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Total cross section measurements for positrons and electrons colliding with molecules: II. HCl

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Abstract. Total cross sections (TCSs) for 0.7–400 eV positrons and 0.8–400 eV electrons colliding with hydrogen chloride (HCl) have been measured using a linear transmission method. The data were corrected for the effects of forward scattering using the differential cross section (DCS). The magnitude of the correction was very large in the low energy region. The method of the correction is given in detail. The TCS curve of electrons has a small hump near 3 eV. The TCS for positrons is somewhat lower than that for electrons in the low energy region. In the intermediate energy region, the values of the TCSs for positrons and electrons approach each other.

1. Introduction

As a typical polar molecule, hydrogen chloride (HCl) has been interesting for electron scattering in the low energy region. There are many theoretical studies (Itikawa and Takayanagi 1969, Allen and Wong 1981, Padial *et al* 1983, Padial and Norcross 1984, Morgan *et al* 1990, Mengoni and Shirai 1991, Fabrikant *et al* 1991, Fabrikant 1991, Pfingst *et al* 1992) mainly concerned with vibrational and rotational excitations by electron impact. Some experimental studies have been carried out (Rohr and Linder 1975, 1976, Knoth *et al* 1989, Rädle *et al* 1989, Schafer and Allen 1991). As regards the total cross section (TCS) for electron scattering, theoretical studies were performed by Itikawa and Takayanagi (1969), Padial *et al* (1983), Pfingst *et al* (1992) and Jain and Baluja (1992). The only experimental measurement is the study of Brüche (1927). The pure elastic cross section which was obtained from differential cross section (DCS) measurements for e^-–HCl scattering has been presented by Rädle *et al* (1989). However, no experimental data for positrons have been reported.

This report presents the first TCS measurements for 0.7–400 eV positrons colliding with HCl using a linear transmission type time-of-flight (TOF) apparatus. By the same method, TCS measurements for 0.8–400 eV electrons have been performed. The TCS was determined relatively to the e^+–N_2 data of Hoffman *et al* (1982). For a polar molecule, the contribution of small angle forward scattering is very large due to the lepton–dipole interaction. In the transmission type measurement, it is necessary to correct for the influence of forward scattering on the TCS data. This correction to the measured data

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was performed taking into account the effect of the magnetic field and the configuration of the apparatus.

The cross sections for positronium formation are measured just above the threshold. The measurements were performed using a strong magnetic field to collect positrons that fail to form positronium.

Preliminary data that were not corrected for the effect of forward scattering have been reported elsewhere (Sueoka and Hamada 1990).

2. Experimental procedure

A transmission method was used in the present measurement, with a weak magnetic field parallel to the axis of the equipment. The apparatus and experimental procedure are almost identical with the previous works (Sueoka and Mori 1986, Sueoka *et al* 1994 hereafter referred to as TI) except for the careful exhausting of HCl gases from the pumping system out of the room. It should be pointed out here that a correction due to the effect of inelastic scattering to the TCS is necessary when the energy loss spectrum has some structures in low energies (TI). Inelastically scattered particles can merge with the unscattered beam and be detected as unscattered particles. For the case of HCl this effect was found to be unimportant by the analysis, which was described in TI. Therefore, the data were not corrected for this effect.

3. Correction for forward scattering

In an experiment, it is impossible to discriminate elastically scattered projectiles at small angles from unscattered ones. When the DCS is strongly forward peaked, as in e^-–HCl, the effect of forward scattering is serious. Recently, Okamoto *et al* (1993) and Yuan and Zhang (1992) pointed out this effect for electron scattering by H_2O. In our experimental system, the e^+ beam is spatially wide with 8 mm diameter. The effect of forward scattering is not negligible even in the low magnetic field that is used for the beam transportation parallel to the flight path.

