Born approximation. This figure also shows, for comparison, the $p+H$ charge-transfer cross section.

It is of some interest to compare the experimental cross sections for ionization of the hydrogen atom with Born approximation calculations for both electron and proton impact. Figure 4 shows this comparison plotted on a relative velocity scale. The values for the electron-impact ionization of atomic hydrogen are taken from the paper by Fite and Brackmann.[21] The first point of interest is that for the two processes the relative discrepancies between experiment and the Born approximation calculations are similar, irrespective of the ionizing particle. Second, it is to be noted that the maximum of the theoretical electron-impact ionization curve appears at a higher velocity than that of the proton-impact ionization curve, and the experimental evidence seems to confirm this velocity shift. Similar velocity shifts have been observed in the comparison of the cross sections for ion- and electron-impact ionization in other gases.[22]

ACKNOWLEDGMENTS

We are greatly indebted to F. C. Burke for his aid in the construction of the components of the apparatus, to J. A. Rutherford for his assistance in carrying out the present measurements, and to Dr. Edward Gerjuoy for numerous discussions of the theory of heavy-particle collisions.

[21] W. L. Fite and R. T. Brackmann, Phys. Rev. **112**, 1141 (1958).

[22] N. V. Fedorenko, Uspekhi Fiz. Nauk **68**, 481 (1959).

PHYSICAL REVIEW VOLUME 119, NUMBER 2 JULY 15, 1960

Charge Transfer and Electron Production in H^-+H Collisions*

DAVID G. HUMMER,† R. F. STEBBINGS, AND WADE L. FITE

John Jay Hopkins Laboratory for Pure and Applied Science, General Atomic, San Diego, California

AND

LEWIS M. BRANSCOMB

National Bureau of Standards, Washington, D. C.

(Received March 14, 1960)

The cross sections for charge transfer and electron production in collisions between hydrogen atoms and hydrogen negative ions (H^-) have been measured over the energy range 100 to 40 000 ev using modulated atomic-beam techniques in a crossed-beam experiment. Agreement of the experimental results with the perturbed-stationary-states calculation for charge transfer of Dalgarno and McDowell is quite satisfactory.

I. INTRODUCTION

IN the preceding paper,[1] the rather good agreement of experiment with the predictions of the method of perturbed stationary states for low-energy charge transfer in collisions between protons and atomic hydrogen[2] was noted. It is natural to question whether this good agreement is indicative of the merit of the method of perturbed stationary states, or whether the agreement is fortuitously good for this one process. Clearly, an experimental investigation of some other collision process to which the method of perturbed stationary states has been applied would be desirable.

This approximation method has been applied to two other processes—elastic scattering of hydrogen atoms by hydrogen atoms,[3] and charge transfer between negative hydrogen ions (H^-) and atomic hydrogen.[4] Since the examination of the latter process could be carried out with the apparatus described in the preceding paper, it was deemed desirable to carry out the measurement of the H^-+H charge-transfer cross section simultaneously with the measurements of the cross sections for collisions between protons and hydrogen atoms.

During the course of these measurements on the cross sections for collisions between H^- and H, McDowell communicated to us a calculation of the cross section for electron detachment in such collisions, which has since been published.[5] The experimental testing of this calculation constituted a second reason for carrying out the measurements which are the subject of the present paper.

II. EXPERIMENTAL APPROACH

The apparatus which was used in the measurements of the cross sections for charge transfer and for free-electron production in collisions between hydrogen nega-

* This research was supported by the Advanced Research Projects Agency through the Office of Naval Research.

† Present address: Department of Physics, University College, London, England.

[1] W. L. Fite, R. F. Stebbings, David G. Hummer, and R. T. Brackmann, preceding paper [Phys. Rev. **119**, 663 (1960)].

[2] A. Dalgarno and H. N. Yadav, Proc. Phys. Soc. (London) **A66**, 173 (1953).

[3] V. S. Kudriavtsev, Zhur. Eksp. Teoret. Fiz. **33**, 243 (1957), [translation: Soviet Phys. JETP **6**, 188 (1958)].

[4] A. Dalgarno and M. R. C. McDowell, Proc. Phys. Soc. (London) **A69**, 615 (1956).

[5] M. R. C. McDowell and G. Peach, Proc. Phys. Soc. (London) **A74**, 463 (1959).

tive ions and atomic hydrogen was the same as that described in the preceding paper. The experimental method, however, was slightly different, since in collisions of H^- and H it was necessary to distinguish between the resulting electrons and negative ions.

