tion.
[7]C. E. Kuyatt, S. R. Mielzyarek, and J. A. Simpson, Phys. Rev. Lett. 12, 293 (1964).
[8]C. E. Kuyatt, S. R. Mielzyarek, and J. A. Simpson, J. Chem. Phys. 44, 437 (1966).
[9]G. J. Schulz, Phys. Rev. 135, A988 (1964).
[10]A. Weingartshofer, H. Ehrhardt, V. Hermann, and F. Linder, Phys. Rev. A 2, 294 (1970).
[11]J. W. McGowan, M. A. Fineman, E. M. Clarke, and H. P. Hanson, Phys. Rev. 167, 52 (1968).
[12]D. P. Stevenson, J. Amer. Chem. Soc. 82, 596 (1960).
[13]V. H. Debeler, R. M. Reese, and M. Krauss, J. Chem. Phys. 42, 2045 (1965).
[14]See, for example, D. Rapp and P. E. Golden, J. Chem. Phys. 43, 1464 (1965). The ratio of ion current to electron current was automatically recorded. The measurements of Ref. 11 were normalized to the absolute cross sections given in the above work.

# Small-Angle Charge Exchange in $He^+ + N_2$ Collisions*

S. M. Fernandez, F. J. Eriksen, and E. Pollack
*University of Connecticut, Storrs, Connecticut 06268*
(Received 2 June 1971)

Small-angle charge-exchange measurements are made on the $He^+ + N_2$ collision in an energy range from 0.50 to 3.00 keV and in an angular region out to 2.0°. The experimental results directly show that charge exchange plays a major role in the collision. At each energy the probability of charge exchange increases monotonically with increasing angle of scattering and then attains a relatively constant value with further increase in angle.

A great deal of experimental and theoretical effort has gone into the study of charge-exchange scattering. Such scattering plays an important role in many phenomena; and in addition, since charge-exchange processes are generally inelastic, experimentally obtained results may serve as an important guide in the development of inelastic-scattering theory. While ion-atom charge exchange is understood for select systems (examples are the resonant case or when a curve crossing is responsible), much less is known about ion-molecule charge-exchange. To date the velocity dependence of the total cross section has been reported by many laboratories for a large variety of ion-molecule combinations; and although a great deal of information about charge exchange is extractable from such experiments, much more may be learned about the dynamics of the collision from studies of the angular distributions of the scattered charge-exchanged atoms. This paper presents results on the probability of charge exchange in small-angle scattering of $He^+$ by $N_2$. Recent experimentally determined total-cross-section results for this collision may be found in an article by Koopman,[1] while Inn[2] has provided information on optical excitations resulting from these collisions.

Figure 1 shows the experimental arrangement.[3] Helium ions are formed in an electron-impact ion source $A$, are extracted from the source at $B$, and focused at a suitable point in front of a mass spectrometer magnet $D$ by ion optics at $C$. The mass-analyzed beam passes through additional ion optics $E$ and is collimated by two small holes $F$ and $G$ before reaching the scattering chamber which is supplied with appropriate target gas. The beam scattered through an angle $\theta$ passes through holes $H$ and $I$ into a parallel-plate electrostatic analyzer terminated by separate multipliers for the neutral and ion signals. The half width at half-maximum is typically 0.07° for the incident beam. In this experiment the analyzer voltages are set to transmit only those ions with energies appropriate to the scattered $He^+$ beam. In addition the slits on the analyzer are made sufficiently wide to ensure collection of almost all the $He^+$ ions independent of small energy losses. The results are obtained by finding the ratio of neutral to total scattered signal at each of the angles investigated. Although the ratio of scattered neutral to scattered total signal gives the probability of a scattered particle being neutral, it is reasonable to assume that at the angles investigated this is the probability of charge exchange (since forward scattering of $N_2$ is unlikely). The experimental results contain information on the scattered beams as a function of angle and also on the probability of charge exchange. Although the measured angular dependence of the scattered ion and neutral beams may depend on apparatus conditions (beam stability,