A schematic diagram of the scattering region is shown together with the applied magnetic field in figure 1. The calculation of the forward scattering correction is in the following framework. For the calculation, it was assumed that the magnetic field of the

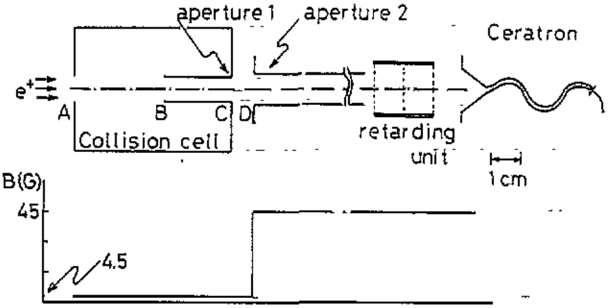

Figure 1. Top: section of the collision cell and the aperture. Bottom: the magnetic field for the calculation of the correction.

solenoid increases at D stepwise. All projectiles entering at D are transported to a Ceratron detector by the strong magnetic field. In the interests of simplicity, some hypotheses were made for the collision process, as follows. The incident beams are uniform spatially, and are parallel to the flight path. Projectiles enter into collision cell from a hole A (8 mm in diameter). Unscattered projectiles pass through the exit cylinder BY (8 mm in diameter, 10 mm in length), and go into the second cylinder DE (10 mm in diameter). Scattered projectiles move along a helical path after a collision, as they have a perpendicular component of velocity. The projectiles which did not stop at the cylindrical wall contribute the intensity of forward scattering. The pitch of the helix is larger than the length of the cylinder BC except at very low energies. Even if the helical radius of the projectile is greater than that of the cylinder, projectiles have a possibility to pass through the cylinder and enter into the hole D. The calculation of this quantity is important.

The correction to the TCS for electrons scattered from the cylinder BC was performed by the same method mentioned in TI. For collisions at the BC cylindrical wall, we assumed that a positron annihilates at the cylinder, and the small angle scattered electron reflects at an equal angle with 100% efficiency.

The corrected TCS (Q_t) was obtained by adding the cross section for the forward scattering contribution (Q_f) to the measured TCS ($Q_{t(\mathrm{measured})}$),

$$Q_t = Q_{t(\mathrm{measured})} + Q_f. \tag{1}$$

Q_f was calculated using the scattered beam intensity ($I_{\mathrm{scattered}}$) and the intensity of the elastic forward scattering (I_{forward}),

$$Q_f = Q_t \frac{I_{\mathrm{forward}}}{I_{\mathrm{scattered}}} \tag{2}$$

where

$$I_{\mathrm{scattered}} = I_0[1 - \exp(-Q_t n l)] \tag{3}$$

$$I_{\mathrm{forward}} = \frac{1}{\pi R_2 Q_t} \int_0^l \mathrm{d}I(x) \int_0^R 2\pi r \,\mathrm{d}r \int_0^{\theta_{\max}} \Phi(\theta, r, x, E, B) q(\theta) \sin\theta \,\mathrm{d}\theta \tag{4}$$

$$\mathrm{d}I(x) = I_0 \{\exp(-Q_t n x) - \exp[-Q_t n(x + \mathrm{d}x)]\}. \tag{5}$$

Here, θ is the scattering angle, x is the distance from the beginning of the scattering region, r is the radial distance from the centre of the scattering cell, R is the radius of the beam, l is the effective length of the collision cell, $\mathrm{d}I(x)$ is the attenuation of the beam intensity in the interval $x - x + \mathrm{d}x$, $q(\theta)$ is the DCS for elastic scattering, $\theta_{\max}$ is the maximum scattering angle, Φ is the transmission function. The calculation of Φ is essential for the beam transport under the magnetic field B. Namely, Φ is a measure of the fraction of scattered projectiles passing through D. Every trajectory of all scattered projectiles was calculated whether passing through D or not at all positions concerned under the configuration of the present apparatus. The values of Φ were determined for each incidence energy.

