Electron excitation of the resonance lines of the alkali-metal atoms

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We have measured the relative optical-excitation functions and polarizations of the K, Rb, and Cs resonance lines, using crossed electron and atom beams, for electron energies from threshold to 1500 eV. The electron energy resolution was ~0.25 eV for energies below 13 eV, and the atom beam was optically thin. The atomic resonance-level (n^2P) excitation functions have been normalized to the Born theory in the high-energy limit. Comparisons are made with other measurements and calculations. The polarizations and total cross sections for H, Li, Na, K, Rb, and Cs are also compared with each other in reduced units to investigate systematic behavior

I. INTRODUCTION

The alkali-metal atoms are primarily one-electron hydrogenlike elements that can provide valuable tests of electron collision theory. Interestingly, despite this relative simplicity of electronic structure, various calculations of the electron excitation cross sections for the $ns - np$ resonance transition have differed considerably. These resonance-line excitations play a role in a variety of plasmas, such as stellar atmospheres and alkali vapor lamps. The present measurements are intended to provide reliable numbers for use in modeling such plasmas and in testing electron collision theories. Intercomparisons between the alkalis are also presented to stimulate quests for simpler, more universal but accurate theories.

Electron-impact excitation cross sections and polarizations for the resonance transitions of alkaline-earth elements have been previously studied and intercompared.[1] The resonance-line excitation cross sections and polarizations for Na and Li have been also reported in previous papers[2,3] from this laboratory. In this paper we present measured optical excitation cross sections and polarizations for the atomic resonance transitions of K, Rb, and Cs. As these are the last of this series of measurements for alkali elements, we summarize and compare results here.

Previous measurements of these excitation cross sections for K, Rb, Cs have been reported.[4-11] These measurements frequently disagree on the magnitude and energy dependence of cross sections, and generally give results for a limited energy range, usually below 30 eV. Several theoretical calculations[12-25] of these resonance-level excitation cross sections have been performed using Born theory and its extensions, correlation model, unitarized distorted wave polarized orbital model, classical impulse, VPS, Glauber, and close-coupling calculations. None of these papers reported the polarization functions.

We have measured the optical excitation functions and polarizations of the K, Rb, and Cs resonance lines for electron-impact energies from the thresholds to 1500 eV. We used crossed, low-density beams of electrons and atoms, thereby minimizing space-charge and optical-depth problems. Furthermore, by going to sufficiently high energy we are able to accurately normalize our measured relative excitation functions to the Born theory to obtain the normalized excitation cross sections.

II. MEASUREMENTS AND CORRECTIONS

The apparatus used in this experiment has been described in detail in Refs. 2 and 3. Briefly, a beam of atoms from an oven intersects an electron beam at right angles and the resonance radiation, in a cone along the third orthogonal axis, is detected. The electron current is kept well below space-charge limited conditions and the atom beam is optically thin (estimated as typically 10^{10} cm^{-3} density in the interaction region). The $f/2.5$ detection optics uses a lens to make the rays parallel as the light passes through a linear polarization analyzer and an interference filter (typical half bandwidth ~50 Å) for the spectral line under study. A second lens focuses the light onto slits which are used to define the part of the interaction region observed. In the present measurements the slits are imaged onto a gallium-arsenide photocathode of a dry-ice-cooled photomultiplier.

The phototube is constructed with the internal surface of the photocathode inclined at ~45° to the incident radiation direction; we have observed that it has about 10% sensitivity to the polarization of the incident radiation. Consequently a quarter-wave plate is attached behind the rotating linear polarizer to circularly polarize (within 10% for the

K resonance line, and almost completely for Rb and Cs resonance lines) light transmitted by the linear polarization analyzer, thereby largely eliminating the dependence of the photomultiplier sensitivity on initial radiation polarization. The instrumental polarization of the final optics system was measured to be about -1.0% for the K resonance line, and was negligible for Rb and Cs resonance lines. The correction due to the imperfect polarization analyzer ($k_\perp/k_\parallel \neq 0$) was found to be negligible for K and Rb resonance lines, but was as much as 48% of the measured polarization for the longer-wavelength Cs resonance line. Other small corrections, such as for finite electron beam and optical solid angles and for radiation entrapment have been described in detail in previous papers.[1-3] They have been evaluated, and taken into account here, when significant.

Using a retarding-potential analyzer, we have measured the electron-beam energy distribution: the energy spread was about 0.25 eV full width at half maximum for energies below 13 eV and increased slightly at higher energies. We have adjusted the energy scales by reference to the excitation thresholds, an adjustment of less than 0.1 eV relative to the energy obtained with the retarding-potential analyzer.

III. NORMALIZATION

We have measured separately the relative excitation functions of the resonance doublets $n^2P_{1/2}$ and $n^2P_{3/2}$ for K and Rb with $n=4$ and 5 respectively, but only the $6^2P_{3/2}$ component for Cs since the photomultiplier response is much lower at the $P_{1/2}$ component wavelength. In order to obtain the total n^2P excitation cross sections for K and Rb we have first summed the $n^2P_{1/2}$ and $n^2P_{3/2}$ relative excitation functions to obtain a total n^2P relative excitation function. The latter is then normalized to the Born cross section (plus cascades) at high energy to obtain the total n^2P cross sections. Since the $n^2P_{1/2}$, $n^2P_{3/2}$, and n^2P relative excitation functions have the same shape, the same n^2P cross section would be obtained if any of these were normalized to the Born total n^2P cross section. We have combined the $n^2P_{1/2}$ and $n^2P_{3/2}$ relative excitations first only to decrease the statistical uncertainties. Since only the $6^2P_{3/2}$ relative excitation function was measured for Cs, this has been normalized to the Born-total 6^2P cross section to obtain the total 6^2P cross section. The theories calculate excitation to n^2P without consideration of the fine structure, so this normalization procedure includes an implicit assumption of a statistical $P_{3/2}:P_{1/2}$ intensity ratio of 2:1. For the K and Rb cases we have measured a $P_{3/2}:P_{1/2}$ intensity ratio of 2.00 ± 0.03, so it appears highly likely that the same ratio holds for Cs.

