Measurement of electron-impact-excitation cross sections and oscillator strengths for Kr

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Differential excitation cross sections have been measured for Kr $4p^6(^1S_0)\rightarrow 4p^5(^2P_{1/2,3/2})5s$ transitions at 300- and 500-eV impact energies and for 1.5°–10° scattering angles by electron-energy-loss spectroscopy. The integrated cross sections for these impact energies are reported here. The generalized oscillator strengths have also been obtained to determine the optical oscillator strengths. The errors are estimated to be less than 15%.

I. INTRODUCTION

Recently the importance of knowledge about electronic and atomic collisions has been recognized from viewpoints of its application. Pumping mechanisms in gas lasers, modeling of high-temperature plasmas, and plasma processing technology are typical examples of the field where the atomic collision processes play the key role. We obtained here data of electron-impact excitation for krypton, which could be useful for the design of a highly efficient KrF excimer laser.

In this paper, we report experimental data on the cross sections of electron-impact excitation:

$$e+\mathrm{Kr}[4p^6(^1S_0)]\rightarrow e'+\mathrm{Kr}^*[4p^5(^2P_{1/2,3/2})5s] ,$$

where e and e' are the incident and scattered electrons, respectively. To our knowledge, there have been no reports on accurate calculation for the e-Kr scattering process for energies used in these experiments, although a few theoretical calculations have been published for lower energies than about 100 eV.[1,2] Experimentally, Trajmar *et al.*[3] measured the differential cross sections (DCS's) and the integrated cross sections at the impact energies of 15–100 eV by electron-energy-loss spectroscopy (EELS), and Lewis *et al.*[4] measured the DCS's at the impact energies of 50–60 eV. We report the EELS at 300 and 500 eV to obtain the DCS's, the generalized oscillator strengths (GOS's), and the optical oscillator strengths (OOS's). These results replenish the previous data on e-Kr scattering processes.

II. EXPERIMENTAL PROCEDURES

Details of the experimental apparatus are described in our previous work:[5] the apparatus consists of an electron gun, an energy selector, a target source, and an energy analyzer. All of these components are enclosed in a vacuum chamber (3×10^{-7} Torr).

The energy resolution of the apparatus is 25–40 meV [full width at half maximum (FWHM)] at 30 nA electron current and 10–500-eV impact energies. The angular resolution is 0.8° (FWHM), which was determined by measuring the angular distribution of the direct electron beam from the energy selector. This angular resolution may cause larger values of DCS's of about 5% than the true one. A careful calibration of the scattering angles has been performed by the use of the symmetry of the scattering intensity ratio $I_{2\,^1S}/I_{2\,^1P}$ (the $2\,^1S$ and the $2\,^1P$ excitation transitions in He), which is known to be a steep function of the scattering angle. This procedure is particularly important for the experiments of forward scattering.

The absolute DCS's are determined from the relation

$$\left[\frac{d\sigma}{d\Omega}\right]_{\mathrm{inel}}\Bigg/\left[\frac{d\sigma}{d\Omega}\right]_{\mathrm{el}}=I_{\mathrm{inel}}/I_{\mathrm{el}} , \qquad (1)$$

where the inel and el indices denote inelastic and elastic scattering, respectively; $I_{\mathrm{inel}}/I_{\mathrm{el}}$ is given by the ratio of

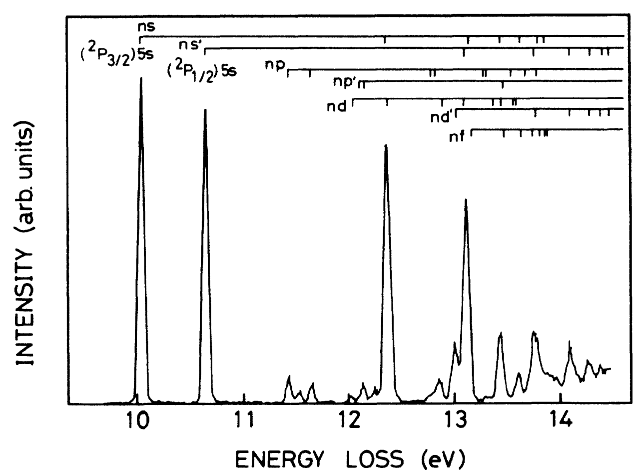

FIG. 1. A typical electron-energy-loss spectrum of Kr (200 eV, 5°).