The angular distribution of the scattered projectiles, namely DCS, determines the effect of forward scattering. The contributions of forward scattering from inelastic scattering with large energy loss and large angle elastic scattering are eliminated by the retarding potential, as mentioned in the previous papers (TI, Sueoka *et al* 1986, 1987, Sueoka and Mori 1986). Therefore the DCS that did not include excitation and ionization

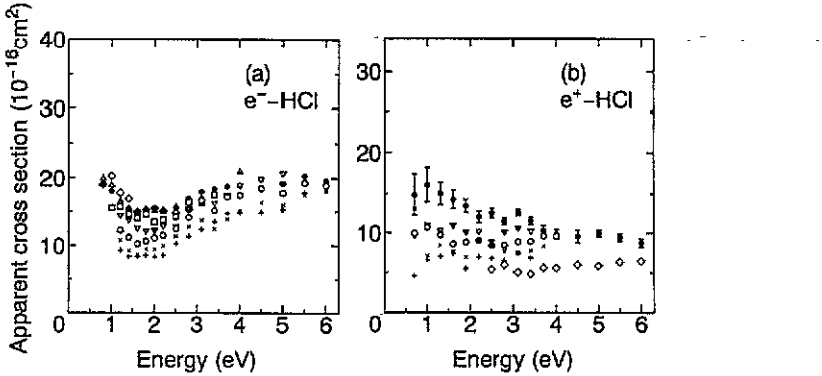

Figure 2. Apparent TCS in various magnetic fields: (*a*) for electrons; ◇, 2.7 G; △, 3.6 G; ●, 4.5 G; □, 5.4 G; ▽, 6.8 G; ○, 9 G; ×, 11.3 G; +, 13.5 G: (*b*) for positrons; ●, 4.5 G; ▽, 6.8 G; ○, 9 G; ×, 11.3 G; +, 13.5 G; ◇, 22.5 G. The statistical errors are indicated for 4.5 G only. Marks without error bars have smaller bars than the size of the mark.

cross section was used for the correction. Below 10 eV, the data of Rädle *et al* (1989) were taken as DCS for electrons. For very small angle scattering and above 10 eV, the first Born approximation (FBA) was used, because there are no data in this region. In the calculation of the FBA, only the contribution of the rotational transition for $j=3$, corresponding to the average rotational state at room temperature, was considered. DCS data for e$^+$-HCl do not exist. It was assumed that the DCS values for positrons were equal to those for electrons.

We calculated the quantity of forward scattering for the electrons and positrons in various magnetic fields, and corrected the TCS values. The measured TCS and the corrected results are shown in figures 2 and 3 respectively. The quantity of correction is very large at low energies; for instance, the corrected result is 1.6 times the measured e$^-$-TCS at 0.8 eV, even at the weakest magnetic field 2.7 G. The values of corrected TCS for both positrons and electrons agree within the experimental uncertainty. This result supports the notion that the correction method is reasonable at least for the effect of

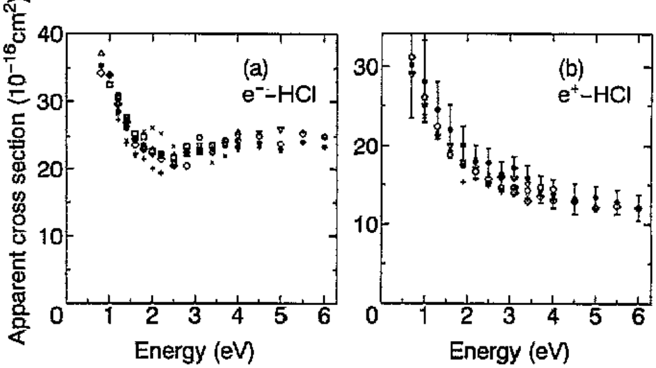

Figure 3. Corrected TCS in various magnetic fields: (*a*) for electrons, symbols as in figure 2 (*a*); (*b*) for positrons, symbols as in figure 2 (*b*). The error bars that include the uncertainties in the present experiment, but do not include the uncertainties caused by the correction, are indicated for 4.5 G only.

the magnetic field. As mentioned in TI, in the correcting calculation for the magnetic field dependence of the TCS for SiH_4 this method is proved to be appropriate.