To obtain the absolute excitation cross sections for the atomic resonance levels, we normalize the measured resonance-line relative excitation functions at high energy to the Born direct-excitation cross sections plus cascade contributions, all obtained from Ref. 12. Figure 1 illustrates the normalization method. The high-energy behavior of the total cross section Q_T, for a dipole-allowed transition can be expressed as[26]

$$Q_T E(\pi a_0^2\ \mathrm{Ry}) = 4(f_n/\Delta_n)\ln(4C_nE) + O(\Delta_n/E)\ , \quad (1)$$

where Q_T is in units of πa_0^2, E is the impact energy in rydbergs, and Δ_n and f_n are, respectively, the excitation energy in rydbergs and the optical oscillator strength from the ground state to the upper level in this dipole-allowed transition. The constant C_n can be evaluated from the Born or Bethe

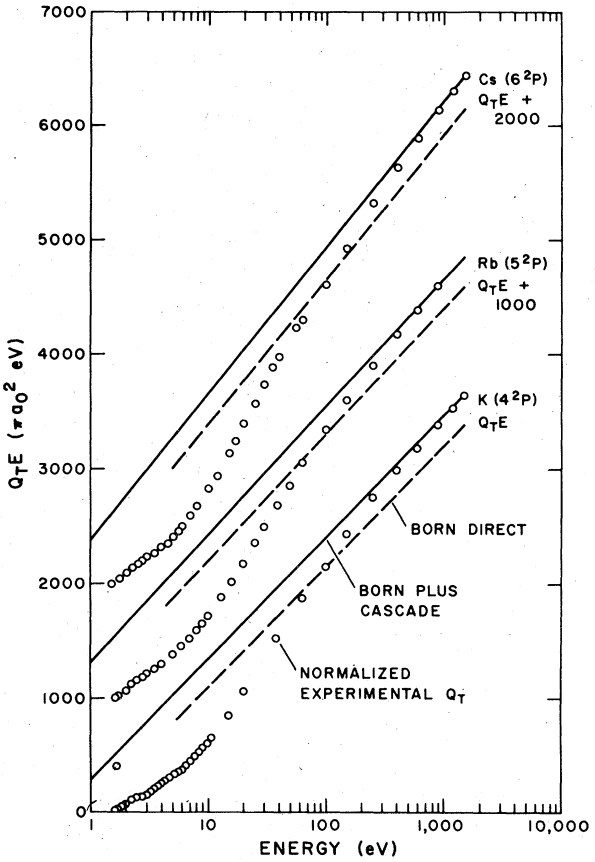

FIG. 1. Method of normalizing the relative cross section for the K, Rb, and Cs resonance levels. The Born-approximation calculations by Vainshtein *et al.* (Ref. 12) have been used for the resonance levels and for the cascade contributions (see Sec. III). The present total cross section Q_T (dots) is normalized to the sum of the Born direct- and cascade-excitation cross sections.

approximation, and $O(\Delta_n/E)$ represents higher-order terms that are neglected in high-energy limits.

The Born cross sections calculated by Vainshtein *et al.*[12] for K, Rb, and Cs resonance level excitation (to both $^2P_{1/2}$ and $^2P_{3/2}$ levels) approach at high energy,

$$Q_B E(\pi a_0^3\ \text{Ry}) = 4\frac{1.138}{0.119}\ln(4\times 3.906E) \quad \text{for K}(4^2P)\ ,$$

$$Q_B E(\pi a_0^2\ \text{Ry}) = 4\frac{1.127}{0.116}\ln(4\times 4.167E) \quad \text{for Rb}(5^2P)\ , \tag{2}$$

$$Q_B E(\pi a_0^2\ \text{Ry}) = 4\frac{1.175}{0.104}\ln(4\times 4.31E) \quad \text{for Cs}(6^2P)\ ,$$

corresponding to $f_n = 1.138$, 1.127, and 1.175 for K(4^2P), Rb(5^2P), and Cs(6^2P), respectively. These f_n are not in agreement with experiment, so we will use selected, averaged experimental values[27] of 1.00, 1.02, and 1.05 for these transitions, respectively. We replace the theoretical f_n in Eq. (2) by the experimental values; thus we are using the Born cross sections of Ref. 12 to obtain only constants C_n in Eq. (1). The Born cross sections for the resonance-level direct excitation are then

$$Q_B E(\pi a_0^2\ \text{eV}) = 49.24 + 1053\log_{10}E \quad \text{for K}(4^2P)\ ,$$

$$Q_B E(\pi a_0^2\ \text{eV}) = 97.16 + 1102\log_{10}E \quad \text{for Rb}(5^2P)\ , \tag{3}$$

$$Q_B E(\pi a_0^2\ \text{eV}) = 130.15 + 1266\log_{10}E \quad \text{for Cs}(6^2P)\ ,$$

with the electron-impact energy E in units of eV. In Eq. (3), the constant term and the energy-dependent term are separated, which is more convenient when we have to add the cascade contributions to the direct level-excitation cross section.