the respective peak areas of the energy-loss spectra. The $(d\sigma/d\Omega)_{el}$ were obtained by a calculation using a fitting function, which was made based on the experimental data of the absolute elastic scattering cross sections which have been measured by Bromberg[6] and by Jansen *et al.*[7] The DCS, $(d\sigma/d\Omega)_{inel}$, can be simply determined by multiplying the scattering intensity ratio with the $(d\sigma/d\Omega)_{el}$ for the same collision energy.

When the kinetic energy of incident electrons is large enough to ensure the validity of the Born approximation, the GOS, $F(K)$, is related with the DCS, $d\sigma/d\Omega$, using the following equation (in a.u.):

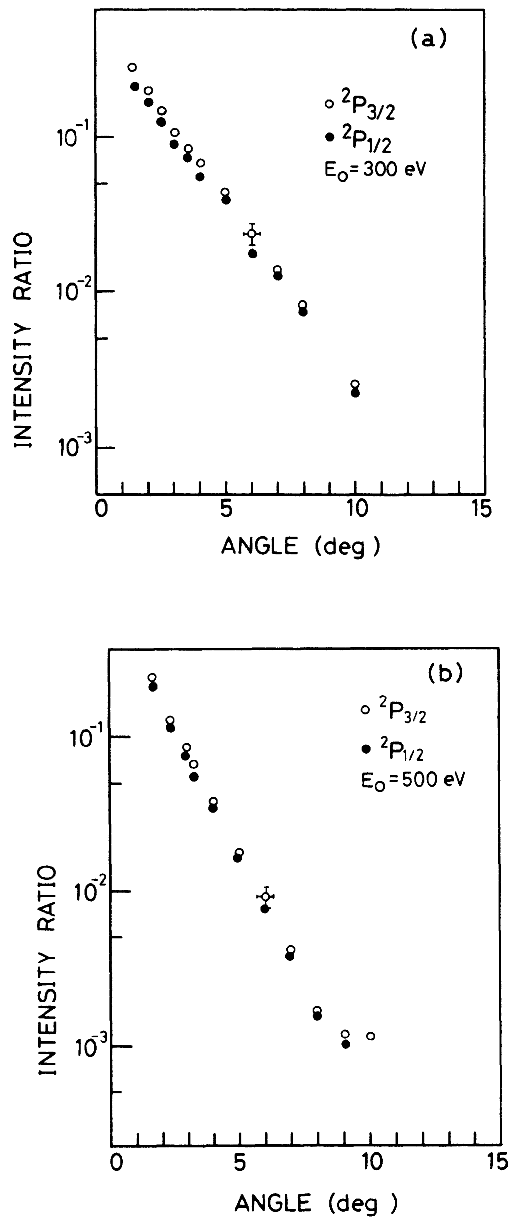

FIG. 2. Angular dependence of the intensity ratio I_{inel}/I_{el} for the excitation of the $4p^5(^2P_{1/2})5s$ and $4p^5(^2P_{3/2})5s$ states in Kr at impact energies of (a) 300 eV and of (b) 500 eV.

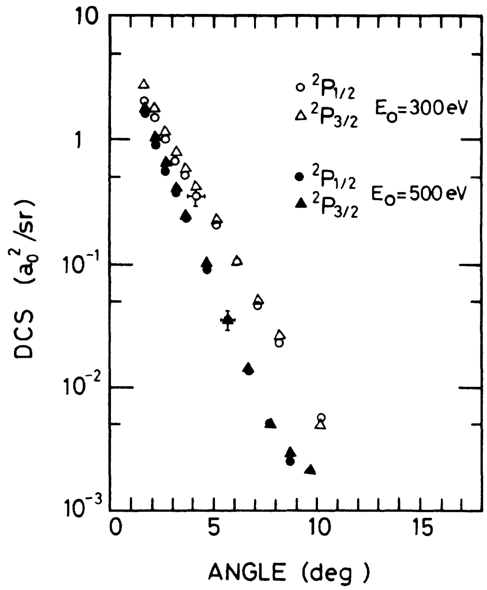

FIG. 3. Absolute differential cross sections for the excitation of the $4p^5(^2P_{1/2})5s$ and $4p^5(^2P_{3/2})5s$ states in Kr as a function of the scattering angle.

