Generalized oscillator strengths for $5s$, $5s'$, and $5p$ excitations of krypton

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The absolute generalized oscillator strengths (GOSs) for 5s, $5s'$, $5p\ [5/2]_{3,2}$, $5p\ [3/2]_{1,2}$, and $5p\ [1/2]_0$ transitions of krypton have been determined in a large K^2 region at a high electron-impact energy of 2500 eV. The positions of the minima and maxima of these GOSs have been determined. The present results show that the angular resolution and pressure effect have great influence on the position and the amplitude of the minimum for the GOS of $5s+5s'$ transitions. When these effects are considered, the measured minimum position for the GOS of $5s+5s'$ transitions is in excellent agreement with the calculation of Chen and Msezane [J. Phys. B **33**, 5397 (2000)].

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I. INTRODUCTION

Krypton has been applied extensively in many fields, such as the plasma diagnostics for the thermonuclear reactor, plasma processing of flat-panel displays technology, pumping mechanisms in KrF gas-laser system. In addition, there are tremendous challenges for theoretical models because of the complications of many-electron heavy atom and non-LS-coupled nature in krypton. Furthermore, a comparison of the shape as well as the absolute magnitude of the measured and calculated generalized oscillator strengths (GOSs) profiles can help both in the evaluation of computational procedures and in determining correct spectral assignments [1], and the deviation of the magnitudes and positions of the minima or maxima predicted by theoretical calculations from experimental results will serve as a test of the Born approximation as well as the accuracy of the wave function [2]. Therefore, the differential cross sections (DCSs) and GOSs for electron impact are needed greatly in the industrial application as well as in the fundamental atomic collision processes.

The GOS was introduced to describe the electron collision processes by Bethe and Inokuti [3,4], which is defined as (in atomic units)

$$f(E,K)=\frac{E}{2}\frac{p_0}{p_a}K^2\frac{d\sigma}{d\Omega}. \tag{1}$$

Here $f(E,K)$ and $d\sigma/d\Omega$ stand for GOS and DCS, respectively. E and K are the excitation energy and momentum transfer, respectively, while p_0 and p_a are the incident and scattered electron momenta, respectively.

There are many DCS measurements for krypton with incident electron energy lower than 100 eV [5–8], which have been summarized by Khakoo *et al.* [9]. Guo *et al.* [10] recently measured and calculated the absolute DCSs for several transitions at 12–20-eV incident electron energy and obtained the differential cross sections ratios of the four $4p^5 5s$ transitions. For the middle and high electron-impact energy studies, only a few researchers reported the GOSs for several excitations of krypton. Wong *et al.* [11] reported a minimum and a maximum in the relative GOS for $5s+5s'$ excitations with 25-keV incident electrons, their energy resolution is 1 eV that is not good enough to resolve $5s$ and $5s'$ transitions, and the GOS profile was much different from theoretical work (see Sec. III). Delâge and Carette [12] measured the apparent generalized oscillator strengths for transitions lower than 13.5 eV with impact energies from 15 to 400 eV. Takayanagi *et al.* [13] also reported the GOSs for $5s$ and $5s'$ transitions with high energy resolution of 25–40 meV and incident energies of 300 and 500 eV. But their K^2 region was limited to 0.018–1.04 a.u., the positions of the minimum and maximum for the GOSs of $5s$ and $5s'$ transitions could not be covered. As for the dipole-forbidden transitions of $4p^6 \rightarrow 4p^5(3/2)5p$, the only available GOSs measurement was made by Suzuki [14] with incident electron energies of 100, 300, and 500 eV, but they only observed the first maximum because of the limited K^2 region.

With regard to theoretical researches, many calculations were performed for the GOSs of the $4p^6 \rightarrow 4p^5 5s,5s'$ transitions [2,15–20]. Briefly, Kim *et al.* [2] measured and calculated the first minimum of GOS for the $4p^6 \rightarrow 4p^5 5s$ transition. Utilizing the analytic atomic independent particle model, Ganas and Green [15] calculated the generalized oscillator strengths for the single-particle excitation of the rare gases and their work shows a very complex nodal structure of GOSs at large K^2 region. Dependence of GOSs extrema on momentum transfer and effective nuclear charge for atomic transition were systematically studied by Miller [16] in the first Born approximation within a one-electron approximation employing scaled hydrogenlike orbitals. Padma [17] computed the GOSs of $5s$ and $5s'$ using the relativistic local-density-potential method. Recently, the GOSs for the transitions of $4p^5(5s+5s')$ were calculated by Shi *et al.* [18] to investigate the relativistic, correlation, and relaxation effects. Furthermore, the positions of the characteristic minimum and maximum in the GOS for the same transitions were reported by Chen and Msezane [19] using the random-

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TABLE I. The positions of minima and maxima for GOSs of $5p\ [5/2]_{3,2}$, $5p\ [3/2]_{1,2}$, and $5p\ [1/2]_0$ transitions of krypton.

