collisions.

In addition to the results of the present work, Fig. 3 shows the resonance charge-exchange cross-section values for protons in hydrogen atoms obtained in previous experimental[10-12] and theoretical[3,4] studies. All of the experimental results are in good agreement among themselves. The agreement with the theoretical calculations is also quite

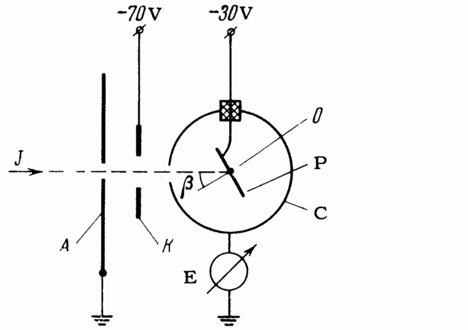

FIG. 4. Diagram of apparatus for determining χ: J – atomic, ionic beam, A – aperture diaphragm, P – metallic plate, O – axis of rotation of plate, C – collecting cylinder, K – reflector, E – electrometer.

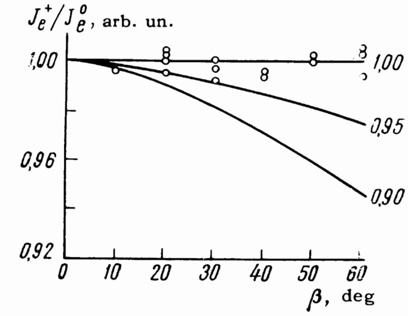

FIG. 5. Ratio of currents of secondary electrons knocked out of a metal plate by fluxes of protons (J_e^+) and hydrogen atoms (J_e^0), as a function of angle of incidence of the particles on the plate. The smooth curves show the expected behavior of the ratio J_e^+/J_e^0 for different values of χ; the values of χ were taken for $\varphi = 0°$.

satisfactory, although the set of experimental data presented in Fig. 3 indicates a discrepancy between experiment and theory arising with decreasing energy. The cause of this discrepancy is unknown.

6. CONCLUSION

The experiments performed have shown that the method of overtaking beams can be used to study ion-atom collisions in the energy range 1—100 eV which is difficult to approach with the methods ordinarily used. The extension of this range towards higher energies encounters no essentially new difficulties and therefore is easily achievable.

A feature of the method is that it provides the possibility of studying ion-atom collisions for practically any vapors and gases, including those in which atomic targets can be obtained only by neutralization of ion beams (for example, N). This makes the method of overtaking beams extremely promising for study of ion-atom collision processes over a wide energy range.

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APPENDIX

DETERMINATION OF χ

To determine the ratio of the secondary electron emission coefficients χ for impact on a metallic surface of atoms and ions of the same material with the same energy, we carried out the following experiment.

Immediately behind the Faraday cup (F, Fig. 1) we placed a system which is sketched in Fig. 4. Atoms and ions which pass through the diaphragm A hit the plate P made of the same material as the bottom of the Faraday cup (stainless steel) and knock out secondary electrons. The plate is inside a cylinder C and at a negative potential with respect to it. The potential is sufficient to provide complete collection by the cylinder of all electrons knocked out of the plate. The negative potential of the electrode K prevents electrons from leaving the cylinder. The plate can be rotated around an axis O perpendicular to the direction of the incident beam; in this way the angle of incidence β of the beam on the plate can be varied.

According to the point of view generally accepted at the present time (see, for example, Arifov's book[14]) in the energy region considered by us the number of secondary electrons knocked out by an ion from the surface of the metal is $N_e^+ = N_e^0 + N_e^1$, where N_e^0 is the number of secondary electrons knocked out under the same conditions by an atom of the same material with the same energy; N_e^1 is the number of secondary electrons from field emission induced by the ion in its approach to the surface. While N_e^1 is practically independent of the velocity of approach of the ion to the surface, and consequently also of the angle of incidence of the ion on the surface, N_e^0, on the contrary, has a rather sharply expressed dependence on angle of incidence.[14] Consequently, if $\chi = N_e^0/N_e^+ \neq 1$, the ratio of the currents of secondary electrons, knocked out of a metal surface by fluxes of ions and atoms of the same material of arbitrary intensities but with the same energies, should change with a change of φ. The nature of this change will be uniquely determined by the value of χ.

As the result of measurements performed with beams of protons and hydrogen atoms having an energy of 1 keV, we obtained (see Fig. 5) $\chi = 1$. The accuracy of this value in the calculations of the cross sections was taken to be 3%. Similar measurements for deuterons and deuterium atoms having, as in the first case, an energy of 1 keV gave a value $\chi = 1$ with the same accuracy.

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