4. Results

For the TCS measurements of positrons, the magnetic field was mainly 9 G in the vicinity of the collision cell, while in the range below 10 eV a magnetic field was used to reduce the influence of the magnetic field. The data for two measurements at 10 eV coincided well with each other. For electrons, a magnetic field of 3.6 G was used throughout the energy range.

The results of TCS measurements were normalized to the e^+–N_2 data that were measured by Hoffman *et al* (1982). The effect of forward scattering was small in the data.

4.1. Electron scattering at low energies

The present results below 20 eV for HCl are shown in figure 4, along with the uncorrected data, the experimental data of Brüche (1927) for total scattering and Rädle *et al* (1989) for pure elastic scattering and the theoretical data of Itikawa and Takayanagi (1969), Padial *et al* (1983), Pfingst *et al* (1992) and Jain and Baluja (1992). The present results are lower than the previous TCS data, though the agreement is quite improved by the correction in comparison with the uncorrected data.

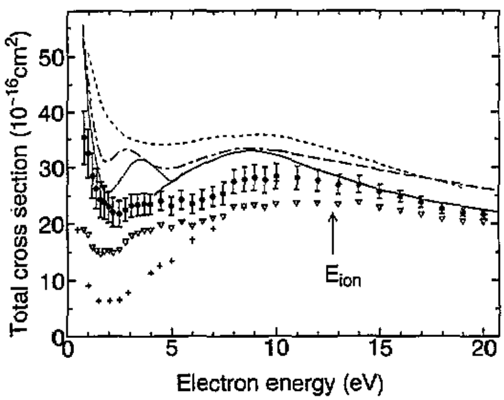

Figure 4. TCS for the electrons colliding at the energies below 20 eV with HCl. Experimental data: ●, corrected data; ▽, uncorrected data (data taken at 3.6 G for all the energy range); +, pure elastic cross section of Rädle *et al* (1989); ——, total cross section of Brüche (1927). Theoretical data: ——, Pfingst *et al* (1992); - - -, Jain and Baluja (1992); — · —, Padial *et al* (1993); · · · ·, Itikawa and Takayanagi (1969). The threshold for ionization is indicated by the arrows.

Above 15 eV Brüche's experimental TCS data are coincident with corrected results, but are about 25% higher below 15 eV. The values of all theoretical data are considerably higher than the present in all energy regions. The broad maximum around 10 eV and steep increase at very low energies in our TCS curve conform to those in theoretical data.

In the present measurement the TCS curve looks like it has a small hump near 3 eV. In the data of Rädle *et al* such a hump does not appear. The small hump, if real, is not an artifact of the corrections that we have made. It corresponds to the lower maximum of the theoretical studies (Padial *et al* 1989, Pfingst *et al* 1992), associated with the peak due to the rotational transition $j=0\rightarrow2$.

4.2. Positron scattering at low energies

The TCS for positrons with energies below 20 eV scattered by HCl are shown in figure 5 along with the uncorrected data. The TCS values increase steeply with decreasing

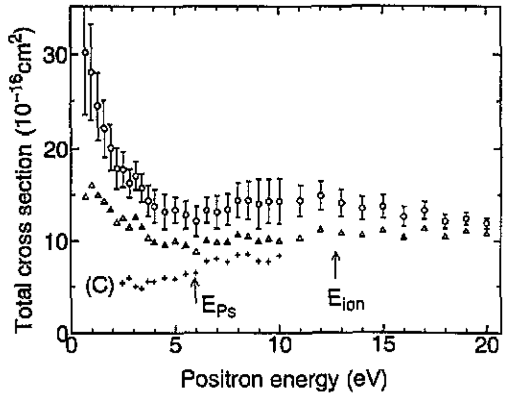

Figure 5. Measured TCSs for the positrons colliding with the energies below 20 eV with HCl. Data taken at 4.5 G for 0.7–10 eV and at 9 G above 10 eV: ○, corrected data; △, uncorrected data. The data (C) were obtained under a magnetic field of 22.5 G. The threshold energies of the positronium formation and ionization are shown by the arrows.

energy below 2 eV. There is a broad peak near 10 eV. However, in the uncorrected data, this peak is not found. It is revealed by the DCS used for the correction. The size of correction for positrons is larger than 10 eV. However, in the uncorrected data, this peak is not found. It is revealed by the DCS used for the correction. The size of correction for positrons is larger than that for electrons, because the measurements were performed under a stronger magnetic field.