	The first maxima K^2 (a.u.)		The first minima K^2 (a.u.)	The second maxima K^2 (a.u.)
	Present work	Ref. [14]	Present work	Present work
$5p\ [5/2]_{3,2}$	0.19	0.23	1.61	3.39
$5p\ [3/2]_{1,2}$	0.17	0.21	1.55	3.37
$5p\ [1/2]_0$	0.20	0.22	1.74	3.54

phase approximation with exchange effect and the Hartree-Fock approximation. To investigate many-electron correlation effects, Amusia *et al.* [20] calculated GOSs for the monopole, dipole, and quadrupole, discrete and continuous excitation spectrum of the rare gases.

All the previous experimental studies were somewhat limited, so it is necessary to continue experimental study at high energy, high-energy resolution and covering a large K^2 region. In this work, we reported generalized oscillator strengths of $5s$ and $5s'$ with an energy resolution of 65 meV at an incident electron energy of 2500 eV for K^2 region of 0.07–4.0 a.u. It was found that the pressure effect and instrumental angular resolution have great influence on the measured amplitude and positions of the extrema, which will be described in detail in Sec. III. We also determined the GOSs for the nondipole transitions of $5p\ [5/2]_{3,2}$, $5p\ [3/2]_{1,2}$ and $5p\ [1/2]_0$ excitations and found that there were two maxima and one minimum in their GOSs, these were listed in Table I (see Sec. III). To the best of our knowledge, it is the first time the characteristic extrema for these resolved forbidden transitions of krypton were studied.

II. EXPERIMENTAL METHOD

The angular-resolved electron-energy-loss spectrometer used in this experiment has been described in detail in Refs. [21–23]. Briefly, it consists of an electron gun, a hemispherical electrostatic monochromator made of aluminum, a rotable energy analyzer of the same type, an interaction chamber, a number of cylindrical electrostatic lenses, and a one-dimension position sensitive detector for detecting the scattered electrons. All of these components are enclosed in four separate vacuum chambers made of stainless steel. The impact energy of the spectrometer can be varied from 1 to 5 keV. For the present experiment, the impact energy was set at 2500 eV and the energy resolution was 65 meV [full width at half maximum (FWHM)]. The background pressure in the vacuum chamber was 3×10^{-5} Pa. The true zero angle was calibrated by the symmetry of the angular distribution of the $4p^6\rightarrow4p^5(5s+5s')$ inelastic scattering signal around the geometry nominal zero. The angular resolution is about 1.2° FWHM at present.

In order to determine the GOSs of $5s$, $5s'$, and $5p$, the electron-energy-loss spectra have been measured from 1.0° to 8.5° with an interval of 0.5°, which correspond to different momentum transfer. A typical electron-energy-loss spectrum is shown in Fig. 1. In the energy-loss region of 9.5–12.5 eV, the transitions of $5p\ [5/2]_{3,2}$, $5p\ [3/2]_{1,2}$, and $5p\ [1/2]_0$ are well separated at an energy resolution of 65 meV. In order to minimize the system errors caused by the instability of the intensity of the incident electron beam, the dipole forbidden transitions of $4p^6\rightarrow4p^5(\mathrm{P}_{3/2})5p$ at the angle of 3° were measured before and after the measurements of the electron-energy-loss spectra at individual angle, and the intensity of individual transition was normalized by the area of the forbidden transitions of $4p^6\rightarrow4p^5(\mathrm{P}_{3/2})5p$. Besides the instability of the incident electron beam, two types of double scattering processes could also cause errors in the DCS measurements, which have been described in details in Ref. [22]. Because the cross section of double scattering process depends on the square of pressure, while the cross section of the single scattering process depends on pressure, the relation between the measured intensity ratios and pressure is as follows:

$$\frac{I_p(\theta)}{I_{ref}(\theta)}\approx\left(\frac{I_p(\theta)}{I_{ref}(\theta)}\right)_{P=0}+c(\theta)P. \tag{2}$$

Here $c(\theta)$ is a coefficient which depends on the scattering angle and the cross section of the measured excitation. $I_p(\theta)$ and $I_{ref}(\theta)$ represent the intensity of individual excitation to be measured and the inelastic excitation of $4p^5(\mathrm{P}_{3/2})5p$, respectively. $(I_p(\theta)/I_{ref}(\theta))_{P=0}$ is a ratio extrapolated to zero gas pressure. There are some differences between the present and our previous methods [22]. In our previous work, the $I_{ref}(\theta)$ represents the scattering intensity of elastic excita-

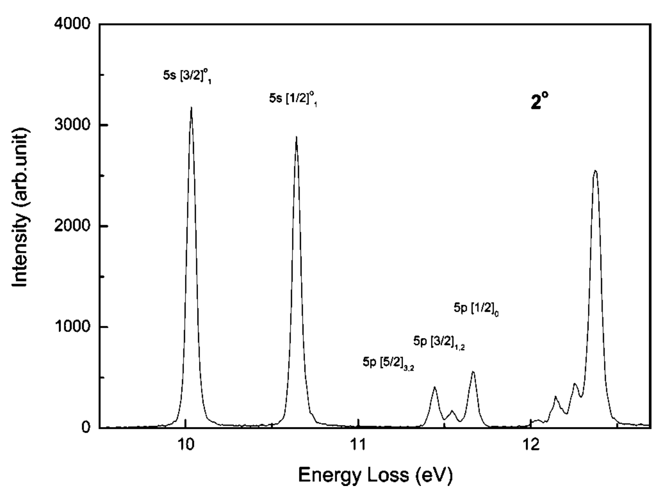

FIG. 1. A typical electron-energy-loss spectrum of krypton taken at the pressure of 2×10^{-3} Pa.

