Scattering of Ions

IV. Elastic Scattering of He^+-Ions on Ne, Ar, Kr, and Xe

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Differential cross-sections for the elastic scattering of He^+ on Ne, Ar, Kr, and Xe were measured at different energies. At energies between 3 eV and several 100 eV, Stueckelberg oscillations could be observed. Between 1 eV and 8 eV rainbow structures were detected, but the rapid oscillations could not be resolved. The measured differential cross-sections were compared with calculated curves. The angular positions of the primary rainbows indicated a very weak interaction in the order of the polarisation energy between the He^+-ion and the noble gases. Thus a 12–4 potential was used for the calculations since the attractive part of this potential describes the ion induced dipole potential. The depth of the potential well was obtained as < 0.05 eV for He^+-Ne, 0.19 eV for He^+-Ar, 0.22 eV for He^+-Kr and 0.28 eV for He^+-Xe. A method is described which allows for correction of the nominal energy of the primary ion beam for contact potentials.

Introduction

A rainbow structure including the rapid oscillations has already been described and evaluated for the system He^+-He[1]. It was possible to derive the potential function from the scattering data and to determine the potential depth of $He_2{}^+$, ε as 2.55 eV, and the equilibrium distance, r_m as 1.05 Å. In the present paper, the elastic scattering of He^+ on Ne, Ar, Kr, and Xe is reported. The apparatus was described in the first paper of this series[2]. The angular spread of the He^+-beam was 1.4°. The energy of the ion beam was determined using the retarding potential method. The half width was measured as 0.2 eV to 0.3 eV.

Experimental Results

A typical differential cross-section for the system He^+-Xe is shown in Fig. 1 at energy 1.3 eV (cm-system). The primary and two secondary rainbows can be recognized. Fine oscillations could not be resolved under the above mentioned experimental conditions. In the case of He^+-Ar and He^+-Kr the differential cross-sections look similar but the last secondary rainbow was poorly resolved. No rainbow structure could be traced in the scattering of He^+ on Ne. Only at $E_L \approx 1$ eV (E_L: energy in the lab system) a shoulder in the primary ion peak could be observed at small angles and attributed to the primary rainbow. The angular positions of the rainbows were measured at various energies in the range from 1 eV to 8 eV.

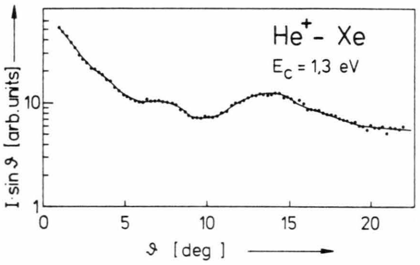

Fig. 1. Elastic differential cross-section of the system He^+-Xe at $E_c = 1.3$ eV.

Stueckelberg oscillations were observed at higher energies. In the case of He^+ on Xe such oscillations had already appeared at large angles at energies above 3 eV[3]. The oscillations are shifted towards

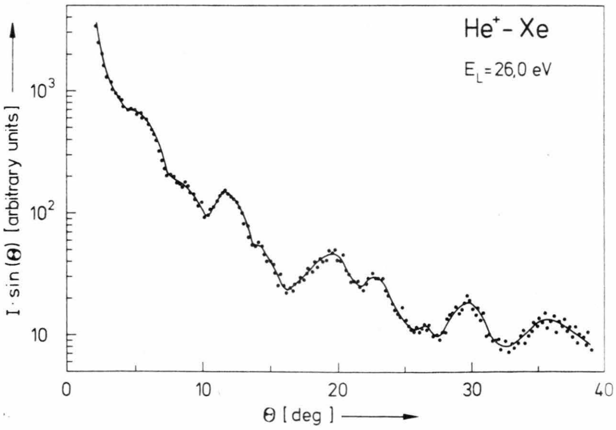

Fig. 2. Elastic differential cross-section of the system He^+-Xe at $E_L = 26.0$ eV (E_L: energy in the lab-system).

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smaller angles with increasing energy and additional groups of oscillations with various periodicities become evident whose superimposition yields a complicated pattern (Figure 2). Four groups of oscillations of different periodicity could be recognized at $E_L = 26$ eV [4]. They are probably caused by crossings or pseudocrossings with states of the system $He - Xe^{+*}$ since many states of this system lie close to the ground state of the $He^+ - Xe$ system [5]. Stueckelberg oscillations were also observed in the $He^+ - Kr$ system, appearing at higher energies than in the $He^+ - Xe$ system [3]. No attempts were made to analyse the Stueckelberg oscillations in detail.

