J. Phys. B: At. Mol. Opt. Phys. 24 (1991) 2737–2746. Printed in the UK

Absolute total cross section measurements for intermediate-energy electron scattering: IV. Kr and Xe

Antonio Zecca, Grzegorz Karwasz†, Roberto S Brusa and Rolly Grisenti
Department of Physics, University of Trento, 38050 Povo, Trento, Italy

Received 5 November 1990, in final form 1 March 1991

Abstract. Absolute total cross section measurements with an overall experimental uncertainty below 5% were performed for Kr and Xe in the energy range from 80 eV to 4000 eV. The Xe measurements above 750 eV are the first available in the literature. In the overlapping energy range the present data are in good agreement with other experimental and semi-empirical results. Comparing the total cross sections for all noble gases it has been found that their energy dependencies do not follow the Born approximation even at the highest measured energies.

1. Introduction

During the last few years several measurements of total cross sections have been performed in the intermediate-energy range ($100\,\mathrm{eV} < E < 10\,\mathrm{keV}$). These measurements were aimed mainly at comparing the corresponding values for electron and positron scattering (see the review of Kauppila and Stein 1990). Common features of these experiments are an energy range below 750 eV, relatively few experimental points and an accuracy of 5–10%. Nevertheless, a relative scarcity of total cross section data in the intermediate-energy range exists even for noble gases. Apart from our previous results (Dalba *et al* 1981, Zecca *et al* 1987a), the only measurements extending over 750 eV are those of Garcia *et al* (1986). However, the energy range of this experiment does not overlap with other ones (Wagenaar and de Heer 1985, Dababneh *et al* 1982, Nickel *et al* 1985). In particular, no experimental data exists for xenon in the energy range above 750 eV.

The precise values of the total cross section in a large energy range are, together with the zero-angle differential elastic cross sections, the input data for the dispersion relation (Gerjoy and Krall 1960).

$$\mathrm{Re}\, f(E,0) = f_{\mathrm{Born}}(E,0) - g_{\mathrm{Born}}(E,0) + \frac{P}{\pi}\int_0^\infty \frac{\mathrm{Im}\, f(E',0)}{E'-E}\,\mathrm{d}E' \qquad (1)$$

where f and g are the direct and exchange scattering amplitudes respectively. As follows for example from the discussion made by Kauppila *et al* (1981) for e^-–Ar scattering, the total cross section at energies above 100 eV contributes more than 50% of the integral on the right-hand side of the expression (1).

The measurements of the near-to-zero angle elastic differential cross sections for all noble gases have been performed by Wagenaar *et al* (1986) but the practical check

† Permanent address: Polish Academy of Sciences, IMP-PAN, 80-952 Gdańsk, Poland.

0953-4075/91/112737+10$03.50

of the validity of different forms of the dispersion relations (de Heer *et al* 1976, Kuchiev 1985, Bhatia and Temkin 1988) is impeded by the lack of the appropriate total cross sections. The total cross sections in a broad energy range serve also for the direct evaluation of the scattering potential via the inversion procedure in the non-quantum models (Miller 1969). Actually, the reconstruction of the scattering potential has been performed only for the e^--He (Allen 1986) system and quite recently for Ne and Ar (Kukulin *et al* 1990). No relevant work has been done for heavier noble gases due to the lack of appropriate data.

The only systematical calculations of total (elastic+inelastic) cross sections for all noble gases up to 3000 eV have been performed by McCarthy *et al* (1977). However, for Ne and Ar those data are 20% lower than the experimental ones (Zecca *et al* 1987b). Total elastic cross sections have been computed by Fink and Yates (1970) up to 1500 eV and by Riley *et al* (1975) from 1000 eV up to 256 keV.

The Born approximation, predicting in the limit of high energies a $1/E$ dependence of the total cross section, is the most frequently used in the intermediate-energy range region, although the conditions of its applicability for total cross sections have not yet been verified with sufficient certainty. The Born-like expansions of the form

$$\sigma(E) = \sum_{n=1} \frac{1}{E^n} \tag{2}$$

are commonly used to fit both experimental total (Evans and Mansour 1987, Garcia *et al* 1986) as well as inelastic (Krishnakumar and Srivastava 1988) cross sections at energies above 100 eV.