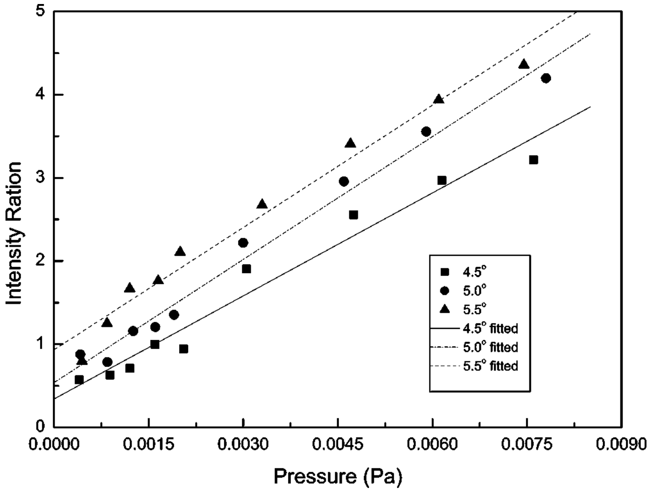

FIG. 2. Intensity ratios $I_p(\theta)/I_{ref}(\theta)$ as a function of pressure for 5s transition.

tion. In the present measurement, the inelastic excitation of $4p^5(P_{3/2})5p$ was used instead of the elastic excitation because of the saturation of the intensity for the elastic scattering even at large angles when the one-dimension position sensitive detector is used. In this experiment, we measured the electron-energy-loss spectra at different low pressures for every measured angle. The values of $[I_p(\theta)/I_{ref}(\theta)]_{P=0}$ were obtained by using the least-squares fit to the data points $I_p(\theta)/I_{ref}(\theta)$ after the correction of instability of the beam current. Some results for double-scattering correction of 5s transition are shown in Fig. 2, the lines are the least-square fits of the data points. It is obvious that the pressure effect is very strong for this transition, it is also the same case for the 5s' transition. At the angle of 5.0°, the ratio of $I_p(\theta)/I_{ref}(\theta)$ at the pressure of 8×10^{-3} Pa is about eight times as large as the extrapolated value of $[I_p(\theta)/I_{ref}(\theta)]_{P=0}$. So, the pressure effect should be corrected very carefully.

In the present experiment, a gas cell was used and the reaction region is not a "point" but a "line." At large scattering angles, the scattering length seen by the analyzer is proportional to 1/sin(θ). However, at small scattering angles, the scattering length is not proportional to 1/sin(θ) for the fixed length of the gas cell [22]. In addition, the different experimental condition, such as the different incident energy or electronic optics, will affect the angular factor $A(\theta)$. So, the angular factor $A(\theta)$ must be remeasured before a new experiment. Briefly, it was obtained by dividing the DCS values of $1^{1S}\rightarrow2^{1P}$ transition for helium from Kim and Inokuti [24] by the measured counts for this transition at different angles with the results normalized at 7°. In addition, the angular resolution has a great influence on the measurement of DCSs at small angles. Using the method described in Ref. [25], the angular resolution of 1.2° was determined and the influence of angular resolution was corrected for GOSs measurements of small angles less than 2°.

III. RESULTS AND DISCUSSION

In this section, the GOSs of 5s, 5s' are reported first and compared with the available experimental and theoretical results, then the apparent GOSs of the 5p $[5/2]_{3,2}$, 5p $[3/2]_{1,2}$, and 5p $[1/2]_0$ dipole-forbidden transitions are reported.

After the electron-energy-loss spectrum was obtained, each peak area for the 5p $[5/2]_{3,2}$, 5p $[3/2]_{1,2}$, and 5p $[1/2]_0$ dipole-forbidden transitions at every angle was determined by the least-squares-fitting program. During the fitting procedure, we assumed that all of them have the same peak profile and their energy positions taken from the spectroscopic data given by Moore [26] were locked. After correcting the instability of beam current, the effects of double scattering, the angular factors $A(\theta)$, and the angular resolution at small angle, the relative DCSs and relative GOSs for the 5s, 5s', 5p $[5/2]_{3,2}$, 5p $[3/2]_{1,2}$, and 5p $[1/2]_0$ excitations were determined. According to the Lassettre limit theorem, the GOS converges to the optical oscillator strength (OOS) as $K^2\rightarrow0$. The relative GOS of 5s excitation was extrapolated using the following formula [27]:

$$f(E_0,K)=\frac{1}{(1+x)^6}\left[f_0+\sum_{n=1}^{m}f_k\left(\frac{x}{1+x}\right)^n\right]. \qquad (3)$$

Here $x=K^2/\alpha^2$, $\alpha=(2I)^{1/2}+[2(I-E)]^{1/2}$, and E and I are the excitation energy and the ionization threshold, respectively. Here, f_0 is the OOS and f_k are the fitted constants. By this procedure, the relative GOS of 5s excitation was normalized to the OOS of 0.214 determined by Dipole (e, e) method [28]. Then, the GOSs for other transitions were determined with reference to 5s transition.