We use the Born cross sections from Ref. 12 for higher levels and theoretical transition probabilities[28] to estimate the cascade contributions to the resonance-level cross sections. We include the n^2S ($n=5,6$), n^2P ($n=5,6$), and n^2D ($n=3,4$) levels in cascade estimates for the K resonance level, and the corresponding $n+1$ and $n+2$ levels for Rb and Cs, respectively. The result is about 7% cascade into the resonance levels of K, Rb, and Cs at 1500 eV. We thus obtain total theoretical excitation cross sections for these resonance levels, including cascade contributions from the levels mentioned above:

$$Q_T E(\pi a_0^2\ \text{eV}) = 275 + 1060\log_{10}E \quad \text{for K}(4^2P)\ ,$$

$$Q_T E(\pi a_0^2\ \text{eV}) = 319 + 1115\log_{10}E \quad \text{for Rb}(5^2P)\ , \tag{4}$$

$$Q_T E(\pi a_0^2\ \text{eV}) = 381 + 1280\log_{10}E \quad \text{for Cs}(6^2P)\ .$$

Our measured relative-resonance excitation functions are normalized to converge to the cross sections in Eq. (4) in the high-energy limits (Fig. 1); this is nearly identical to normalizing the excitation function at 1500 eV. We estimate that the uncertainty of the normalized cross section scales is about ±6% for all the resonance levels, due to ~5% uncertainty in the resonance-level optical oscillator strength, ~2% due to uncertainty in C_n, plus 3% due to uncertainty in cascade contributions.

IV. RESULTS

The present results are given in Tables I and II and in Figs. 2 and 3. All of the corrections mentioned in Sec. II have been taken into account. The

TABLE I. Normalized optical excitation cross sections of K, Rb, and Cs resonance lines.

Energy (eV)[a]	Q_T[b] (πa_0^2) K (4^2P)	Rb (5^2P)	Cs ($6^2P_{3/2}\times\frac{3}{2}$)
1.55(1)[c]			12.50(83)
1.60(1)			18.70(100)
1.65(1)	10.75(40)	9.99(80)	25.10(150)
1.70(1)	15.20(40)	13.70(100)	31.45(150)
1.80(1)	22.40(85)	23.35(150)	45.75(140)
2.00(1)	36.40(150)	44.55(150)	62.10(140)
2.25(1)	41.50(140)	60.69(150)	71.00(120)
2.50(1)	43.80(170)	65.16(160)	73.79(110)
2.75(1)	47.75(180)	68.01(140)	75.78(105)
3.00(1)	52.00(105)	70.32(140)	76.99(100)
3.50(1)	58.05(115)	73.19(150)	79.20(100)
4.00(1)	60.71(90)	74.98(120)	81.12(95)
6.00(2)	61.73(90)	75.69(100)	83.88(95)
10.00(3)	60.50(85)	72.26(85)	82.67(92)
15.00(4)	57.40(76)	64.98(85)	75.47(90)
20.00(6)	53.45(70)	59.27(77)	69.53(85)
30.00(8)	45.20(54)	49.91(59)	58.08(82)
40.0(1)	38.92(40)	43.08(44)	49.59(70)
50.0(1)	34.12(34)	37.75(37)	42.82(62)
63.3(2)	29.70(24)	32.41(27)	36.46(31)
99.0(2)	21.97(17)	23.71(19)	26.34(22)
149.3(2)	16.32(13)	17.40(14)	19.58(16)
250.9(2)	10.96(8)	11.55(9)	13.24(11)
400.9(3)	7.452(75)	7.898(80)	9.060(95)
602.1(3)	5.285(63)	5.635(67)	6.450(76)
902.3(6)	3.745(45)	3.995(48)	4.583(54)
1202.3(8)	2.950(35)	3.109(37)	3.582(42)
1500.4(10)	2.426(30)	2.566(32)	2.959(36)

[a] Besides the given uncertainties, an additive uncertainty of ±0.03 eV affects the entire energy scale; see Sec. V.

[b] Q_T is the corrected normalized optical excitation cross section for $^2P_{1/2}$ and $^2P_{3/2}$ components combined (cascade included). The uncertainty does not include ~±6% uncertainty in the normalization of the cross-section scale. For the Cs case $\frac{3}{2}$ of the $^2P_{3/2}$-state cross section is given since the difference in $^2P_{1/2}$ vs $^2P_{3/2}$ threshold energies is significant.

[c] Numbers in parentheses give the uncertainty in the last places of the preceding number. The uncertainties represent roughly 2σ including estimated systematic uncertainties.

TABLE II. Polarizations for the resonance radiation ($n^2P_{3/2} \rightarrow n^2S_{1/2}$) of K, Rb, and Cs.