Some experimental evidence indicates that the low-energy limit, from which the Born approximation can be applied, is related to the energy at which merging of total cross sections for positrons and for electrons is observed. The only noble gas for which an effective merging of TCS curves for e^- and e^+ has been observed is He above 200 eV (Kauppila *et al* 1981). Similarly, only for helium does the Born approximation apply reasonably well at these energies (Brenton *et al* 1977). On the contrary, even for neon the low-energy limit of its applicability exceeds 700 eV, both for positrons (Brenton *et al* 1978) and electrons (Wagenaar and de Heer 1980) and no merging of e^- and e^+ cross sections has been observed (Kauppila *et al* 1981).

Recently several semiempirical formulae, alternatives to the Born approximation have been proposed. They describe total cross sections for electron and positron scattering on hydrocarbons in the energy range 100–400 eV (Floeder *et al* 1985), for electron and positron scattering on different targets in the energy range 100–500 eV (Szmytkowski 1989) and for electron–noble gas scattering in the 100–3000 eV energy range (Karwasz 1989). All these formulae contain a $1/\sqrt{E}$ term dominant in the energy dependence of the total cross sections.

2. Experimental procedure and errors

The present measurements conclude our investigations of total cross sections for electron–noble gas scattering in the intermediate energy range (Dalba *et al* 1979, Zecca *et al* 1987b). They were performed with essentially the same apparatus as used in our previous investigations for Ne and Ar (Zecca *et al* 1987b), i.e. the modified Ramsauer-type spectrometer of 20 cm beam trajectory radius. The experimental set-up used in these measurements has been described extensively in previous papers (Dalba *et al*

1979, Zecca *et al* 1987b). We refer to these papers for all details regarding the apparatus and the data taking procedure.

A cleaner vacuum system, based on turbomolecular pumps, and a better compensation of the Earth's magnetic field allowed us to extend the energy range from 80 to 4000 eV.

The systematic errors were evaluated to have the same value as in the Ne–Ar paper (Zecca *et al* 1987b). A figure of 2.4% has been assumed for these measurements.

To evaluate the error introduced by the finite angular resolution of the apparatus, we used the elastic differential cross sections of Wagenaar *et al* (1986) at 100 eV and of Jansen and de Heer (1976) extrapolated to zero angle at 3000 eV. The error is calculated as the contribution to the elastic scattering for angles smaller than the apparatus angular acceptance (3.4×10^{-4} sr). This contribution amounts to 0.11% for Kr, 0.16% for Xe at 100 eV and 0.49% in Kr, 0.66% in Xe at 3000 eV. Due to the lack of appropriate data in the literature, we did not include the inelastic contribution to the angular resolution error. We believe that this is smaller than the elastic one due to the energy discrimination of the apparatus.

The gas purities were 99.97% for Kr and 99.95% for Xe with main contaminants Xe and Kr respectively (<450 PPMV); O_2 (<3 PPMV); H_2O (<5 PPMV).

The statistical errors affecting these measurements vary from 3% at 100 eV to 1.8% at 500 eV, lowering to 1% at 4000 eV. These errors are slightly higher than in the case of Ne and Ar. The higher cross sections for Kr and Xe required lower gas pressures in the scattering chamber. Maximum pressures used at 100 eV were of the order of 0.5 Pa for both gases. Therefore, the capacitance manometer zero drift introduced higher random errors in the pressure read-out and consequently in the total cross sections, especially below 200 eV.

3. Results and discussion

Absolute total electron scattering cross sections for Kr and Xe are given in table 1. They are almost equal (about $12\times10^{-20}\,\mathrm{m}^2$) at our low energy limit and fall down to $1.12\times10^{-20}\,\mathrm{m}^2$ and $1.71\times10^{-20}\,\mathrm{m}^2$ values at 4000 eV for Kr and Xe respectively.