For the study of charge transfer alone, one method employed the mass spectrometer, which, when tuned to detect H^-, automatically rejected electrons produced in the collisions. To study both charge transfer and electron production, the parallel-plate detector was used in conjunction with the horizontal and vertical magnetic fields described in the preceding paper. When the vertical field was used, the negative charge signal arose both from electrons and from slow negative ions produced by charge transfer. When the horizontal field was used, the electrons were prevented from reaching the collecting plate, whereas the heavier negative ions responded to the electrostatic field only and were collected. Thus, under the latter circumstances the signal was representative only of the charge-transfer process.

The source of negative atomic-hydrogen ions was the hot-cathode arc source discussed in the previous paper. This source provided resolved currents of H^- of the order of $1\mu a$ at kev energies, with suitably small current fluctuations when water vapor was the gas in the arc. From stopping potential curves it was found that the total energy spread of the H^- beam was about 20 ev and that adequate ion beams could be extracted from this source down to a mean energy of 30 ev.

To determine absolute cross sections, the procedure was to reverse the ion-source potential and the analyzing magnetic field, and to compare the signals per unit current arising from both proton and H^- impact upon the same neutral atom beam for the same ion energy. Indeed, a major advantage of the ion source used in these experiments was that the proton and H^- currents produced were comparable in magnitude, so that this comparison was quite straightforward to make. The absolute cross sections for the $p+H$ charge transfer presented in the previous paper were taken as the standards for the present experiment.

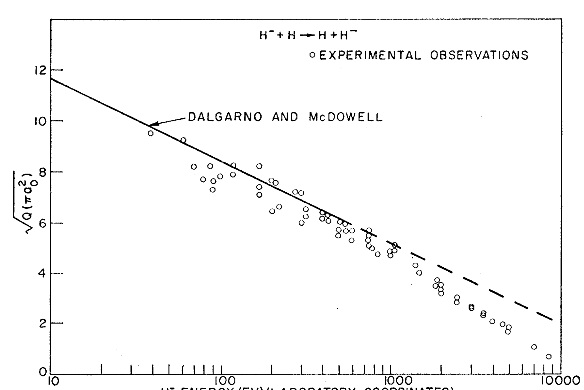

FIG. 1. Cross section for charge transfer between hydrogen negative ions and hydrogen atoms, comparing a number of experimental points and the perturbed-stationary-states calculation of Dalgarno and McDowell (reference 4).

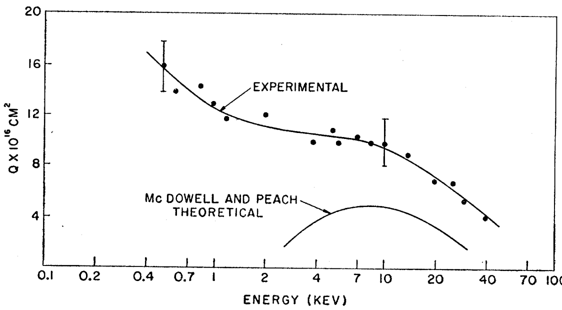

FIG. 2. Cross section for electron production in H^-+H collisions, comparing the experimental values with the calculations of McDowell and Peach (reference 5) for the process $H^-+H \rightarrow H+H+e$.

III. RESULTS AND DISCUSSION

The measured cross section for the charge-transfer process $H^-+H \rightarrow H+H^-$ is shown in Fig. 1. In this figure the square root of the cross section is plotted as a function of the logarithm of the ion energy. This system of coordinates was chosen because the calculations of Dalgarno and McDowell[4] indicate that the cross-section curve in these coordinates should be a straight line. Although the theoretical results are slightly above the experimental values, we feel that Fig. 1 satisfactorily confirms the validity of the method of perturbed stationary states for the H^-+H charge transfer for ion energies of less than about 1 kev. Deviations at higher ion energies are as expected qualitatively from the Dalgarno and McDowell calculations and represent the inherent deficiencies of the scattering approximation at high energies. A similar deviation occurs at high energies in the case of charge transfer between protons and hydrogen atoms.[1]

It is interesting to note that the behavior of the cross sections for charge transfer in $p+H$ and H^-+H collisions is quite different. While the $p+H$ cross section varies rather slowly, going from about 30×10^{-16} to 10×10^{-16} cm^2 over the energy range 100 to 10 000 ev, the H^-+H cross section drops from 60×10^{-16} to less than 1×10^{-16} cm^2 over the same energy range. The method of perturbed stationary states as applied by Dalgarno and his collaborators accurately predicts the markedly different energy dependences.