Energy (eV)[a]	Polarization (%) K ($4^2P_{3/2} \rightarrow 4^2S_{1/2}$)	Rb ($5^2P_{3/2} \rightarrow 5^2S_{1/2}$)	Cs ($6^2P_{3/2} \rightarrow 6^2S_{1/2}$)
1.55(1)[b]			+10.85(215)
1.60(1)			+9.90(180)
1.65(1)	+16.55(140)	+12.15(55)	+9.83(175)
1.70(1)	+16.45(120)	+11.24(45)	+9.35(150)
1.80(1)	+16.2(100)	+10.85(35)	+8.25(135)
2.00(1)	+15.35(60)	+10.25(34)	+7.95(120)
2.25(1)	+14.55(55)	+9.90(32)	+7.50(110)
2.50(1)	+14.16(53)	+9.62(32)	+7.13(78)
2.75(1)	+13.55(50)	+8.90(30)	+7.38(70)
3.00(1)	+12.55(50)	+8.50(28)	+6.03(70)
3.50(1)	+10.26(45)	+7.00(20)	+5.10(55)
4.00(1)	+8.15(35)	+6.35(18)	+4.53(44)
6.00(2)	+4.76(26)	+3.70(15)	+2.93(25)
10.00(3)	+2.15(25)	+1.67(15)	+1.77(20)
15.00(4)	+0.50(25)	+0.40(20)	+0.42(28)
20.00(6)	−0.55(26)	−0.30(20)	−0.17(24)
30.00(8)	−1.80(25)	−1.07(22)	−0.75(24)
40.0(1)	−2.50(25)	−1.74(18)	−0.90(26)
50.0(1)	−3.20(24)	−2.25(16)	−1.15(23)
63.3(2)	−3.75(20)	−2.62(10)	−1.43(18)
99.0(2)	−4.65(15)	−3.27(10)	−1.93(13)
149.3(2)	−5.51(15)	−3.86(10)	−2.41(13)
250.9(2)	−6.45(12)	−4.10(10)	−3.02(14)
400.9(3)	−7.00(14)	−4.64(9)	−3.25(15)
602.1(3)	−7.53(15)	−4.99(10)	−3.58(15)
902.3(6)	−7.96(20)	−5.14(11)	−3.78(16)
1202.3(8)	−8.18(16)	−5.47(11)	−3.94(17)
1500.4(10)	−8.42(17)	−5.64(12)	−4.18(19)

[a] Besides the given uncertainties, an additive uncertainty of ±0.03 eV affects the entire energy scale; see Sec. V.

[b] Numbers in parentheses give the uncertainty in the last places of the preceding number. The uncertainties represent roughly 2σ including estimated systematic uncertainties.

uncertainties in the cross sections quoted in Table I include uncertainty in the crossed beams' overlap at low energy and the observed statistical uncertainty, but not the normalization uncertainty. The uncertainties in the polarization values quoted in Table II are mainly from the counting statistics, combined with uncertainty in the instrumental polarization and in the imperfect polarization analyzer correction. The uncertainty quoted in the energy scale does not include the additional ±0.03 eV uncertainty in identifying the position of threshold, which will be discussed in the next section.

The data were obtained at energy intervals of less than 0.1 eV below 15 eV, at ~0.25 eV between 15 and 60 eV, and at nine energy values between 63 and 1500 eV. Tables I and II contain all the data above 63 eV, and representative, averaged values, below that. Figure 2(a) shows the normalized optical excitation cross sections for the n^2P resonance levels of K, Rb, and Cs, for the energies from threshold to 1500 eV. Figure 2(b) shows the polarizations for the corresponding $n^2P_{3/2} \rightarrow n^2S_{1/2}$ resonance transitions. The detailed low-energy data below 4 eV can be seen in Fig. 3. To produce our results for the excitation cross sections shown in Fig. 3(a), we averaged the low-energy cross section data in groups, and plotted a smooth curve with error bars that encompass about 80% of these averaged points. Figure 3(b) shows the original polarization data for $n^2P_{3/2} \rightarrow n^2S_{1/2}$ resonance transitions.

V. DISCUSSION

The behavior of the excitation cross sections and polarizations near the excitation thresholds were obscured by the energy spread of the electron beam as shown in Fig. 3(a). To find the threshold energy we have assumed that the cross section has either the form $Q_T \propto (E - E_{th})^{1/2}$ or $Q_T \propto (E - E_{th})$ in the first 0.25 eV above threshold and then connects smoothly to the measured apparent cross

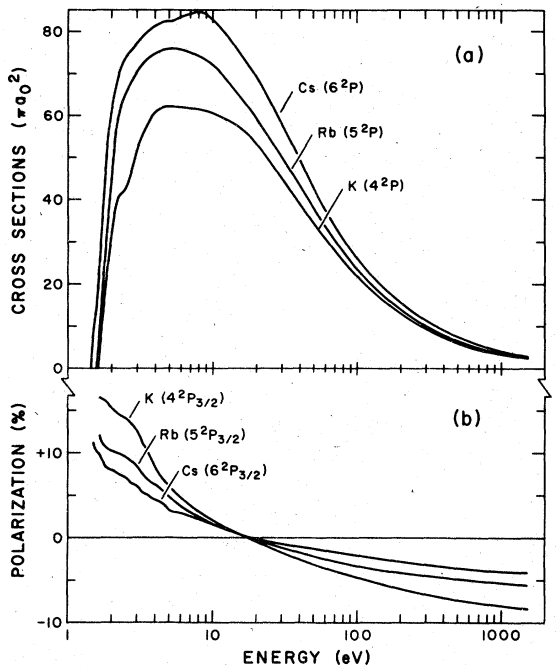

FIG. 2. (a) Normalized total excitation cross section for the resonance level (both fine-structure components); $4P$, $5P$, and $6P$ for the K, Rb, and Cs, respectively. (b) Polarization of the resonance transition: $4^2P_{3/2} \rightarrow 4^2S_{1/2}$, $5^2P_{3/2} \rightarrow 5^2S_{1/2}$, and $6^2P_{3/2} \rightarrow 6^2S_{1/2}$ for K, Rb, and Cs, respectively. All data include cascades.