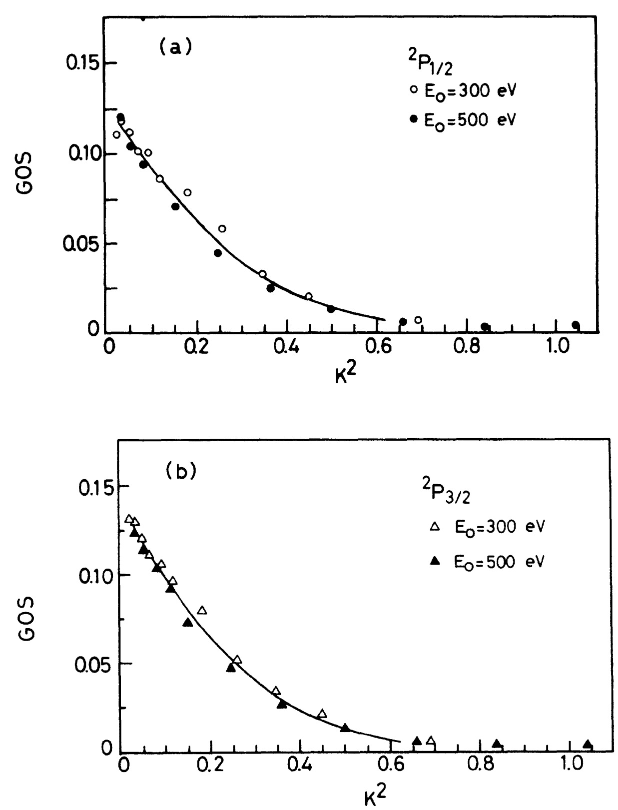

FIG. 4. Generalized oscillator strengths for the $4p^5(^2P_{1/2})5s$ and the $4p^5(^2P_{3/2})5s$ states in Kr as a function of the squared momentum transfer K^2: (a) for the $4p^5(^2P_{1/2})5s$ state, the solid curve is calculated by Eq. (8); (b) for the $4p^5(^2P_{3/2})5s$ state, the solid curve is calculated by Eq. (9).

TABLE I. The intensity ratios $(d\sigma/d\Omega)_{\rm inel}/(d\sigma/d\Omega)_{\rm el}$ for excitation of the $4p^5(^2P_{1/2})5s$ and $4p^5(^2P_{3/2})5s$ states. The absolute elastic differential cross sections (in a.u.) at the impact energy E_0 (300 and 500 eV) are also listed. Square brackets denote the power of 10. The $(d\sigma/d\Omega)_{\rm el}$ are given by the interpolation or extrapolation of the results by Bromberg and by Jansen *et al.*