The overall errors in this work came from the statistics of counts, δ_s, angular determination and angular factor δ_a, angular resolution determination for small angle δ_r, pressure correction δ_p, and the normalizing procedure δ_n as well as the error resulting from the deconvolution procedure δ_d. In this work, the maximum of each error is $\delta_s=2.5\%$ for the weakest transition, $\delta_a=4\%$, $\delta_r=6\%$, $\delta_p=2\%$, $\delta_n=10\%$, $\delta_d=3\%$. The total maximum errors are 13%.

The absolute GOSs and DCSs of 5s and 5s' transitions are listed in Table II and illustrated in Fig. 3 along with the experimental ones of Takayanagi *et al.* [13] at an incident electron energy of 500 eV. It can be seen that the GOSs for both of 5s and 5s' transitions in this work show a minimum and a maximum which are absent in the work of Takayanagi *et al.* because of their limited momentum transfer. The reason that present results are higher than that of Takayanagi *et al.* in the region of $K^2<0.7$ a.u. may be attributed to the normalizing procedures and the pressure effect. The present GOS was normalized to OOS of 5s transition (0.214), which is consistent with other results [28], while the extrapolated OOS for 5s transition of Takayanagi *et al.* is much lower (0.143 ± 0.015). For the trends of the GOSs of 5s and 5s' transitions, the results of Takayanagi *et al.* drop more slowly than the present results as K^2 increase, which may be caused by the pressure effect. So, the trends of GOSs will lead to a low OOSs for 5s and 5s' transitions when using the extrapolated formula (3).

For comparison, the GOSs for the sum of the 5s and 5s' excitation are shown in Fig. 4 along with previous experi-

TABLE II. The GOSs and DCSs for $5s$, $5s'$, $5p\ [5/2]_{3,2}$, $5p\ [3/2]_{1,2}$, and $5p\ [1/2]_0$ transitions of krypton. Square brackets denote the power of ten.

	GOS					DCS ($a_0^2 sr^{-1}$)				
K^2 (a.u.)	$5s$	$5s'$	$5p\ [5/2]_{3,2}$	$5p\ [3/2]_{1,2}$	$5p\ [1/2]_0$	$5s$	$5s'$	$5p\ [5/2]_{3,2}$	$5p\ [3/2]_{1,2}$	$5p\ [1/2]_0$
0.07			6.02[−3]	2.78[−3]	9.13[−3]			4.07[−1]	1.87[−1]	6.06[−1]
0.14			9.71[−3]	3.76[−3]	1.41[−2]			3.29[−1]	1.26[−1]	4.70[−1]
0.24	8.10[−2]	7.68[−2]	8.49[−3]	3.30[−3]	1.30[−2]	1.85	1.65	1.69[−1]	6.53[−2]	2.55[−1]
0.36	3.69[−2]	3.47[−2]	7.26[−3]	2.63[−3]	1.13[−2]	5.49[−1]	4.88[−1]	9.48[−2]	3.41[−2]	1.45[−1]
0.52	1.63[−2]	1.57[−2]	4.82[−3]	1.71[−3]	7.84[−3]	1.71[−1]	1.55[−1]	4.42[−2]	1.55[−2]	7.06[−2]
0.70	7.01[−3]	6.56[−3]	3.11[−3]	1.09[−3]	6.33[−3]	5.43[−2]	4.79[−2]	2.11[−2]	7.35[−3]	4.22[−2]
0.91	2.30[−3]	2.32[−3]	1.72[−3]	5.82[−4]	3.80[−3]	1.37[−2]	1.30[−2]	9.00[−3]	3.02[−3]	1.95[−2]
1.15	8.38[−4]	8.14[−4]	5.72[−4]	2.19[−4]	2.05[−3]	3.96[−3]	3.63[−3]	2.37[−3]	8.99[−4]	8.33[−3]
1.41	9.95[−4]	9.73[−4]	2.64[−4]	6.22[−5]	1.81[−3]	3.82[−3]	3.52[−3]	8.88[−4]	2.08[−4]	5.99[−3]
1.70	1.37[−3]	1.30[−3]	2.14[−4]	1.00[−4]	1.38[−3]	4.35[−3]	3.89[−3]	5.96[−4]	2.76[−4]	3.78[−3]
2.02	2.10[−3]	1.98[−3]	4.13[−4]	2.20[−4]	1.67[−3]	5.61[−3]	5.00[−3]	9.68[−4]	5.12[−4]	3.84[−3]
2.37	2.26[−3]	2.22[−3]	6.34[−4]	2.41[−4]	1.72[−3]	5.14[−3]	4.77[−3]	1.27[−3]	4.78[−4]	3.38[−3]
2.75	2.24[−3]	2.42[−3]	8.23[−4]	3.24[−4]	2.13[−3]	4.42[−3]	4.48[−3]	1.42[−3]	5.55[−4]	3.61[−3]
3.15	2.73[−3]	2.37[−3]	9.24[−4]	3.75[−4]	2.46[−3]	4.68[−3]	3.83[−3]	1.39[−3]	5.60[−4]	3.63[−3]
3.59	2.33[−3]	2.05[−3]	9.87[−4]	3.85[−4]	2.49[−3]	3.51[−3]	2.92[−3]	1.31[−3]	5.05[−4]	3.24[−3]
4.04	1.79[−3]	1.63[−3]	8.44[−4]	3.10[−4]	2.37[−3]	2.39[−3]	2.05[−3]	9.89[−4]	3.60[−4]	2.73[−3]