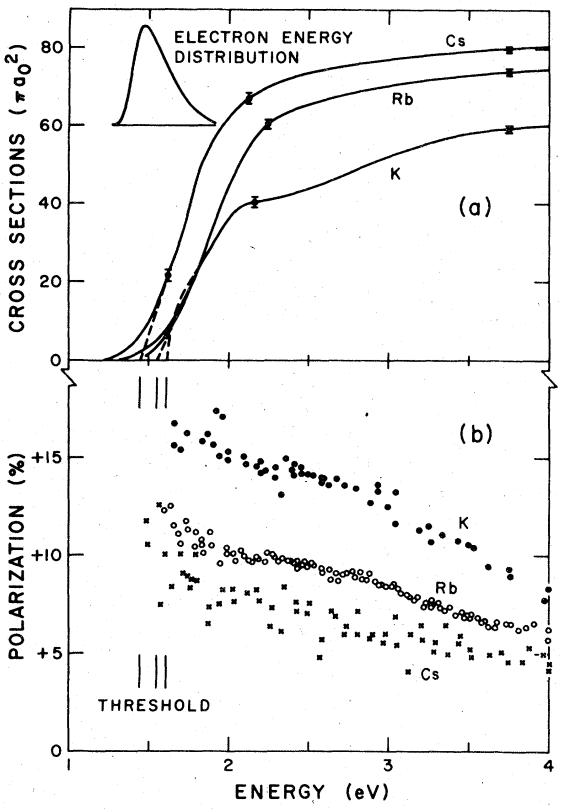

FIG. 3. Detailed low-energy experimental data, as in Fig. 2. The assumed form of the cross sections near threshold are shown as dashed lines, and the excitation thresholds are shown as bars in Fig. 3(a). The electron-energy distribution is also shown in Fig. 3(a).

section. We have convoluted this with the electron energy distribution for comparison to the data. The square-root law yielded the most satisfactory fits to the K data, whereas the linear law fitted the Rb and Cs data better. We have adopted the position of the Q_T threshold as the known excitation energies for K, Rb, and Cs resonance levels (see Fig. 3). From uncertainties in this convolution procedure we believe that the energy scale is uncertain to about ±0.03 eV.

Cascading into the n^2P resonance level begins at 2.6, 2.4, and 1.8 eV for K, Rb, and Cs, respectively; these may cause the structures discernible in the data of Fig. 3. According to the previous measurements of Zapechonyi *et al.*[5,6] the dominant cascade contributions are from n^2D and $(n+2)^2S$ terms with $n=3$, 4, and 5 for K, Rb, and Cs, respectively. The maximum cascade contributions were estimated[5] to be about 10% in the region of 4–5 eV for all cases. Solomon[8] has estimated that the total amount of cascade contributions to the 4^2P resonance level of K at an energy of 10.5 eV is about 25% of the apparent cross section at this energy. It is therefore believed that the estimation of the cascade contributions in the low-energy region is still uncertain. As mentioned in Sec. III, Born calculations predict ~7% cascade contribution to the resonance-level total excitation cross section at higher energy for all cases, also predominantly from the same states.

The relatively sharp feature in the K data near 2.1 eV (Fig. 3) is indicative of a resonance and cannot be due to cascading since it happens below the threshold of any possible cascading level. As one can see from Figs. 1 and 2, the high-energy cross-section data show smooth behavior and gradually converge to Born theory as expected.

According to the theory of Flower and Seaton,[29] the theoretical threshold polarizations are expected to be 22.4, 17.1, and 15.5%, respectively for K, Rb, and Cs $n^2P_{3/2} \rightarrow n^2S_{1/2}$ resonance transitions. Our data do not converge smoothly to these values, indicating that a rapid decrease occurs just above threshold and is obscured by our electron energy spread. This behavior is indicated by calculations for Li and Na, as discussed in Refs. 2 and 3. In the high-energy region, our polarization data show the expected gradual (logarithmic) convergence to the theoretical values of −9.39, −7.69, and −6.42% for K, Rb, and Cs, respective-

ly. More detailed discussions regarding polarization will be given in the next section. We will now compare our experimental results with other measurements and calculations.

A. K $4^2P \rightarrow 4^2S$

Our normalized optical excitation cross section for the K 4^2P resonance level is compared with previous measured results in Fig. 4. Zapechonyi and co-workers[5] have measured the absolute excitation cross section of the resonance lines for alkali elements using a crossed-beam apparatus. They carried out their measurements at an atom beam density of about 10^{11} atoms/cm^3, which is about 10 times larger than in our experiments. Their K results, including cascading (denoted by Z1 in Fig. 4) disagree with ours in magnitude as well as in energy dependence. Being aware of the possible influence of the resonance reabsorption due to the optically thick atom beam, they remeasured[6] the resonance excitation cross section in relative units at much lower atom density (~10^9 atoms/cm^3), and normalized to Born theory at ~50 eV. The result of the latter measurements (denoted by Z2) agrees somewhat better with ours in shape in the energy range of 50–300 eV, but its peak cross section is about a factor of 1.8 larger than ours. Note that the curve Z2 is cascade corrected, but this correction was estimated[5] to be a maximum of 10% only. The experimental results for energy dependence reported by Volkova and Devyatov[4] are in reasonable agreement with ours except in the near-threshold region where they did not give detailed data; however their results are about a factor of 2.3 larger than ours. Korchevoi and Przonski[7] have measured the resonance excitation cross section of K, Rb, and Cs atoms by means of the "trapped-electron" method. The result for K (shown in Fig. 4) agrees with ours within 10%. Note that both observed similar features near 2.1 eV. The result reported by Solomon[8] shows an unexpected energy dependence and is not included in the figure. The relative optical excitation cross sections measured by Phelps and Lin[9] have been normalized to our cross section at 400 eV. The agreement is excellent in the energy range of 10–400 eV, although their cross section at 5.5 eV is about 10% higher than ours. Williams and Trajmar[10] have also reported the excitation cross section (cascade free) at 6.7, 16, and 60 eV. The discrepancies in the shape and magnitude of our results versus those reported in Ref. 10 are much greater than can be reasonably accounted for by cascading.

