SOVIET PHYSICS JETP VOLUME 17, NUMBER 6 DECEMBER, 1963

TWO-ELECTRON CHARGE EXCHANGE OF LOW-ENERGY PROTONS

V. F. KOZLOV, Ya. M. FOGEL', and V. A. STRATIENKO

Physico-technical Institute, Academy of Sciences, Ukrainian S.S.R.

Submitted to JETP editor January 11, 1963

J. Exptl. Theoret. Phys. (U.S.S.R.) **44**, 1823-1825 (June, 1963)

The effective cross sections σ_{1-1} for two-electron charge exchange of 0.5—5 keV protons in hydrogen, argon and krypton were measured. For two-electron charge exchange in hydrogen the velocity dependence $\sigma_{1-1}(v)$ obeys the Hasted formula. [4]

INTRODUCTION

THE behavior of the function $\sigma(v)$, where σ is the effective cross section of the process and v is the relative velocity of the colliding particles, for various processes of atomic collisions in the adiabatic region, is of considerable theoretical and practical interest. As is known, the adiabatic region is determined by the condition $a|\Delta E|/hv \gg 1$ (a is the distance over which the interaction forces act between colliding particles, ΔE is the resonance defect, i.e., the change of the internal energy of the particles as a result of the process, and h is Planck's constant) and lies consequently in the region of low relative velocities of the colliding particles. From general considerations it is evident that in this region the cross sections for atomic collision processes are small and rapidly decrease with decrease of the velocity.

However, we know nothing as yet about the actual form of the $\sigma(v)$ function in the adiabatic region. This is because measurement of the cross sections σ in the adiabatic region is a very complex experimental problem, owing to the difficulty of obtaining a sufficiently intense beam of low-energy primary particles and the smallness of the measured cross sections. On the other hand, considering the problem of the shape of the $\sigma(v)$ curve in the region of low velocities, we should bear in mind that this shape may be distorted both because of the presence of excited particles in the primary beam and because of the formation of slow excited particles in the collision process.[1)] Moreover, as shown by Bates and Massey, [2] anomalies in the adiabatic region may appear in those cases when the potential energy curves of the initial and final states of the system of colliding particles approach one another at some internuclear distance R_M so closely that the minimum difference of the potential energies $\Delta V(R_M)$ becomes much smaller than ΔE. From this it follows that in order to study the true shape of the $\sigma(v)$ curve in the adiabatic region it is necessary to select with great care both the collision process and the pair of colliding particles investigated. Fogel' [1] gave reasons for concluding that the most suitable process for the study of the shape of the $\sigma(v)$ curve in the adiabatic region is the process of two-electron charge exchange of singly charged positive ions. In this process the most reliable results may be obtained in the case of two-electron charge exchange of protons or alkali-metal ions, obtained from a thermionic source, in hydrogen or helium or some other inert gas.

Earlier [3] the shape of the functions $\sigma_{1-1}(v)$ was investigated for Li^+, Na^+ and K^+ ions, obtained from a thermionic source, in several inert gases; here σ_{1-1} is the cross section for two-electron charge exchange. In some of these cases it was possible to draw conclusions on the shape of the function $\sigma_{1-1}(v)$ in the adiabatic region. The main conclusion of this work [3] was the fact that the cross section σ_{1-1} decreases with decrease of the primary-ion velocity in the adiabatic region much more slowly than follows from the formula $\sigma = \sigma_0 \exp(-ka|\Delta E|/hv)$ postulated by Hasted. [4] The reasons for this were discussed in [1], but it was clear that a further study of the shape of the $\sigma_{1-1}(v)$ curve in the adiabatic region was necessary, especially in the case of two-electron charge exchange of protons. The present work gives the first results of a study of two-electron charge exchange of protons of 0.5—5 keV energies in hydrogen, argon and krypton. The experimental apparatus and measurement method were described earlier. [5] The ion gun enabled beams of protons of energies down to 0.1 keV to be obtained, but the

[1)]The distortion of the $\sigma(v)$ curve in the adiabatic region because of the participation of excited particles in the collision process has been considered in [1].

cross sections σ_{1-1} at these energies were so small that they could not be measured by the method employed. For the same reason it was not possible to measure in this region of energies (0.5—5 keV) the cross section σ_{1-1} for the pair H^+—He.

RESULTS OF MEASUREMENTS

Figure 1 gives the $\sigma_{1-1}(v)$ curves obtained from an investigation of two-electron charge exchange of protons of 0.5—5 keV energies in hydrogen, argon and krypton. The same figure gives the $\sigma_{1-1}(v)$ curves for protons of energies > 5 keV, taken from [6,7], in which the cross sections were measured by the mass-spectrometric method. It should be noted that measurement of the cross sections σ_{1-1} for the pairs investigated in the present work at proton energies greater than 5 keV has also been carried out by the method of combined collision chamber and analyzer,[8] and the results obtained agreed within the experimental error with the results of the mass-spectrometric method.