To measure the positronium (Ps) formation cross sections just above the threshold energy ($E_{Ps}=5.94$ eV), 'apparent total cross sections' were measured under a much stronger magnetic field of 22.5 G. From the data (C) in figure 5, the cross section for Ps formation in HCl is deduced to be about 2.2×10^{-16} cm^2 at 2 eV above E_{Ps}. This high cross section for Ps formation is not a common character of polar molecules, as is evident in the data for H_2O and NH_3 (Sueoka *et al* 1987). The increase of TCS above the threshold energy of ionization ($E_{ion}=12.74$ eV) was not remarkable.

4.3. Scattering at intermediate energies

The TCS results for positrons and electrons in the range 10–400 eV are shown together with the uncorrected data for positrons and electrons and the data of Jain and Baluja

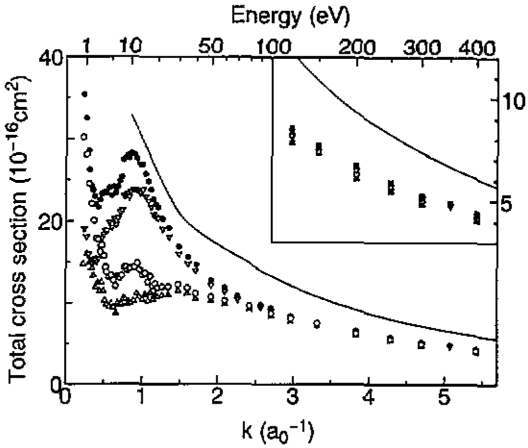

Figure 6. The TCS for positrons and electrons colliding with HCl extending to intermediate energies. The experimental points, this experiment: ○, positrons; ●, electrons; uncorrected data: △, positrons; ▽, electrons. The theoretical data: ——, Jain and Baluja (1992). The inset shows the enlargement in the ordinate at higher energies.

(1992) in figure 6. The present cross sections for electrons are smaller than those of Jain and Baluja (1992) in all energy regions. In the intermediate energy range, the ratio of forward scattering correction to measured TCS is much smaller than in the low energy range. The DCS used for the correction takes no account of the contribution of pure elastic scattering. The reflection of electrons along the flight path, except at the aperture of the exit of the collision cell, is also not considered. It is deduced that the TCS values are increased by several per cent by these contributions.

The data below about 50 eV show typical differences between positron and electron interactions with HCl. In the intermediate energy region TCS values for positrons and electrons approach each other, almost merging at 400 eV.

5. Discussion

The values of TCS for positrons and electrons are given in tables 1 and 2. The errors shown are the addition of $\Delta I/I (=3\text{–}17\%$ for positrons, 0.5–2% for electrons), $\Delta I_{\mathrm{inela}}/I$ (<1%), $\Delta n/n$ (=0.3%), $\Delta l/l$ (=2%) and $\Delta Q_f/Q_f$. The errors for the correction for forward scattering, $\Delta Q_f/Q_f$, for each energy were estimated as the sum of the uncertainties caused by the DCS data (=3%, Rädle *et al* 1989), the interpolation of the DCS data (=1.5%), the assumption on the shape of the magnetic field (<5%) and the assumption of the reflection rate for electrons at the aperture wall (<7%). The large statistical errors result from the durations of the runs, which were kept short to prevent corrosion.