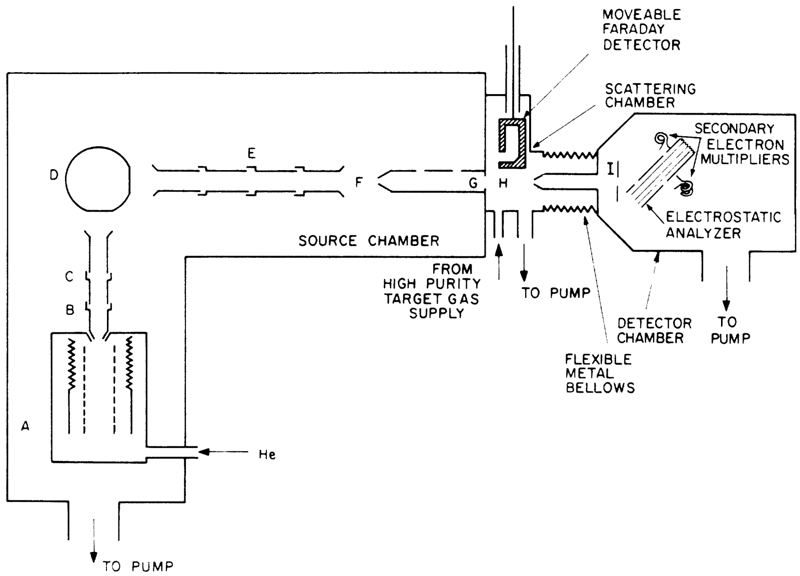


FIG. 1. The experimental arrangement.

scattering-gas pressure fluctuations, etc.) the data-taking procedure results in $P_0$ values generally independent of these conditions. All measurements are made under single-collision conditions.

It is generally difficult to make scattering measurements at small angles, but by applying a simple correction to the data it is possible to find $P_0$ even at angles inside the incident beam profile. (Scattering studies at these very small angles generally provide information about interactions occurring in soft collisions.) By definition $P_0(\theta) = N(\theta)/T(\theta) = N(\theta)/[N(\theta) + I(\theta)]$, where $N(\theta)$, $T(\theta)$, and $I(\theta)$ are the scattered neutral, total, and ion signals, respectively, at angle $\theta$. For small scattering angles the measured ion signal $I_m(\theta)$ is the sum of (1) the scattered ion signal $I(\theta)$ and (2) the signal $I_0'(\theta)$ due to the attenuated incident beam at the angle under study. Thus to obtain the correct value of $P_0(\theta)$ it is necessary to subtract $I_0'(\theta)$ from the measured $I_m(\theta)$. This is easily accomplished since during a measurement, at scattering-gas pressure $p$, $I_0'(\theta) = I_0(\theta)\exp(-kp\sigma)$, where $I_0(\theta)$ represents the incident beam without scattering gas. When the detector is set at 0°, for suitable beam profiles, the measured ion signal as a function of pressure is given by $I_0'(0) = I_0(0)\exp(-k'p\sigma)$. At any angle, $\sigma$ is the effective total cross section for scattering ions (originally heading toward the detector) beyond the detector acceptance angle (angular resolution of the detector) and $k$ (essentially a geometry factor) is to a reasonable approximation equal to $k'$ at all angles inside the beam. This results in $I_0'(\theta) = I_0(\theta)[I_0'(0)/I_0(0)]$. The technique is applied by first obtaining a beam profile without scattering gas. The scattering-gas pressure is set at $p$, and the forward beam is observed to be attenuated to $x\%$ of its original value. $I_m(\theta)$ is now measured at the same pressure $p$, and $I(\theta)$ is found by subtracting $x\%$ of the incident beam present at the appropriate angle without scattering gas.

This correction technique is currently under study and as of this writing has been applied to our 3.0-keV $He^+ + N_2$ data and to a measurement of symmetric charge exchange in $He^+$ at very small angles.[4] Additional corrections which account for beam and detector geometries can be made to further refine the data, and the basic technique may be useful in correcting general scattering data.