Our normalized optical excitation cross section for the $4^2S \rightarrow 4^2P$ resonance transition of K is compared with theoretical calculations in Fig. 5. The excitation cross section of K 4^2P has been calculated by Vainshtein *et al.*[12] (first Born and VPS), Green and Williamson[13] (first Born, Bethe and Ochkur), McCarvert and Rudge[16] (truncated Born-Oppenheimer approximation), Felden and Felden[19] (correlation model), Walters[17] (Glauber approxi-

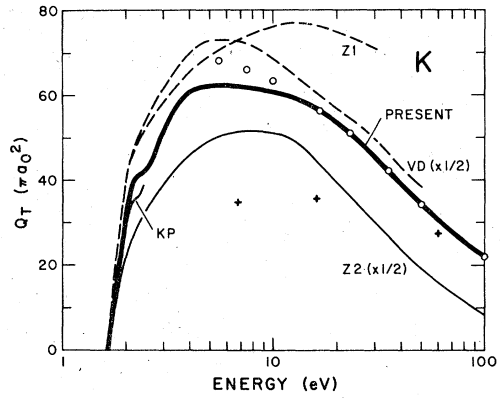

FIG. 4. Present normalized optical excitation cross section Q_T (heavy solid line) for K resonance level 4^2P compared with previous experimental results. Zapechonyi *et al.* (Refs. 5 and 6), Z1 and Z2; Volkova and Devyadov (Ref. 4), VD; Korchevoi and Przonski (Ref. 7), KP; Williams and Trajmar (Ref. 10), plus symbols; the open circles show the relative data of Phelps and Lin (Ref. 9) which they normalized to our results at 400 eV. Data of Z2, KP, and Williams and Trajmar are cascade free. All others include cascade.

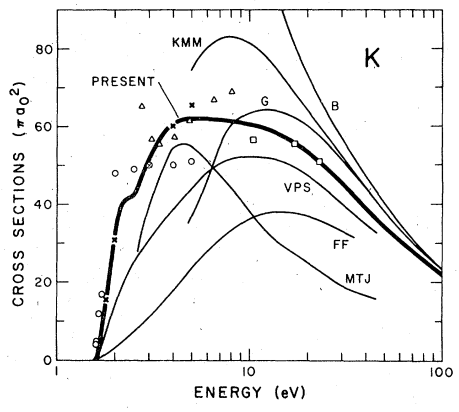

FIG. 5. Present normalized optical excitation cross section Q_T (heavy solid line) for K resonance level 4^2P compared with results of theoretical calculations; the approximations used are given in Sec. V A. Calculations by Vainshtein *et al.* (Ref. 12), B and UPS; McCarvert and Rudge (Ref. 16), Δ; Felden and Felden (Ref. 19), FF; Walters (Ref. 17), G; Kennedy *et al.* (Ref. 24), KMM; Mathur *et al.* (Ref. 18), MTJ; Karule and Peterkop (Ref. 15), ×; Moores (Ref. 14), ○; Korff and Lin (Ref. 25), □. Our experimental result includes cascade contribution, whereas all the theoretical calculations do not include cascades.

mation), Kennedy *et al.*[24] [unitarized-distorted-wave-polarized-orbital model (UDWPO)], and Mathur *et al.*[18] (classical impulse approximation). There are also three independent close-coupling calculations; the two-state ($4S$-$4P$) coupling including exchange by Karule and Peterkop,[15] the three-state ($4S$-$4P$-$3D$) coupling including exchange by Moores,[14] and the 15-state coupling without exchange by Korff and Lin.[25] All these close-coupling results show reasonable agreement with our experimental data in the low-energy region. Note that the three-state close-coupling calculation predicted a sharp peak near 2.1 eV, which is consistent with the observed peak near 2.1 eV although the predicted peak is much sharper than the observed one. However, the comparison between our experimental result and the calculations is not complete since our experimental result includes cascade contributions whereas all the theoretical calculations are for cascade-free excitations only. No measurements or calculations for the polarization of the K resonance line are available for comparison.

B. Rb $5^2P \rightarrow 5^2S$

Our normalized optical excitation cross section for the Rb 5^2P resonance level is compared with previous measured results in Fig. 6, and with theoretical calculations in Fig. 7. All symbols are the same as those used in the discussion in Sec. V A. The results by Zapechonyi's group[5,6] were obtained under the similar experimental conditions as those for K results. The agreements with our result in magnitude are somewhat better than that for K, but they still obtain a different energy dependence than ours. The result by Korchevoi and Przonski[7] is much higher than ours. The slope of the initial linear segment of the present excitation curve was estimated to be $\sim 8.5\times10^{-15}$ cm^2/eV compared to a value of 20×10^{-15} cm^2/eV reported in Ref. 7. Theoretical calculations for the Rb resonance-level excitation have been performed using Born,[12,13] VPS,[12] correlation model,[19] and classical impulse approximations.[18] As seen in Fig. 7, none of these theories gives good agreement with our experimental data in the intermediate and low-energy region. No close coupling calculation is available for comparison. No other measurements or calculations for the polarization of the Rb resonance line are available for comparison.