In regard to the production of electrons in collisions of H^- and H, the only available theoretical work is the recently published Born approximation calculation of McDowell and Peach,[5] who considered only the single process $H^-+H \rightarrow H+H+e$. This calculation is compared in Fig. 2 with our experimental results for electron production by all processes, including those in which one or both product atoms are ionized. The experimental values between 500 ev and 4 kev were obtained by comparison of the cross section for electron production with that for H^-+H charge transfer, using for the latter cross-section values taken from Fig. 1. Above 4 kev, the charge-transfer cross section becomes too small for this method to be reliable. At the higher energies the relative cross section for electron production was determined by comparing electron signals per unit ion current as a function of ion energy. This high-energy relative cross section was then normalized at 10 kev to the value obtained by comparing the H^-+H electron-production cross section with the $p+H$ charge-transfer cross section, the absolute value for the latter being taken from the preceding paper. At energies of less than 500 ev, the results obtained by comparing the cross sections for electron production and charge transfer in H^-+H collisions were not sufficiently reproducible to warrant their being shown in Fig. 2. However, from these lower-energy data, it appears that the cross section for electron production does not decrease for ion energies down to 50 ev and probably continues to increase. The experimental uncertainties shown in Fig. 2 do not include uncertainties in the charge-transfer cross sections which were used as standards in this measurement.

The degree to which the experimental values should be expected to agree with the results of McDowell and Peach is not entirely clear. In their calculations, only the process $H^-+H \rightarrow H+H+e$ was considered, whereas in our experiments, processes which would result in ionization of the end products of the collisions also contributed to the electron-production signal. Certainly the condition that the experimental values should exceed the cross section for only the simple electron-detachment process is satisfied.

It would be expected that processes leading to ionization of the final collision products would be operative only at the higher ion energies in this experiment, and that such processes cannot be invoked to explain the deviations of the two curves in Fig. 2 as the energy is reduced below 5 kev. It also seems unlikely that the associative detachment process, $H^-+H \rightarrow H_2+e$, can contribute appreciably to the electron-production processes at energies as high as the lower energies of these measurements.[6]

It is interesting to note that McDowell and Peach calculate the energy distribution of the electrons produced in the simple detachment process and find that where their approximation is valid, less than 10% of the ejected electrons should have energies exceeding 13.6 ev. In measuring the cross section for total slow negative particle production, it was found that curves of signal versus vertical magnetic field saturated at about 20 oersteds for all ion energies. Considering the experimental geometry, this implies that a negligible fraction of the electrons had energies in excess of about 20 ev.

IV. ACKNOWLEDGMENTS

We are indebted to R. T. Brackmann and J. A. Rutherford for their interest and assistance in these measurements, and to Dr. M. R. C. McDowell for communication of the McDowell and Peach calculations prior to their publication.

[6] A. Dalgarno (private communication).

PHYSICAL REVIEW VOLUME 119, NUMBER 2 JULY 15, 1960

Dissipation in Quantum Mechanics. The Harmonic Oscillator

I. R. SENITZKY
U. S. Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey
(Received February 29, 1960)

The need for a quantum-mechanical formalism for systems with dissipation which is applicable to the radiation field of a cavity is discussed. Two methods that have been used in this connection are described. The first, which starts with the classical Newtonian equation of motion for a damped oscillator and applies the conventional formal quantization techniques, leads to an exact solution; but subsequent discussion shows that this method is invalid, the results being unacceptable from a quantum-mechanical viewpoint. The second method, which considers the interaction of two systems, the lossless oscillator and the loss mechanism, is adopted in the present article. No special model is used for the loss mechanism, but this mechanism is assumed to have a large number of densely-spaced energy states.

The approximations with respect to the loss mechanism that underlie the concept of dissipation are discussed. These approximations are then applied to the analysis, and a differential equation for a coordinate operator of the harmonic oscillator is obtained which has the formal appearance of the Newtonian equation of motion for a driven damped harmonic oscillator, the driving term being an operator referring to the loss mechanism. The presence of the driving term is responsible for the difference between the present theory and that of the first method mentioned above. A solution of the differential equation for the coordinate operator is given explicitly. An examination of the physical significance of the solution shows that the driving term is responsible not only for the thermal fluctuations which are due to the loss mechanism, but also for the proper commutation relationship of the conjugate coordinates of the oscillator and for its zero-point fluctuations.

A generalization of the solution to provide for a classical driving force and coupled atomic systems is given. The results are then restated in a form that refers to the loss mechanism only through the two parameters by which it is usually described—the dissipation constant and the temperature.

INTRODUCTION

MOST quantum-mechanical analyses deal with microscopic phenomena, and since dissipation is a macroscopic concept, there has been little interest, during the historical development of quantum mechanics, in a formalism for systems with dissipation. There is, however, a type of problem, which has acquired considerable interest in recent years, in which dissipa-