Figure 2 shows $P_0$ as a function of laboratory scattering angle at energies of 0.50, 1.00, 2.00, and 3.00 keV in the $He^+ + N_2$ collision. The 3.00-keV data are corrected at angles of 0.10°, 0.15°, 0.20°, and 0.25° (for comparison the uncorrected data are shown at these angles by the lower dashed curve). No corrections are required at larger angles for the energies reported. Additional measurements at 3.00 keV were made at angles of 3° and 4°. The $P_0$ values obtained at these angles indicate that the curve could simply be extrapolated to these larger angles. The experimental results show that inelastic scattering plays an important role at these energies in $He^+$

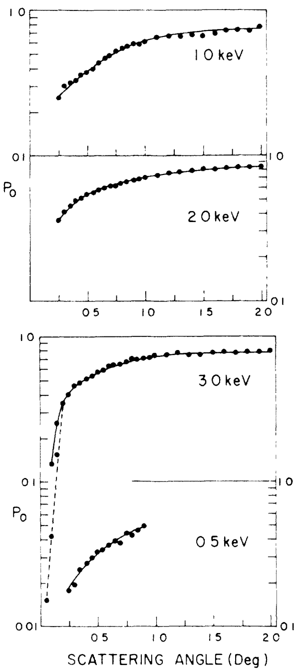


FIG. 2. The probability of charge exchange as a function of laboratory scattering angle in $He^+ + N_2$ collisions. The $P_0$ values for the 0.50- and 2.0-keV collisions are given on the right side of each diagram. The 3.0-keV data are corrected at angles below 0.25° and the uncorrected data are shown at these angles by the lower dashed curve. For the energies reported no corrections are required at angles larger than 0.25°.

$+N_2$ collisions. Since both the $He^+ + N_2 \rightarrow He + N_2^+$ and $He^+ + N_2 \rightarrow He + N + N^+$ channels participate in the charge exchange (with the latter one making the more important contribution in our energy range),[5,6] it is generally difficult to analyze the collision processes without simplifying assumptions. One possible model that would allow an interpretation of the experimental results in terms of collision parameters involves the capture of an electron by the incident $He^+$ ion. The target molecule is left in an excited state of $N_2^+$ which may dissociate after the collision to $N + N^+$ or survive as $N_2^+$. With the assumption that the scattering angle is related to the impact parameter, the data (especially in the 3-keV case) suggest that for all impact parameters less than a critical impact parameter charge exchange occurs with essentially the same probability. A comparison of the results at the different energies also shows that $P_0$ increases as the collision time increases at fixed values of $E\theta$ (the product of beam energy and scattering angle). Figure 3 shows preliminary results of similar experiments in the $He^+ + H_2$ collision at 2.00 keV.

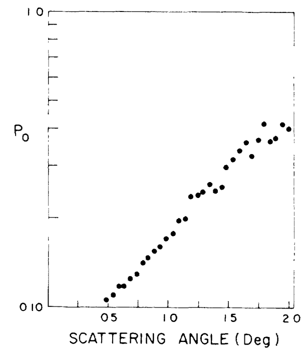


FIG. 3. Preliminary results showing the probability of charge exchange as a function of laboratory scattering angle in the $He^+ + H_2$ collision at 2.0 keV.

The authors gratefully acknowledge useful discussions with Dr. A. Russek and Dr. T. F. O'Malley.

*Research supported by the Connecticut Research Commission, the U. S. Army Research Office (Durham), and the University of Connecticut Research Foundation.

[1]D. W. Koopman, Phys. Rev. 166, 57 (1968).

[2]E. C. Y. Inn, Planet. Space Sci. 15, 19 (1967).

[3]S. W. Nagy, S. M. Fernandez, and E. Pollack, Phys. Rev. A 3, 280 (1971).

[4]F. J. Eriksen, S. M. Fernandez, and E. Pollack, Bull. Amer. Phys. Soc. 16, 563 (1971).

[5]R. F. Stebbings, J. A. Rutherford, and B. R. Turner, Planet. Space Sci. 13, 1125 (1965).

[6]N. G. Utterback and R. C. Amme, unpublished.