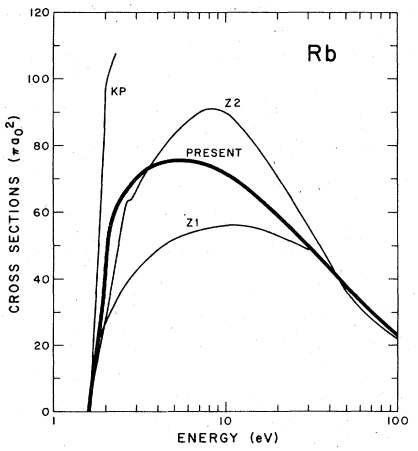

FIG. 6. Present normalized optical excitation cross section Q_T (heavy solid line) for Rb resonance level 5^2P compared with previous experimental results. All symbols have the same meaning as in Fig. 4.

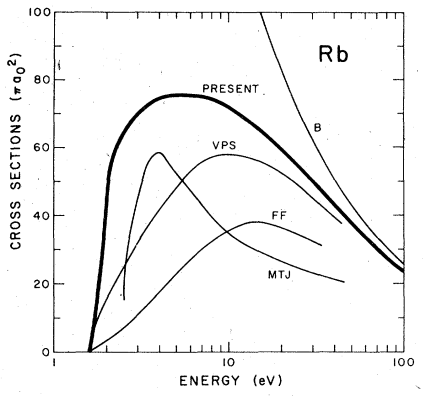

FIG. 7. Present normalized optical excitation cross section Q_T (heavy solid line) for Rb resonance level 5^2P compared with results of theoretical calculations. All symbols have the same meaning as in Fig. 5.

C. Cs $6^2P \rightarrow 6^2S$

Our normalized optical excitation cross section for the Cs 6^2P resonance level is compared with previous measured results in Fig. 8, and with the theoretical calculations in Fig. 9. The results by the Zapechonyi group[5,6] were obtained under the similar experimental conditions as those for K and Rb experiments. Again, their results disagree with ours in energy dependence as well as in magnitude. The results reported by Korchevoi and Przonski,[7] and by Nolan and Phelps[11] (optical curve) are also shown in the figure for comparison. The slope of the initial linear segment of the excitation curve in the present result was estimated to be about 11×10^{-15} cm^2/eV compared to the 7.1×10^{-15} cm^2/eV reported in Ref. 11 and the 15×10^{-15} cm^2/eV reported in Ref. 7.

Theoretical calculations for the cross sections of $6^2S - 6^2P$ excitation have been performed by Hansen[20] (modified Bethe approximation). Brandus[22] (modified Bethe), Vainshtein *et al.*[12] (Born and VPS), Witting and Gyftopoulos[21] (impact-parameter method), Sheldon and Dugan[23] (semiclassical),

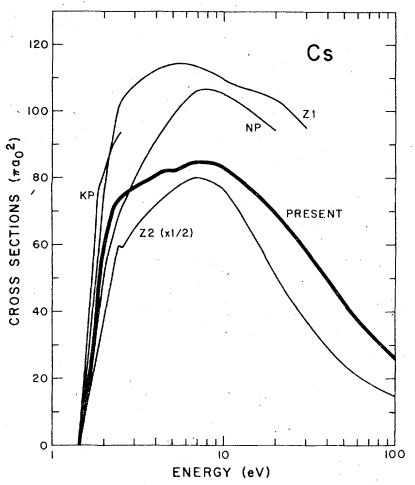

FIG. 8. Present normalized optical excitation cross section Q_T (heavy solid line) for Cs resonance level 6^2P compared with previous experimental results. Nolan and Phelps (Ref. 11), NP; other symbols have the same meaning as in Fig. 4.

Felden and Felden[19] (correlation model), Mathur *et al.*[18] (classical model approximation),[18] and Karule and Peterkop[15] (close coupling). The VPS approximation gives reasonable agreement in the energy range 10–40 eV, while the close coupling result gives reasonable agreement from 2–5 eV, considering that the present experimental data include cascade contributions, for which we do not have reliable estimates at the present time. However, the close-coupling calculation[15] predicts a sharp peak near 1.7 eV, which is not observed in the present experiment. No other measurements or calculations for the polarization of the Cs resonance line are available for comparison.

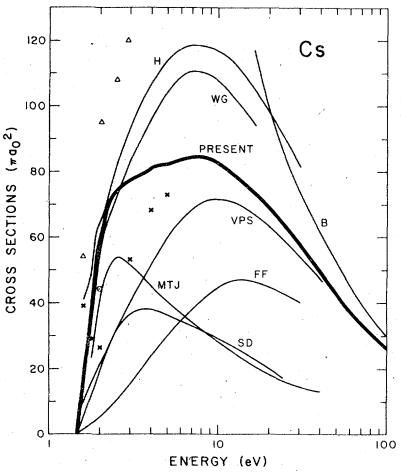

FIG. 9. Present normalized optical excitation cross section Q_T (heavy solid line) for Cs resonance level 6^2P compared with results of theoretical calculations; the approximations used are given in Sec. V C. Calculations by Hansen (Ref. 20), H; Brandus (Ref. 22), Δ; Witting and Gyftopoulos (Ref. 21), WG; Sheldon and Dugan (Ref. 23), SD; Karule and Peterkopf (Ref. 15), HF wave functions, ×; Ref. 15, Stone wave functions ⊗; other symbols have the same meaning as those in Fig. 5.