The comparison with previous measurements is given in figure 1(a) for Kr and in figure 1(b) for Xe. These figures were drawn in the following way. Our experimental data have been fitted in the energy range between 80 and 1000 eV by the formula

$$\sigma_{\mathrm{tot}} = A_1 + \frac{A_2}{\sqrt{E/R}} + \frac{A_3}{E/R} \tag{3}$$

where $R = 13.6$ eV and the coefficients equal to $A_1 = -0.65$, $A_2 = 32$, $A_3 = 0$ for Kr and $A_1 = -2.12$, $A_2 = 62.4$, $A_3 = -66.9$ for Xe (units are $10^{-20}\,\mathrm{m}^2$). In the energy region from 800 to 4000 eV the present data has been approximated by the formula

$$\sigma_{\mathrm{tot}} = \frac{B_1 \ln(E/R)}{E/R} + \frac{B_2}{E/R} \tag{4}$$

with the coefficients equal to $B_1 = 71.4$, $B_2 = -80.4$ for Kr and $B_1 = 139.0$, $B_2 = -292.0$ for Xe. The use of these formulae is justified in the next section.

The numerical values of these fits are represented in figure 1 as the horizontal broken lines. Experimental points from different groups are plotted against the scattering energy as their percentage discrepancy from this fit. Data plotted with a positive discrepancy are higher than the fitted values.

Table 1. Present experimental total cross sections for electron-krypton and xenon scattering.

Energy (eV)	Total cross section (10^{-20} m^2) krypton	xenon
81	12.83	12.45
90.25	11.98	12.39
100	11.47	12.24
110.25	10.62	11.95
121	10.05	11.53
132.25	9.547	11.15
144	9.034	10.81
169	8.348	10.39
196	7.829	9.476
225	7.273	9.069
256	6.782	8.612
289	6.354	8.273
324	5.932	7.717
361	5.589	7.376
400		7.244
441	4.946	
484		6.599
576	4.328	5.890
676	3.896	5.245
784	3.519	4.956
900	3.250	4.516
1000	3.088	4.171
1156	2.777	3.857
1296	2.572	3.553
1444	2.410	3.309
1600	2.180	3.115
1764	2.079	2.915
1936	1.932	2.749
2000	1.909	2.683
2116	1.769	2.606
2304	1.672	2.458
2500	1.562	2.310
2704	1.473	2.219
3000	1.370	2.078
3200	1.309	1.989
3400		1.896
3500	1.226	1.885
4000	1.122	1.711

As a general comment on these figures we can state that the spread of the experimental values from different groups is somehow larger for these gases than for Ne or Ar (see Zecca *et al* 1987b). All experimental values (apart from the data of Garcia *et al* 1986) and the semiempirical total cross sections of de Heer *et al* (1979) lie within ±7% boundaries for Kr and ±10% for Xe. The best consistency can be noticed between present results and those of Nickel *et al* (1985). As for Ne and Ar, the data of Wagenaar *et al* (1980) are slightly (about 3% for Kr and 7% for Xe) higher than ours and those of Dababneh *et al* (1982) are about 5% lower. This latter discrepancy is, however, within the declared angular resolution error of the Detroit apparatus.