mental and theoretical works [11,13,19]. The experimental result of Wong *et al.* is digitized from Ref. [11] and the theoretical one of Chen and Msezane is digitized from Ref. [19]. The result of Wong *et al.* is normalized to the present data at $K^2 = 0.36$ a.u. For $K^2 < 0.7$ a.u. region, the present results are slightly higher than the experimental ones of Takayanagi *et al.* and the reasons are discussed above. For the region of $K^2 > 0.7$ a.u., the result of Wong *et al.* is much higher than the present one, the difference cannot be explained by the influence of the angular resolution. In Fig. 2, it has been shown that the pressure effect is very strong for $4p^5 5s$ transition, which would affect the extrapolated intensity if the experiments were done in high gas pressures. The difference between the present result and that of Wong *et al.* may also be attributed to pressure effect as pointed out by Wong *et al.* themselves [11].

It is well known that the angular resolution has a great influence on the measured DCSs near zero degree, but the influence of large scattering angles was very small [25,29]. This consideration is reasonable for the transitions whose DCSs are monotonically decreasing as the scattering angle increases. But for the transitions whose DCSs have extrema at nonzero angles such as $5s$, and $5s'$ excitations of krypton, the instrumental angular resolution would have a large influence on the measured DCSs near the extrema positions. In order to demonstrate the influence of the angular resolution on the measured GOSs of $5s$ and $5s'$ transitions, the theoretical result of Chen and Msezane [19] is convoluted with an angular response function $A(u)$ as a Gauss function, $A(u) = 1/\sqrt{(2\pi)}\exp[-u^2/(2\alpha^2)]$, where $\alpha = \Delta\theta/\sqrt{8\ln 2}$ and $\Delta\theta$ is the present instrumental angular resolution 1.2° (FWHM). The dashed line in Fig. 4 is the convoluted result

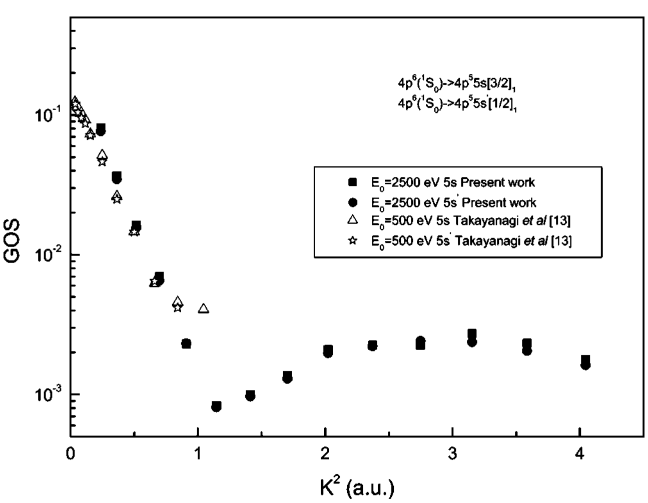

FIG. 3. Absolute GOSs of $5s$ and $5s'$ excitations.

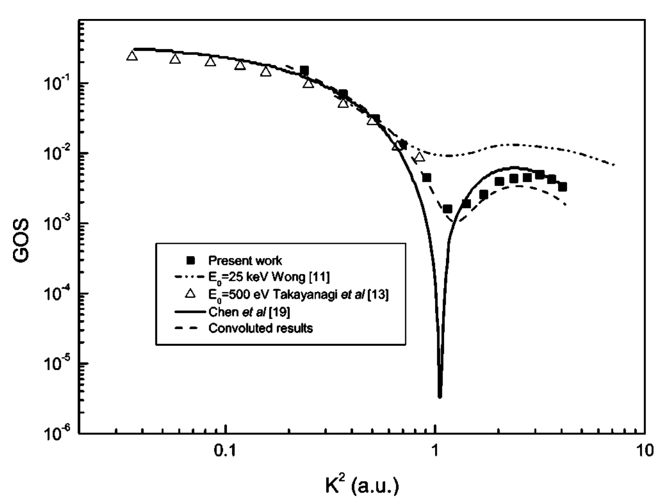

FIG. 4. Absolute GOSs of $5s+5s'$ excitations.