The large TCS at low energies for both positron and electron scattering is consistent with the results of the FBA for electron–dipole interaction. For polar molecules, it is thought that the FBA is a good approximation for small angle scattering in the low energy region (Okamoto *et al* 1993, Itikawa and Takayanagi 1969). However, in the high energy region the validity of the FBA is not clear. The present correction at intermediate energies may not be sufficient.

Although the effect of a magnetic field in TCS measurements was corrected fairly well for both positrons and electrons in figure 3, the present correction for positrons is only

Table 1. Total cross sections (TCS) for electron scattering on HCl. Numbers in parentheses are the correction due to forward scattering.

Energy (eV)	TCS (10^{-16} cm^2)	Energy (eV)	TCS (10^{-16} cm^2)	Energy (eV)	TCS (10^{-16} cm^2)
0.8	35.39 ± 4.82 (16.34)	6.5	24.15 ± 1.73 (3.74)	22	20.26 ± 0.58 (1.20)
1.0	32.55 ± 4.33 (14.44)	7.0	24.84 ± 1.77 (3.73)	25	19.20 ± 0.52 (1.09)
1.2	28.53 ± 3.96 (12.54)	7.5	25.34 ± 2.02 (4.04)	30	16.95 ± 0.43 (0.93)
1.4	26.23 ± 3.53 (10.84)	8.0	27.44 ± 2.06 (4.39)	35	15.67 ± 0.39 (0.84)
1.6	24.27 ± 3.19 (9.52)	8.5	27.80 ± 2.17 (4.68)	40	14.71 ± 0.36 (0.76)
1.8	23.75 ± 2.93 (8.51)	9.0	28.07 ± 2.22 (4.76)	50	12.80 ± 0.32 (0.61)
2.0	22.97 ± 2.76 (7.64)	9.5	27.66 ± 2.27 (4.78)	60	11.94 ± 0.26 (0.54)
2.2	22.03 ± 2.58 (7.02)	10.0	28.31 ± 2.23 (4.78)	70	10.90 ± 0.24 (0.48)
2.5	21.72 ± 2.38 (6.22)	11.0	28.12 ± 2.05 (4.33)	90	9.90 ± 0.19 (0.39)
2.8	22.55 ± 2.05 (5.62)	12.0	27.63 ± 1.89 (3.90)	100	9.43 ± 0.19 (0.35)
3.1	23.26 ± 1.99 (5.26)	13.0	26.92 ± 1.70 (3.47)	120	8.49 ± 0.17 (0.31)
3.4	23.39 ± 1.95 (4.98)	14.0	26.91 ± 1.52 (3.11)	150	7.65 ± 0.15 (0.25)
3.7	23.54 ± 1.91 (4.75)	15.0	25.72 ± 1.25 (2.75)	200	6.68 ± 0.13 (0.20)
4.0	23.43 ± 1.80 (4.54)	16.0	24.82 ± 1.00 (2.43)	250	5.88 ± 0.11 (0.17)
4.5	24.04 ± 1.65 (4.18)	17.0	23.81 ± 0.95 (2.11)	300	5.27 ± 0.10 (0.14)
5.0	23.10 ± 1.62 (3.85)	18.0	22.62 ± 0.94 (1.79)	350	4.89 ± 0.10 (0.13)
5.5	24.18 ± 1.65 (3.84)	19.0	22.01 ± 0.66 (1.50)	400	4.43 ± 0.09 (0.11)
6.0	23.44 ± 1.68 (3.83)	20.0	21.67 ± 0.66 (1.28)		

Table 2. Total cross sections (TCS) for electron scattering on HCl. Numbers in parentheses are the correction due to forward scattering.