Angle (deg.)	$\left(\frac{d\sigma}{d\Omega}\right)_{\rm el}$	Intensity ratio $P_{1/2}$	Intensity ratio $P_{3/2}$	$\left(\frac{d\sigma}{d\Omega}\right)_{\rm inel}$ $P_{1/2}$	$\left(\frac{d\sigma}{d\Omega}\right)_{\rm inel}$ $P_{3/2}$
		$E_0=300$ eV			
1.7	9.70	2.20[−1]	2.85[−1]	2.13	2.77
2.2	8.92	1.72[−1]	2.04[−1]	1.53	1.82
2.7	8.20	1.25[−1]	1.44[−1]	1.02	1.18
3.2	7.53	8.95[−2]	1.04[−1]	6.74[−1]	7.85[−1]
3.7	6.92	7.51[−2]	8.49[−2]	5.20[−1]	5.87[−1]
4.2	6.36	5.67[−2]	6.63[−2]	3.60[−1]	4.21[−1]
5.2	5.36	3.46[−2]	4.00[−2]	1.85[−1]	2.15[−1]
6.2	4.52	2.09[−2]	2.14[−2]	9.46[−2]	9.68[−2]
7.2	3.80	1.22[−2]	1.36[−2]	8.41[−2]	5.17[−2]
8.2	3.20	7.23[−3]	8.04[−3]	2.31[−2]	2.57[−2]
10.2	2.26	2.47[−3]	2.15[−3]	5.58[−3]	4.68[−3]
		$E_0=500$ eV			
1.7	8.75	1.92[−1]	2.13[−1]	1.67	1.86
2.2	8.05	1.13[−1]	1.33[−1]	9.12[−1]	1.07
2.7	7.40	7.65[−2]	8.91[−2]	5.67[−1]	6.60[−1]
3.2	6.80	5.48[−2]	6.20[−2]	3.73[−1]	4.22[−1]
3.7	6.24	3.69[−2]	4.04[−2]	2.31[−1]	2.52[−1]
4.7	5.24	1.79[−2]	2.13[−2]	9.40[−2]	1.11[−1]
5.7	4.39	7.92[−3]	8.78[−3]	3.47[−2]	3.85[−2]
6.7	3.65	4.02[−3]	4.29[−3]	1.47[−2]	1.57[−2]
7.7	3.03	1.63[−3]	1.68[−3]	4.96[−3]	5.08[−3]
8.7	2.51	1.00[−3]	1.17[−3]	2.51[−3]	2.92[−3]
9.7	2.06		1.01[−3]		2.09[−3]

TABLE II. Comparison of the present optical oscillator strengths for the Kr $4p^5(^2P_{1/2})5s$ and $4p^5(^2P_{3/2})5s$ states with other works.

Reference	$4p^5(^2P_{1/2})5s$	$4p^5(^2P_{3/2})5s$
	EELS	
The present work	0.127±0.015	0.143±0.015
Geiger[a]	0.173±0.035	0.173±0.035
	Optical measurements	
Wilkinson[b]	0.159	0.135
de Jongh and van Eck[c]	0.142±0.015	
Tsurubuchi *et al.*[d]	0.139±0.010	0.155±0.011
Lewis[e]	0.174	0.193
	Calculations	
Dow and Knox[f] (A)	0.136	0.138
(B)	0.153	0.152

[a]Reference 9.
[b]Reference 10.
[c]Reference 11.
[d]Reference 12.
[e]Reference 13.
[f]Reference 14.

$$F(K)=\frac{W}{2}\frac{k_i}{k_f}K^2\left[\frac{d\sigma}{d\Omega}\right], \tag{2}$$

where W stands for the excitation energy, k_i and k_f for the incident and scattered momenta, respectively, and K for the momentum transfer. If the Born approximation is valid, $F(K)$ depends only on K and can be expanded as[8]

$$F(K)=\frac{f_0}{(1+x)^6}\left[1+\sum_{n=1}^{\infty}f_n\left[\frac{x}{1+x}\right]^n\right], \tag{3}$$

where f_0 is the OOS, f_n are the coefficients, and parameter x equals $(K/Y)^2$, where Y is related to the ionization potential P_i and excitation energy W as $Y=(P_i)^{1/2}+(P_i-W)^{1/2}$.

The OOS is determined by taking the limit:

$$\lim_{K\to 0}F(K)=f_0\ . \tag{4}$$

Finally, by employing both Eqs. (2) and (3), one obtains the integrated cross section:

$$\sigma=2\pi\int\frac{d\sigma}{d\Omega}\sin\theta\,d\theta=\frac{2\pi}{Wk_i^2}\int F(K)d(\ln K^2)\ . \tag{5}$$

III. RESULTS AND DISCUSSION

A typical electron-energy-loss spectrum for e-Kr scattering is shown in Fig. 1.