TABLE III. The positions of the minimum and maximum for GOSs of $4p^6 \rightarrow 4p^5(5s+5s')$ transitions of krypton.

	Experimental			Theoretical			
K^2 (a.u.)	Present	Ref. [2]	Ref. [11]	Ref. [2]	Ref. [16]	Ref. [19]	Ref. [19] Convoluted results
Minimum	1.24	0.90	1.04	1.21	0.69	1.053	1.25
Maximum	2.97		2.50		1.35	2.40	2.50

of Chen and Msezane and normalized to the present data at $K^2=0.36$ a.u. It could be clearly seen that the angular resolution has great influence on the profiles of the GOSs especially for K^2 region near the extrema positions. The present results are in good agreement with the convoluted one except at the larger K^2 region in which the present ones are slightly higher. It has been shown that not only the position but also the amplitude of the minimum was influenced by the angular resolution.

The positions of minimum and maximum of GOS for $4p^6 \rightarrow 4p^5(5s+5s')$ transitions of krypton are listed in Table III. It is obvious that the positions of the minimum and maximum for present results are larger than the experimental ones of Wong *et al.* [11] and the theoretical ones of Chen and Msezane [19]. From above, it has been shown that the extrema positions will be changed to higher K^2 if the angular resolution is considered. Furthermore, the GOS of Wong *et al.* is larger than ours at the large K^2 which would also cause the shift of the minimum position to smaller K^2. So, there may be some problems for the experimental result of Wong *et al.* and perhaps the difference for the positions of the minimum and maximum between our results and Wong *et al.* can be attributed to the pressure effect. As for the inconsistency of the maximum position between ours and that of Chen and Msezane, the reason is not clear. More accurate experimental and theoretical researches are expected.

In Table II and Figs. 5–7, the GOSs and DCSs for the dipole-forbidden transitions of $5p\ [5/2]_{3,2}$, $5p\ [3/2]_{1,2}$, and $5p\ [1/2]_0$ are shown. The lines in Figs. 5–7 are the present fitting results using the polynomials with the following form [30]:

$$f(E_0,K)=\frac{x^2}{(1+x^2)^2}\sum_{n=0}^{m} c_n\left[\frac{x}{(1+x^2)^{1/2}}\right]^n. \tag{4}$$

Here, c_n are the coefficients and x is the same as that in formula (3). Similar to the profile of the GOS for $4p+4p'$ excitation of Ar [31], $2p_1$ excitation of Ne [32], the GOSs for $5p\ [5/2]_{3,2}$, $5p\ [3/2]_{1,2}$ and $5p\ [1/2]_0$ excitations of krypton also have two maxima and one minimum in the present K^2 region. The positions of these extrema are listed in Table I together with those of Suzuki measured at the incident energy of 500 eV [14].

The inset graphs in Figs. 5–7 show the present results and the ones of Suzuki at the small K^2 in detail. It can be seen that all of the profiles of the apparent GOSs of $5p\ [5/2]_{3,2}$, $5p\ [3/2]_{1,2}$, and $5p\ [1/2]_0$ transitions depend on the impact energy. The amplitudes of the present GOSs for these transitions are inconsistent with those of Suzuki [14], but there are same behaviors with the impact energy increase; that is, the apparent GOSs for $5p\ [5/2]_{3,2}$ and $5p\ [3/2]_{1,2}$ excitations decrease as the impact energy increases, but for $5p\ [1/2]_0$ transition it is reverse. For the transitions of 2^1S and 3^1S in He [33] and $2p_1$ in Ne [32], it has the same behavior as the GOS of $5p\ [1/2]_0$ transition. Because all the states of 2^1S in He, $2p_1$ in Ne [32], and $5p\ [1/2]_0$ in Kr [10,34] have the $^1S_0$ component in the LS coupling notation, the behavior of these GOSs as impact energy increases may be explained by the $^1S_0$ to $^1S_0$ transition character [14]. As the pressure effect has little influence on the measured apparent GOSs for the $5p\ [5/2]_{3,2}$, $5p\ [3/2]_{1,2}$, and $5p\ [1/2]_0$ transitions at

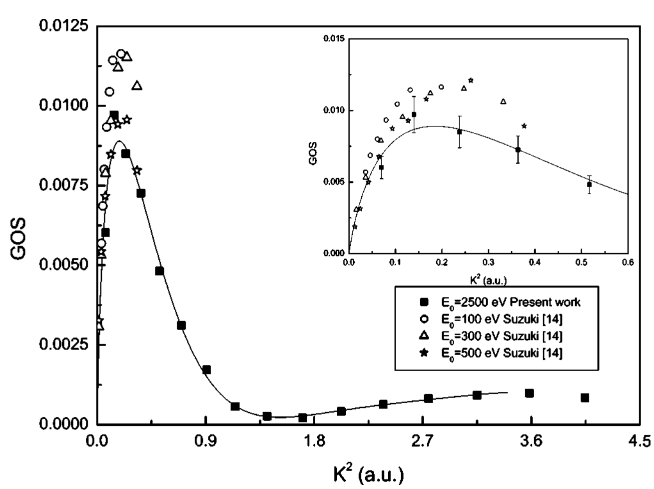

FIG. 5. Apparent GOSs of $5p\ [5/2]_{3,2}$ excitation.