Examination of Fig. 1 leads to the conclusion that the $\sigma_{1-1}(v)$ curves obtained in the 0.5—5 keV region "join" excellently with the corresponding curves for energies greater than 5 keV. From this it may be concluded that the method of measuring the cross sections σ_{1-1} used in the proton energy range 0.5—5 keV gives a reliable result. The same figure shows that the proton energy range investigated in the present work lies, in the case of argon and krypton, quite close to the energy corresponding to the principal maximum of the cross section (cf. [6]). Consequently in these cases there are no grounds for regarding the test region of energies as adiabatic. In the case of hydrogen at least part of the energy range investigated lies sufficiently far from the cross section maximum and therefore there are grounds for assuming that the process $H^+ \rightarrow H^-$ in H_2 was investigated in the adiabatic region.

So that the shape of the function $\sigma_{1-1}(v)$ for the

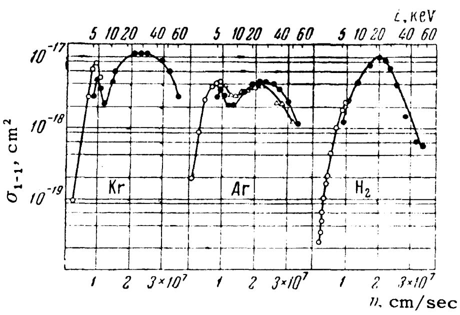

FIG. 1. Cross sections for two-electron charge exchange of protons in H_2, Ar and Kr: o – data of the present work; • – data of [6]; Δ – data of [7].

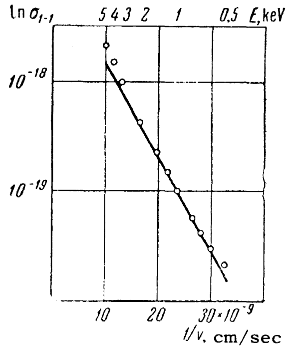

FIG. 2. Dependence $\ln \sigma_{1-1} = f(1/v)$ for the process $H^+ \rightarrow H^-$ in H_2.

process $H^+ \rightarrow H^-$ in H_2 may be determined, Figure 2 gives the dependence $\ln \sigma_{1-1} = f(1/v)$. This figure indicates that most of the experimental points lies on a straight line. Only a few points, lying near the maximum, deviate from the straight line. The linear nature of the dependence $\ln \sigma_{1-1} = f(1/v)$ indicates that over most of the range of velocities investigated the function $\sigma_{1-1}(v)$ obeys the formula suggested by Hasted. Thus in the case of the H^+—H_2 pair there were no deviations from this formula, such as were observed in the case of two-electron charge exchange of alkali-metal ions in inert gases (cf. Introduction). Further studies are necessary in order to establish whether the deviations from the Hasted formula observed in two-electron charge exchange of alkali-metal ions are due to some experimental errors or whether the shape of the function $\sigma_{1-1}(v)$ in the adiabatic region is indeed different for different colliding pairs in the same process. At present, we are developing a new method for measuring cross sections of two-electron charge exchange which will make it possible to determine the cross sections σ_{1-1} for protons of energies less than 0.5 keV and to determine these cross sections for other pairs of colliding particles, particularly the pair H^+—He.

1 Ya. M. Fogel', UFN **71**, 243 (1960), Soviet Phys. Uspekhi **3**, 390 (1960).

2 D. R. Bates and H. S. W. Massey, Phil. Mag. **45**, 111 (1954).

3 Fogel', Kozlov, and Polyakova, JETP **39**, 1186 (1960), Soviet Phys. JETP **12**, 826 (1961).

4 J. B. Hasted, J. Appl. Phys. **30**, 25 (1959).

5 V. F. Kozlov and A. M. Rozhkov, ZhTF **32**, 719 (1962), Soviet Phys. Tech. Phys. **7**, 524 (1962).

6 Fogel', Mitin, Kozlov, and Romashko, JETP **35**, 565 (1958), Soviet Phys. JETP **8**, 390 (1959).

7 Afrosimov, Il'in, and Solov'ev, ZhTF **30**, 705 (1960), Soviet Phys. Tech. Phys. **5**, 661 (1961).

8 Fogel', Mitin, and Kozlov, ZhTF **28**, 1526 (1958), Soviet Phys. Tech. Phys. **3**, 1410 (1959).

Translated by A. Tybulewicz