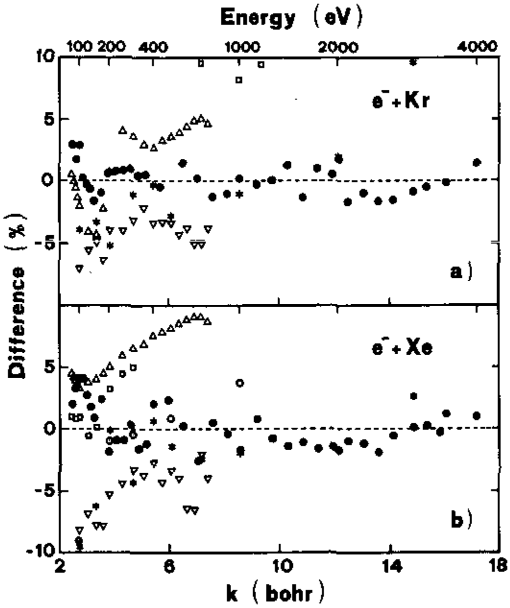

Figure 1. Total absolute cross sections for electron–Kr (a) and Xe (b) scattering presented as differences between the experimental results from different groups and the fit (formulae (3) and (4)). (a) ●, present results; △, Wagenaar and de Heer (1985); ▽, Dababneh *et al* 1982); *, semiempirical data of de Heer *et al* (1979); □, Garcia *et al* (1986). (b) Same symbols as in (a) apart from: □, Nickel *et al* (1985); ○, semiempirical data of Hayashi (1983).

At energies below 100 eV our results are slightly (within the experimental errors) higher than the mean of other values. This can be explained by the poorer beam stability in the low-energy limit of our apparatus; this effect usually leads to a rise in the measured cross section.

Our results confirm in the whole energy range the accuracy of the semiempirical estimations of de Heer *et al* (1979). At energies above 1000 eV our points in figure 1(a) and 1(b) are practically superimposed on those of de Heer *et al* (1979). Minor discrepancies can be noticed only at 100 eV for Xe, where de Heer's values are slightly lower than the average of the experimental data, and at 3000 eV for Kr, where the results of de Heer *et al* seem to be overestimated. Also the agreement with the semiempirical values for Xe of Hayashi (1983), apart from 100 eV, is very good.

A large discrepancy for krypton, rising from 5% at 750 to 30% at 3000 eV (out of scale in figure 1(a)) exists between the results of Garcia *et al* (1986) and the present ones. This difference, much higher than for Ne or Ar, probably should be attributed to the indirect method of the pressure evaluation, based on the optical emission of the gas in the experiment of Garcia *et al.*

4. Comparison with theory

In table 2 we compare our experimental values of the total cross sections with the theoretical calculations. The semiempirical data of de Heer *et al* (1979) and the most recent experimental total ionization cross sections of Krishnakumar and Srivastava

Table 2. Comparison of present experimental values with the theoretical results. At energy values not corresponding to the measured points, the total cross section values obtained from the fit (formulae (3) and (4)) are given. Cross sections are given in 10^{-20} m^2.

(*a*) Krypton

	Elastic cross sections					Inelastic cross sections				Total cross sections			
Energy (eV)	a	b	c	d	e	a	d	e	f	a	d	e	Present expt
100	14.8	5.615		5.713	6.192	17.7	1.458	4.525	4.305	32.5	7.171	10.72	11.47
150	10.4	4.755		4.432	4.394	10.7	1.319	4.133	3.863	21.1	5.751	8.689	8.986
200	7.97	4.200		3.873	3.679	7.88	1.171	3.623	3.451	15.9	5.044	7.302	7.695
300	5.47	3.533		3.494	3.186	5.32	0.9345	2.914	2.823	10.8	4.428	6.100	6.163
400	4.17	3.133		2.883	2.723	4.11	0.8056	2.514	2.414	8.28	3.689	5.237	5.251
500	3.37	2.844		2.642	2.374	3.39	0.7005	2.127	2.110	6.76	3.343	4.500	4.628
700	2.44			2.281		2.55	0.5591	1.734	1.750	4.98	2.840		3.810
1 000	1.72	2.043	1.87	1.888	1.696	1.89	0.4346	1.355	1.377	3.61	2.323	3.051	3.088
2 000	0.872		1.29	1.279	1.127	1.06	0.2509	0.7865		1.93	1.530	1.913	1.909
3 000	0.584			0.980	0.9423	0.752	0.1855	0.5753		1.34	1.166	1.518	1.370
4 000	0.439		0.859			0.589		0.4492		1.03			1.122
128 000			0.0747										
256 000			0.0497										