Energy (eV)	TCS (10^{-16} cm^2)	Energy (eV)	TCS (10^{-16} cm^2)	Energy (eV)	TCS (10^{-16} cm^2)
0.7	30.2 ± 6.7 (15.4)	7.0	13.1 ± 1.8 (3.3)	20	11.9 ± 0.6 (1.1)
1.0	28.1 ± 5.1 (12.1)	7.5	13.4 ± 1.7 (3.6)	22	12.0 ± 0.6 (1.0)
1.3	24.5 ± 3.6 (9.5)	8.0	14.4 ± 1.9 (3.7)	25	12.0 ± 0.6 (0.9)
1.6	22.1 ± 3.0 (7.8)	8.5	14.4 ± 2.1 (4.0)	30	12.3 ± 0.6 (0.8)
1.9	20.1 ± 2.4 (6.7)	9.0	14.0 ± 2.7 (4.1)	35	11.9 ± 0.5 (0.7)
2.2	17.9 ± 2.2 (5.9)	9.5	14.3 ± 2.4 (4.1)	40	11.2 ± 0.4 (0.6)
2.5	17.8 ± 1.9 (5.3)	10.0	14.3 ± 2.5 (4.1)	50	10.8 ± 0.3 (0.5)
2.8	16.3 ± 1.6 (4.9)	11.0	14.4 ± 1.7 (4.1)	60	10.3 ± 0.3 (0.5)
3.1	17.1 ± 1.5 (4.5)	12.0	14.9 ± 1.6 (3.7)	80	9.7 ± 0.3 (0.4)
3.4	15.8 ± 1.6 (4.3)	13.0	14.1 ± 1.5 (3.4)	100	8.8 ± 0.2 (0.4)
3.7	14.4 ± 1.7 (4.1)	14.0	13.5 ± 1.3 (3.0)	120	8.2 ± 0.3 (0.3)
4.0	13.8 ± 1.8 (4.0)	15.0	13.7 ± 1.3 (2.7)	150	7.6 ± 0.2 (0.3)
4.5	13.2 ± 1.9 (3.7)	16.0	12.6 ± 1.1 (2.3)	200	6.3 ± 0.2 (0.2)
5.0	13.4 ± 1.4 (3.5)	17.0	13.3 ± 1.0 (2.0)	250	5.6 ± 0.2 (0.2)
5.5	12.8 ± 1.5 (3.4)	18.0	12.1 ± 0.8 (1.6)	300	5.0 ± 0.2 (0.2)
6.0	12.1 ± 1.6 (3.4)	19.0	12.4 ± 0.7 (1.3)	400	4.2 ± 0.2 (0.1)
6.5	13.3 ± 1.4 (3.3)				

preliminary, because the DCS data for electrons were used in the present correction for positrons. As shown in figure 2, the decrease of apparent TCS for positrons with increasing magnetic field is more noticeable than that for electrons. This suggests that the DCSs for positron scattering are more steeply forward peaked than those for electron scattering. For this reason, the correction for the effect of forward scattering in e^+–HCl may be considerably larger than that presented here. The DCS of positrons is essential to obtain the correct TCS for positron scattering by HCl.

The effect of forward scattering is serious for the TCS measurement of polar molecules in our apparatus, because a wide exit cylinder was used. On the other hand, to reduce the effect of forward scattering, a narrower aperture is used for the e^-–TCS measurement in general. We examined the relation between the diameter of the aperture and the forward scattering correction. The correction was simulated with four values

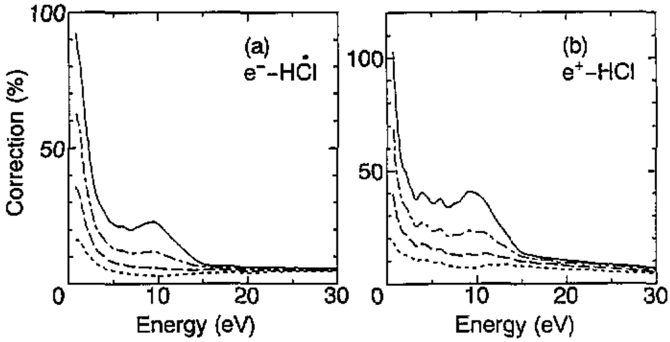

Figure 7. The proportion of correction against four values of diameter of the aperture: (*a*) for electrons; ——, 8 mm diameter; — · —, 4 mm diameter; - - -, 2 mm diameter; · · · ·, 1 mm diameter: (*b*) for positrons; symbols as for electrons.