The intensity ratios $I_{\text{inel}}/I_{\text{el}}$ are shown in Fig. 2 as functions of the scattering angle. The absolute DCS's were obtained by using the absolute DCS's for the elastic scattering measured by Bromberg and by Jansen *et al.* DCS's for the elastic scattering can be well fitted to the formula as follows:

$$\left[\frac{d\sigma}{d\Omega}\right]_{\text{el}}=A\exp(C_1K_0-C_2K_0^2)\ , \tag{6}$$

where K_0 is the momentum transfer of the elastically scattered electron and A, C_1, and C_2 are the fitting parameters. Using the formula, we determined $(d\sigma/d\Omega)_{\text{el}}$ by the interpolation and extrapolation of the results by Bromberg and by Jansen *et al.* The numerical results are given in Table I. Results for the absolute DCS's for the excitations are shown in Fig. 3.

It can be seen from Fig. 3 that the angular dependence of DCS's may be approximated by the following exponential function:

$$\frac{d\sigma}{d\Omega}=B\exp\left[-\frac{|\theta|}{b}\right], \tag{7}$$

where θ is scattering angle, B and b are the fitting parameters; $b=0.99$ and 1.40 for $E_0=500$ and 300 eV give the best fits, respectively. In the Appendix of Ref. 5, we have discussed how the measured DCS's are affected by the finite angular resolution. Based on the same discussion, taking our angular resolution of 0.8° into account, the influence of the effect is estimated to be about 5%.

TABLE III. Integrated cross sections for the excitation in Kr (the present work). E_0 is the impact energy.

	Cross section (10^{-18} cm^2)	
E_0 (eV)	$4p^5(^2P_{1/2})5s$	$4p^5(^2P_{3/2})5s$
300	9.80±0.10	12.6±0.15
500	5.75±0.07	6.91±0.08

The DCS's for the $^2P_{1/2}$ and $^2P_{3/2}$ states are almost the same, but the DCS for the $^2P_{3/2}$ state is slightly larger than that for the $^2P_{1/2}$ state at the small scattering angles.

The GOS's were determined according to Eq. (2) and shown in Fig. 4. We obtained the experimental expression for the GOS's for the $^2P_{1/2}$ and $^2P_{3/2}$ states as follows:

$$F_{1/2}(K)=\{0.127-0.016[x/(1+x)]-4.428[x/(1+x)]^2+\cdots\}/(1+x)^6\ , \tag{8}$$

$$F_{3/2}(K)=\{0.143-0.258[x/(1+x)]-4.100[x/(1+x)]^2+\cdots\}/(1+x)^6\ . \tag{9}$$

We can see some systematic differences between the results at 300 and 500 eV, but it is within the experimental errors. Equations (8) and (9) are given by least-squares fitting to all the data points.

Comparisons of the present results of OOS's with other measurements and calculations are given in Table II. Geiger[9] determined the OOS's by EELS, Wilkinson[10] by optical absorption technique, de Jongh and Van Eck[11] and Tsurubuchi *et al.*[12] by observing the self-absorption of the vacuum-ultraviolet (vuv) radiations, Lewis[13] by observing the collision broadening, Dow and Knox[14] by the calculations (A) based only on *ab initio* calculation of wave functions and (B) based on experimental energies and dipole matrix computed from the wave functions.

Previous experimental data do not agree with each other. Not only the absolute values but also the relative intensities of the $^2P_{1/2}$ state to the $^2P_{3/2}$ state show significant discrepancies. It must be noted that our values agree with the recent data of Tsurubuchi *et al.*, though the experimental method is quite different.

The integrated cross sections were determined for the first time by the use of Eq. (5) (Table III).

The experimental errors in our integrated cross sections are mainly from the determination of the scattering angle: the angular resolution,[5] the offset of the zero scattering angle, and the resettability of the scattering angle. The total error in the cross section is estimated to be less than +10% and −15%. This estimation includes the error due to omission of the integral area where K is larger than 1.5.

The present results may be useful to improve the reliability in the standard data of excitation cross sections and OOS determined by different kinds of methods.

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