(*b*) Xenon

Energy (eV)	Elastic cross sections					Inelastic cross sections				Total cross sections			
	a	b	c	d	e	a	d	e	f	a	d	e	Present expt
100	32.8	4.377		4.643	4.828	1.891	5.848	5.746	6.534	10.68	12.24		
150	22.8	4.794		4.862	4.388	1.683	5.562	5.560	6.545	9.950	10.60		
200	17.5	4.982		4.851	4.727	1.494	4.867	4.961	6.345	9.594	9.600		
300	12.0	4.766		4.614	3.836	1.171	3.954	4.164	5.785	7.790	8.131		
400	9.11	4.366		4.250	3.755	0.9908	3.407	3.632	5.241	7.162	7.244		
500	7.36	4.007		3.917	3.340	0.8535	2.925	3.239	4.770	6.265	6.350		
700	5.32			3.419	2.836	0.6683	2.319	2.697	4.088	5.154	5.277		
1 000	3.76	2.850	2.79	2.863	2.396	0.5063	1.773	2.199	3.369	4.169	4.171		
2 000	1.90		2.00	1.949	1.650	0.2956	1.038		2.245	2.688	2.683		
3 000	1.27			1.489	1.380	0.2160	0.7535		1.705	2.133	2.078		
4 000	0.957		1.39				0.5881				1.711		
128 000			0.150										
256 000			0.102										

a Born approximation, present calculations.
b Fink and Yates (1970).
c Riley *et al* (1975).
d Inelastic total and integrated differential elastic cross sections of McCarthy *et al* (1977).
e Semiempirical data of de Heer *et al* (1979).
f Total experimental ionization cross sections of Krishnakumar and Srivastava (1988).

(1988) are given as well, in order to distinguish the elastic and inelastic parts of the total cross section.

As follows from table 2, all theoretical models (Fink and Yates (1971), Riley *et al* (1975), McCarthy *et al* (1977)) give elastic cross sections which are generally in accord with the semiempirical data (de Heer *et al* 1979). On the contrary, the inelastic part in the calculations of McCarthy *et al* is underestimated, being essentially lower than the ionization cross sections (Krishnakumar and Srivastava 1988). As a consequence also their total cross sections are underestimated in the whole energy range, both for krypton and xenon by approximately 20–40%. It is worth mentioning that the absorption part of the scattering potential in McCarthy *et al* (1977) calculations has been obtained by normalizing to available experimental values.

We have also performed the comparison of the present results with the Born approximation. The elastic part of the total cross section in this approximation is related to the form factors $F(K)$ for x-ray scattering through the formula (Inokuti and McDowell 1974)

$$\sigma_{\mathrm{el}}=\frac{4\pi a_0^2}{E/R}\int_0^{\sqrt{4(E/R)}}(Z-F(K))^2K^{-3}\,\mathrm{d}K \tag{5}$$

where Z is the atomic number, a_0 the Bohr radius and K the momentum transferred during the collision. The inelastic part of total cross section can be evaluated from the formula (Inokuti 1971)

$$\sigma_{\mathrm{in}}=4\pi a_0^2\left(M_{\mathrm{tot}}^2\frac{\ln(E/R)}{E/R}+M_{\mathrm{tot}}^2\frac{\ln(4C_{\mathrm{tot}})}{E/R}+\gamma_{\mathrm{tot}}\frac{R^2}{E^2}\right). \tag{6}$$

To evaluate the elastic cross section we used the analytical five-parameter form factors of Salvat *et al* (1987). The values of the parameters M_{tot}, C_{tot} and γ_{tot} of the inelastic part for Kr were taken from Inokuti *et al* (1981). No appropriate parameters were available for xenon.

The results of our calculations are presented in table 2. The Born approximation predicts the inelastic cross sections for energies above 1000 eV reasonably well but it completely fails for elastic scattering, giving too steep an energy dependence of the cross section. As follows from the relativistic calculations of Riley *et al* (1975) quoted in table 2, even at energies as high as 128 keV the elastic cross sections do not follow the Born $1/E$ dependence.