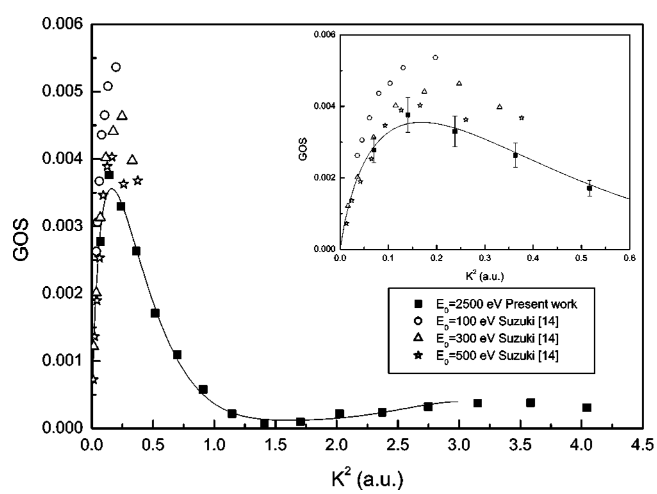

FIG. 6. Apparent GOSs of $5p\ [3/2]_{1,2}$ excitation.

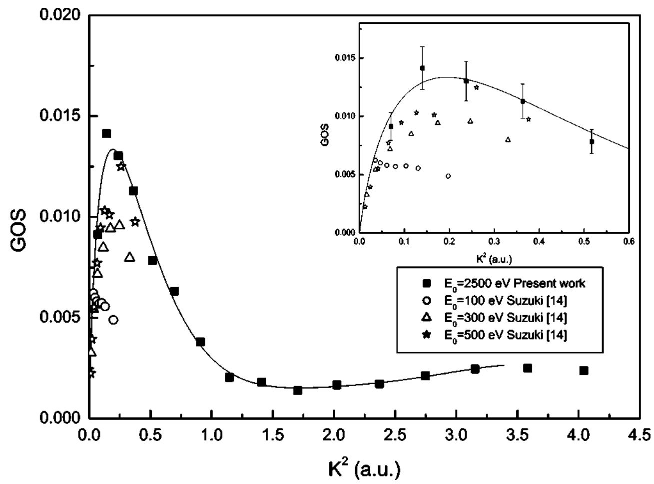

FIG. 7. Apparent GOSs of $5p$ $[1/2]_0$ excitation.

small K^2, the present results for these dipole-forbidden transitions have the same behavior as that of Suzuki [14] in spite of the large difference between ours and Takayanagi *et al.* [13] for the extrapolated OOS of $5s$ transition measured using the same apparatus.

IV. CONCLUSION

Absolute generalized oscillator strengths for $5s$ and $5s'$ excitations have been obtained for large K^2 region from 0.24 to 4.04 a.u., which are listed in Table II, and their minimum and maximum are clearly illustrated in Fig. 3 and Table III. In Sec. II, it is demonstrated the pressure effect has great influence on the measurements of DCSs and GOSs for $5s$ and $5s'$ transitions of krypton. So the pressure effect should be carefully considered especially for atoms and molecules, which have large cross sections. In addition, the instrumental angular resolution has great influence on the position and amplitude of extrema of DCSs and GOSs. After considering the pressure effect and the instrumental angular resolution, the present results for the GOSs of the sum of $5s$ and $5s'$ transitions are in good agreement with the convoluted theoretical ones of Chen and Msezane [19]. But for the large K^2 region, both the GOSs and the maximum position are larger than the convoluted ones, which indicates that more accurate theoretical calculations and experimental measurements are needed.

The extrema positions and the apparent generalized oscillator strengths for $5p$ $[5/2]_{3,2}$, $5p$ $[3/2]_{1,2}$, and $5p$ $[1/2]_0$ transitions are listed in Tables I and II, respectively. The amplitudes of the present GOSs for these transitions are inconsistent with those of Suzuki [14], but there are same behaviors with the impact energy increase. Unfortunately, there are no theoretical results for these forbidden transitions, and further experimental measurements and theoretical calculations are recommended.