Discussion

The observed angles at which the primary rainbows appear are rather small and indicate potential depths of the order of 0.1 eV. It is concluded that essentially polarisation forces act between He^+ and the higher noble gases in contrast to the strong chemical forces that dominate in the $He^+ - He$ system. The data were therefore evaluated using a 12 – 4 potential since the r^{-4} term describes the polarisation of the rare gas atom in the radial electric field of the He^+-ion [6]:

$$V(r) = (\varepsilon/2)\,[(r_m/r)^{12} - 3(r_m/r)^4]\,. \qquad (1)$$

Equating the polarisation potential $V_p(r) = -e^2\,\alpha/2\,r^4$ (α is the polarisability of the rare gas atom) to the attractive term $-3\,\varepsilon\,r_m{}^4/2\,r^4$ in Eq. (1), one obtains

$$r_m{}^4 = e^2\,\alpha/3\,\varepsilon\,; \qquad (2)$$

r_m could not be derived from the measurements since the fine oscillations were not observed. Thus an estimated equilibrium distance was used in the calculations putting r_m equal to the sum of the estimated radius of the He^+-ion (≈ 0.6 Å) and the gas kinetic radius of the rare gas atom (2.4 Å for Ar, 2.5 Å for Kr, 2.6 Å for Xe). The differential cross-section was calculated using the method described in Part 2. ε was varied until agreement in the angular positions of the rainbow oscillations between the calculated and the measured curve was achieved. As the angular positions of the secondary rainbows are sensitive to the shape of the attractive part of the potential, it can be concluded from the close fit that the r^{-4} term of the potential function is a good approximation.

The energy of the ion beam determined by the retarding potential method contains a systematic error due to contact potentials at the surface of the metal grid to which the retarding potential is applied. The contact potential depends on the nature of the residual gas in the scattering chamber. Contact potentials in the electrical leads to the metal grid may be another source of error. The relative error in the energy determination can become rather serious at the low energies used in the present investigations. A dependence of the calculated potential depth ε' on the energy has been found and is thus attributed to differences between the measured nominal energy E_c' and the actual energy of the ion beam.

A correction was made using the relationship

$$\vartheta_R\,E_c/\varepsilon \approx \text{const}$$

which is approximately valid for small scattering angles. The same relation holds for the uncorrected nominal values E_c' and ε', i. e.

$$\vartheta_R\,E_c'/\varepsilon' \approx \text{const}\,.$$

If E_c' is not much different from E_c, the two relations can be equated. Since $E_c = E_c' + V_k$ (V_k: contact potential) one obtains

$$1/\varepsilon' = 1/\varepsilon + V_k/\varepsilon\,E_c'\,.$$

A plot of $1/\varepsilon'$ versus $1/E_c'$ gives a straight line where slope and intercept yield ε and V_k. Table 1 shows the results

Table 1. Potential depths calculated from elastic scattering data.

	Ne	Ar	Kr	Xe
ε [eV]	0.05	0.19	0.22	0.28
ε [eV] [7]	0.047	0.146	—	—

The second row of Table 1 shows the results obtained by Smith et al. [7] by scattering experiments at energies larger than 10 eV. They obtained these values by evaluating the intensity drop on the dark side of the primary rainbow.

The statistical error of our measurements is estimated as ±5%. A systematic error is given by the uncertainty in the assumed value of r_m. A decrease in r_m requires an increase in ε in order to obtain agreement between calculated and measured differential cross-sections [8]. If the error in r_m is 0.5 Å, the calculated ε-values are wrong by about 15%. It is interesting to introduce the calculated ε-value into Eq. (2) and compare the resulting r_m with the value assumed for the computation; values agree to within

10% in all cases. This again is an indication that the 12 – 4 potential used represents a good approximation to the attractive part of the potential.

In mass spectrometric studies the stable molecules $(HeNe)^+$, $(HeAr)^+$ and $(HeKr)^+$ have been detected [9, 10]. The appearance potentials [23.4 eV for $(HeNe)^+$, 17.9 eV for $(HeAr)^+$ and 19.9 eV for $(HeKr)^+$] suggest a much deeper potential well than found in the present study. The potential curves shown in Fig. 3 may explain this discrepancy, i. e. in the case of $He^+ - Ne$. The upper curve represents the potential which determines the elastic adiabatic scattering process. The evaluation of the rainbow structure allowed for the description of this potential for distances larger than r_m. The lower curve, the shape of which has been suggested by Munson et al. [9] to explain the stability of the ionic molecule, represents a lower state of the $HeNe^+$-molecule. The two potential curves might be due to an avoided crossing between a strongly attractive diabatic potential of the He^+-Ne system and a purely repulsive diabatic potential of the charge-exchanged system. The electronic energy of the excited helium which forms the $(HeNe)^+$ molecule in collision with Neon lies between both states. By emission of the electron the molecule can stabilize in the deep potential well in some vibrational state [11]. The same mechanism may prove right for the formation of $(HeAr)^+$ and $(HeKr)^+$ but other ways of formation, i. e. in the case of $(HeAr)^+$ via an electronically highly excited Ar-state may contribute too [9, 12, 13]. In all cases the states reached in the mass spectrometer are lower in energy than the state which determines the elastic adiabatic scattering process.

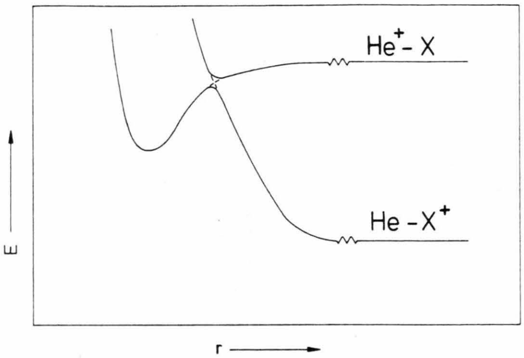

Fig. 3. Schematic representation of the potential curve for the systems $He^+ - X$ (X: rare gas atoms) and an assumed potential curve for the charge-exchanged system.

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