In figure 2 we present the log–log plot of the total cross sections from our laboratory (Dalba *et al* 1981, Zecca *et al* 1987b and the present data) for all noble gases, and we compare them with the $1/\sqrt{E}$ and $1/E$ dependences. For all the gases except for He the total cross sections up to 1000 eV fall approximately as $1/\sqrt{E}$. This dependence becomes steeper at higher energies, but does not reach the $1/E$ limit even at 4000 eV.

The total cross section for scattering on polarization potential is proportional to $\sqrt{\alpha}/\sqrt{E}$, where α is the target polarizability (Vogt and Wannier 1954). From the experimental energy dependences one can expect that the polarization potential also plays a significant role in the intermediate-energy electron scattering. This conclusion is also supported by some other experimental and theoretical observations.

The ratios between the total cross sections for the different noble gases at given energy are close to the ratios between the square roots of the corresponding static polarizabilities (Karwasz 1989). Bromberg (1969) noticed that, in the limit of small momentum transfer, differential elastic cross sections at a few hundred eV can be explained in the Born approximation as scattering on a polarization potential. Jansen

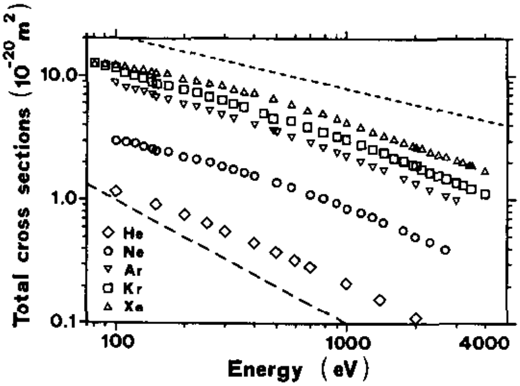

Figure 2. Experimental total cross sections for electron–noble gas scattering in the intermediate-energy range. Data for helium are from Dalba *et al* (1981), for neon and argon from Zecca *et al* (1987b). The short (upper) broken line illustrates the $1/\sqrt{E}$ dependence and the long (lower) broken line the $1/E$ dependence.

and de Heer (1976) showed that experimentally observed small angle differential elastic cross sections for noble gases between 100 and 3000 eV can be obtained assuming scattering on a polarization potential, with the 'effective' polarizabilities diminishing with the collision energy.

Also, the results of theoretical examinations (Karwasz 1989) performed with a classical model have shown that experimental intermediate angle differential cross sections for elastic electron–noble gas scattering between 200–2000 eV can be reasonably well reproduced taking only the polarization potential into account. Additionally, the model allows the intermediate angle elastic scattering to be related to the impact parameters of the order of few au, at which the polarization potential (see Nakanishi and Schrader 1986) dominates over the static part (Salvat *et al* 1987). However, the quantum calculations for different model potentials and all noble gases would be indispensable to make the final assessment on the importance of the polarization potential for electron scattering in the intermediate-energy range.

Further systematical theoretical studies would be required to explain the observed energy dependences. An extension of measurements toward higher energies is also desirable.

Acknowledgments

This work has been supported by the Ministero dell' Universita' e della Ricerca Scientifica e Tecnologica and by the Consiglio Nazionale delle Ricerche. One of us (GK) wants to express thanks for the hospitality at Trento University.

References

Allen L J 1986 *Phys. Rev.* A **34** 2706
Bhatia A K and Temkin A 1988 *Phys. Rev.* A **37** 1415
Brenton A G, Dutton J and Harris F M 1978 *J. Phys. B: At. Mol. Phys.* **11** L15
Brenton A G, Dutton J, Harris F M, Jones R A and Lewis D M 1977 *J. Phys. B: At. Mol. Phys.* **10** 2699

Bromberg J Ph 1969 *J. Chem. Phys.* **51** 4117

Dababneh M S, Hsieh Y F, Kaupilla W E, Pol V and Stein T S 1982 *Phys. Rev.* A **26** 1252

Dalba G, Fornasini P, Grisenti R, Lazzizzera I, Ranieri G and Zecca A 1981 *Rev. Sci. Instrum.* **52** 979