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[1] C.C. Turci, J.T. Francis, T. Tyliszczak, G.G. de Souza, and A.P. Hitchcock, Phys. Rev. A **52**, 4678 (1995).
[2] Y.K. Kim, M. Inokuti, G.E. Chamberlain, and S.R. Mielczarek, Phys. Rev. Lett. **21**, 1146 (1968).
[3] H. Bethe, Ann. Phys. (Leipzig) **5**, 325 (1930); Z. Phys. **76**, 293 (1930).
[4] M. Inokuti, Rev. Mod. Phys. **43**, 297 (1971).
[5] B.R. Lewis, E. Weigold, and P.J.O. Teubner, J. Phys. B **8**, 212 (1975).
[6] S. Trajmar, S.K. Srivastava, H. Tanaka, H. Nishimura, and D.C. Cartwright, Phys. Rev. A **23**, 2167 (1981).
[7] D. Filipovic, B. Marinkovic, V. Pejcev, and L. Vuskovic, Fizika (Zagreb) **20**, 421 (1988).
[8] A. Danjo, J. Phys. B **22**, 951 (1989).
[9] M.A. Khakoo, C.E. Beckmann, S. Trajmar, and G. Csanak, J. Phys. B **27**, 3159 (1994).
[10] X.Z. Guo, D.F. Mathews, G. Mikaelian, M.A. Khakoo, A. Crowe, I. Kanik, S. Trajmar, V. Zeman, K. Bartschat, and C.J. Fontes, J. Phys. B **33**, 1895 (2000); **33**, 1921 (2000).
[11] T.C. Wong, J.S. Lee, and R.A. Bonham, Phys. Rev. A **11**, 1963 (1975).
[12] A. Delâge and J.-D. Carette, J. Phys. B **9**, 2399 (1976).
[13] T. Takayanagi, G.P. Li, K. Wakiya, H. Suzuki, T. Ajiro, T. Inaba, S.S. Kano, and H. Takuma, Phys. Rev. A **41**, 5948 (1990).
[14] T. Y. Suzuki, Ph.D. thesis, University of Electro-Communications, Tokyo, 2000 (unpublished).
[15] P.S. Ganas and A.E.S. Green, Phys. Rev. A **4**, 182 (1971).
[16] K.J. Miller, J. Assoc. Comput. Mach. **59**, 5639 (1973).
[17] R. Padma and P.C. Deshmukh, Phys. Rev. A **46**, 2513 (1992).
[18] Q.C. Shi, S.M. Zhang, H. Cho, K.Z. Xu, J.M. Li, and S. Kais, J. Phys. B **31**, 4123 (1998).
[19] Z.F. Chen and A.Z. Msezane, J. Phys. B **33**, 5397 (2000).
[20] M.Y. Amusia, L.V. Chernysheva, Z. Felfli, and A.Z. Msezane, Phys. Rev. A **64**, 032711 (2001).
[21] S.L. Wu, Z.P. Zhong, R.F. Feng, S.L. Xing, B.X. Yang, and K.Z. Xu, Phys. Rev. A **51**, 4494 (1995).
[22] K.Z. Xu, R.F. Feng, S.L. Wu, Q. Ji, X.J. Zhang, Z.P. Zhong, and Y. Zheng, Phys. Rev. A **53**, 3081 (1996).
[23] X.J. Liu, L.F. Zhu, X.M. Jiang, Z.S. Yuan, B. Cai, X.J. Chen, and K.Z. Xu, Rev. Sci. Instrum. **72**, 3357 (2001).
[24] Y.K. Kim and M. Inokuti, Phys. Rev. **175**, 176 (1968).
[25] L.F. Zhu, Z.P. Zhong, X.J. Liu, R.F. Feng, X.J. Zhang, and K.Z. Xu, J. Phys. B **32**, 4897 (1999).
[26] C.E. Moore, *Atomic Energy Levels* (U.S. GPO, Washington, DC, 1971), Vol. 2.
[27] E.N. Lassettre, J. Chem. Phys. **43**, 4479 (1965); K.N. Klump and E.N. Lassettre, *ibid.* **68**, 886 (1978).
[28] Z.S. Yuan, L.F. Zhu, X.J. Liu, Z.P. Zhong, W.B. Li, H.D.

Cheng, and K.Z. Xu, Phys. Rev. A **66**, 062701 (2002), and references therein.

[29] G.P. Li, T. Takayanagi, K. Wakiya, H. Suzuki, T. Ajiro, S. Yagi, S.S. Kano, and H. Takuma, Phys. Rev. A **38**, 1240 (1988).

[30] M.A. Dillon and E.N. Lassettre, J. Chem. Phys. **62**, 2373 (1975).

[31] Q. Ji, S.L. Wu, R.F. Feng, X.J. Zhang, L.F. Zhu, Z.P. Zhong, K.Z. Xu, and Y. Zheng, Phys. Rev. A **54**, 2786 (1996).

[32] T.Y. Suzuki, H. Suzuki, S. Ohtani, B.S. Min, T. Takayanagi, and K. Wakiya, Phys. Rev. A **49**, 4578 (1994).

[33] Z.P. Zhong, R.F. Feng, S.L. Wu, L.F. Zhu, X.J. Zhang and K.Z. Xu, J. Phys. B **30**, 5305 (1997); Z.P. Zhong, Ph.D. thesis, University of Science of Technology of China, Hefei, 1997 (unpublished).

[34] A. Dasgupta, K. Bartschat, D. Vaid, A.N. Grum-Grzhimailo, D.H. Madison, M. Blaha, and J.L. Giuliani, Phys. Rev. A **64**, 052710 (2001).