of the aperture. The results are shown in figure 7. In the intermediate energy region, the angle at which scattering projectiles pass through the exit aperture of the collision cell is small, because the perpendicular component of the velocity is much smaller than the parallel component. Therefore, the correction for forward scattering is not strongly affected by the diameter of the aperture. Above 20 eV, it is about 4%. In the 5–20 eV range, the narrower aperture successfully reduces the effect of forward scattering. However, below 5 eV, the correction becomes very large and cannot be definitely diminished by reducing the aperture. Even for the smallest diameter of 1 mm, the correction amounts to 16% at 0.8 eV for e^-–TCS. In a very low energy region, the TCS cannot be determined solely by transmission measurements. It is necessary to correct the TCS for the effect of forward scattering by using the DCS data.

The correction for forward scattering was not performed for our measured TCSs before TI. In TI, the ratio of the forward scattering correction to measured TCS for SiH_4 and CF_4 at low energies was much smaller than we have found for HCl. However, with polar molecules such as H_2O and NH_3 the data (Sueoka *et al* 1986, 1987) need to be corrected for the effect of forward scattering. This will be discussed elsewhere.

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References

Allen M and Wong X 1981 *J. Chem. Phys.* **74** 1687
Brüche E 1927 *Ann. Phys., Lpz* **82** 25

Fabrikant I I 1991 *Phys. Rev.* A **43** 3478
Fabrikant I I, Kalin S A and Kazansky A K 1991 *J. Chem. Phys.* **95** 4966
Hoffman K R, Dababneh M S, Hsieh Y-F, Kauppila W E, Pol V, Smart J H and Stein T S 1982 *Phys. Rev.* A **25** 1393
Itikawa Y and Takayanagi K 1969 *J. Phys. Soc. Japan* **26** 1254
Jain A and Baluja K L 1992 *Phys. Rev.* A **45** 202
Knoth G, Rädle M, Gote M, Ehrhardt H and Jung K 1989 *J. Phys. B: At. Mol. Opt. Phys.* **22** 299
Mengoni A and Shirai T 1991 *Phys. Rev.* A **44** 7258
Morgan L A, Burke P G and Gillan C G 1990 *J. Phys. B: At. Mol. Opt. Phys.* **23** 99
Okamoto Y, Onda K and Itikawa Y 1993 *J. Phys. B: At. Mol. Opt. Phys.* **26** 745
Padial N T and Norcross D W 1984 *Phys. Rev.* A **29** 1590
Padial N T, Norcross D W and Collins L A 1983 *Phys. Rev.* A **27** 141
Pfingst K, Thümmel H T and Peyerimhoff S D 1992 *J. Phys. B: At. Mol. Opt. Phys.* **25** 2107
Rädle M, Knoth G, Jung K and Ehrhardt H 1989 *J. Phys. B: At. Mol. Opt. Phys.* **22** 1455
Rohr K and Linder F 1975 *J. Phys. B: At. Mol. Phys.* **8** L200
—— 1976 *J. Phys. B: At. Mol. Phys.* **9** 2521
Schafer O and Allen M 1991 *J. Phys. B: At. Mol. Opt. Phys.* **24** 3069
Sueoka O and Hamada A 1990 *At. Mol. Coll. Japan* **16** 18
Sueoka O and Mori S 1986 *J. Phys. B: At. Mol. Phys.* **19** 18 4035
Sueoka O, Mori S and Hamada A 1994 *J. Phys. B: At. Mol. Opt. Phys.* **27** 1453
Sueoka O, Mori S and Katayama Y 1986 *J. Phys. B: At. Mol. Phys.* **19** L373
—— 1987 *J. Phys. B: At. Mol. Phys.* **20** 3237
Yuan J and Zhang Z 1992 *Phys. Rev.* A **45** 4565