Dalba G, Fornasini P, Lazzizzera I, Ranieri G and Zecca A 1979 *J. Phys. B: At. Mol. Phys.* **12** 3787

de Heer F J, Jansen R H J and Van der Kaay 1979 *J. Phys. B: At. Mol. Phys.* **12** 979

de Heer F J, Wagenaar R W, Blaauw H J and Tip A 1976 *J. Phys. B: At. Mol. Phys.* **9** L269

Evans C J and Mansour H L 1987 *J. Phys. B: At. Mol. Phys.* **20** 5925

Fink M and Yates A C 1970 *At. Data* **1** 385

Floeder K, Fromme D, Raith W, Schwab A and Sinapius G 1985 *J. Phys. B: At. Mol. Phys.* **18** 3347

García G, Arqueros F and Campos J 1986 *J. Phys. B: At. Mol. Phys.* **19** 3777

Gerjuoy E and Krall N A 1960 *Phys. Rev.* **119** 705

Hayashi M 1983 *J. Phys. D: Appl. Phys.* **16** 581

Inokuti M 1971 *Rev. Mod. Phys.* **43** 297

Inokuti M, Dehmer J L, Baer T and Hansen J D 1981 *Phys. Rev.* A **23** 95

Inokuti M and McDowell M R C 1974 *J. Phys. B: At. Mol. Phys.* **7** 2382

Jansen R H J and de Heer F J 1976 *J. Phys. B: At. Mol. Phys.* **9** 213

Karwasz G 1989 *Proc. 16th Int. Conf. on Physics of Electronic and Atomic Collisions (New York)* ed A Dalgarno, R S Freund, M S Lubell and T B Lucatorto (Amsterdam: North-Holland) Abstracts p 141

Kauppila W E and Stein T S 1990 *Adv. At. Mol. Opt. Phys.* **26** 1

Kauppila W E, Stein T S, Smart J H, Dababneh M S, Ho Y K, Downing J P and Pol V 1981 *Phys. Rev.* A **24** 725

Krishnakumar E and Srivastava S K 1988 *J. Phys. B: At. Mol. Opt. Phys.* **21** 1055

Kuchiev M Yu 1985 *J. Phys. B: At. Mol. Phys.* **18** L579

Kukulin V I, Pomerantsev V N and Horáček J 1990 *Phys. Rev.* A **42** 2719

McCarthy I E, Noble C J, Philips B A and Turnbull A D 1977 *Phys. Rev.* **15** 2173

Miller W M 1969 *J. Chem. Phys.* **51** 3631

Nakanishi H, Schrader D M 1986 *Phys. Rev.* A **34** 1810

Nickel J C, Imre K, Register D F and Trajmar S 1985 *J. Phys. B: At. Mol. Phys.* **18** 125

Riley M E, MacCallum C J and Biggs F 1975 *At. Data Nucl. Data Tables* **15** 443

Salvat F, Martinez J D, Mayol R and Parellada J 1987 *Phys. Rev.* A **36** 467

Szmytkowski Cz 1989 *Z. Phys.* D **13** 69

Vogt E and Wannier G H 1954 *Phys. Rev.* **95** 1190

Wagenaar R W, De Boer A, van Tubergen T, Los J and de Heer F J 1986 *J. Phys. B: At. Mol. Phys.* **19** 3121

Wagenaar R W and de Heer F J 1980 *J. Phys. B: At. Mol. Phys.* **13** 3855

—— 1985 *J. Phys. B: At. Mol. Phys.* **18** 2021

Zecca A, Grisenti R, Oss S, Karwasz G and Brusa R S 1987a *XVth Int. Conf. on Physics of Electronic and Atomic Collisions, Abstr. Contr. Papers*, ed J Geddes, H B Gilbody, A E Kingston, C J Latimer and H R J Walters (Brighton) p 135

Zecca A, Oss S, Karwasz G, Grisenti R and Brusa R S 1987b *J. Phys. B: At. Mol. Phys.* **20** 5157