VI. INTERCOMPARISONS OF GROUP I ELEMENTS

In Fig. 10 we compare the electron-impact excitation cross sections of the resonance levels of the hydrogen atom[30] and the alkali elements measured in this laboratory.[2,3] These are similar excitation processes, since the H transition is a $1s^2S \rightarrow 2p^2P$ transition, with $f = 0.4162$, and the alkali elements are $ns^2S \rightarrow np^2P$ transitions with $n = 2$, 3, 4, 5, and 6 for Li, Na, K, Rb, and Cs, respectively, and with $f = 0.75$–1.05. According to the Born approximation, the quantity $Q_T\Delta^2/f$ will become a universal function of E/Δ for dipole transitions in the high-energy limit, so we have used these units in Fig. 10. As can be seen, the measured cross sections (including cascading) in these reduced units converge within ±15% of a common result at $E/\Delta > 2$. On the other hand, the Born cross sections[12,31]

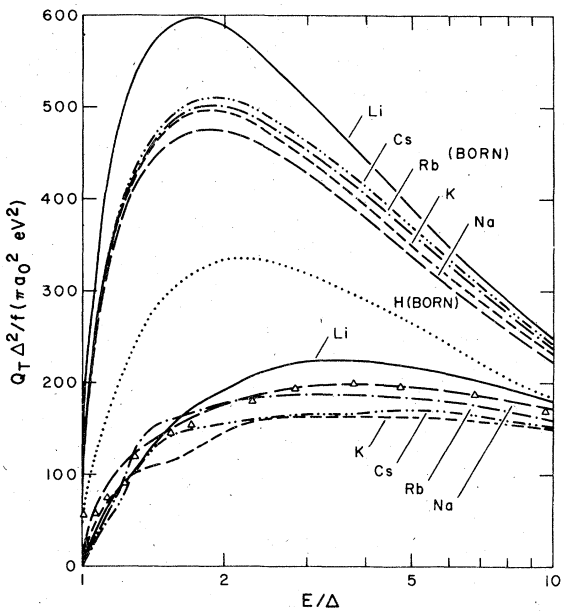

FIG. 10. Comparison of excitation cross sections for the atomic resonance levels of hydrogen (Δ, Ref. 30), and the alkali elements, Li (Ref. 3), Na (Ref. 2), and the present work on K, Rb, and Cs. For each case we have plotted $Q_T\Delta^2/f$ vs E/Δ, where Q_T is the cross section including cascades, Δ the excitation threshold energy, and f the resonance-line optical oscillator strength. The Born excitation cross sections for alkali elements are from Vainshtein *et al.* (Ref. 12). The Born excitation cross section for H resonance level is given by Ref. 31. Apart from minor differences due to cascades all of the curves merge at high energy.

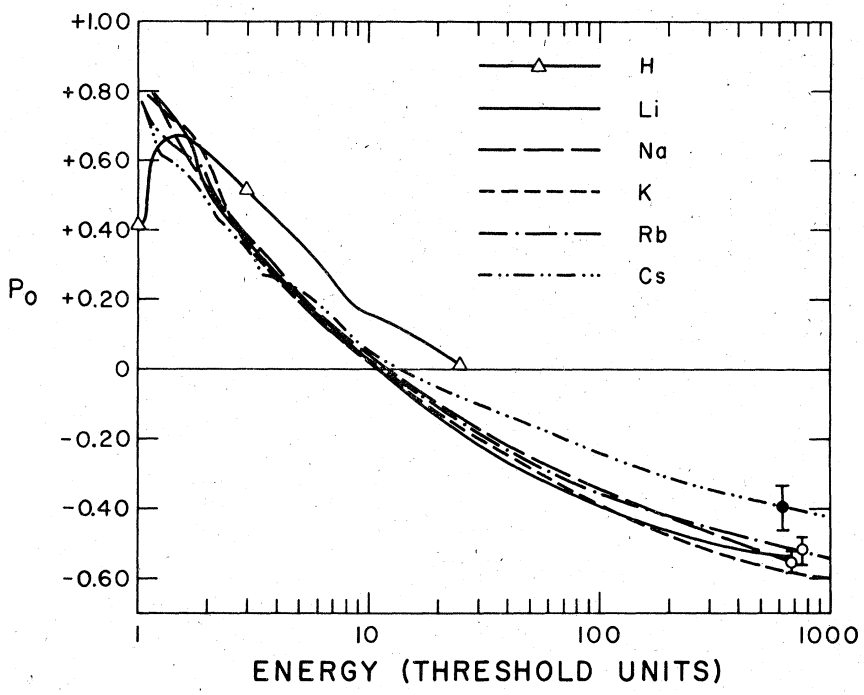

FIG. 11. Comparison of the measured polarization of the Group I resonance transitions $n^2P \rightarrow n^2S_{1/2}$ with $n = 1, 2, 3, 4, 5$, and 6 for H, Li, Na, K. Rb, and Cs, respectively. We have plotted $P_0 \equiv (Q_1 - Q_0)/(Q_1 + Q_0)$ vs E/Δ. The quantity P_0 is independent of fine structure and hyperfine structure. (See Sec. VI.)

are typically a factor of 2–3 too high in this energy range. Thus it appears that a fairly universal result similar to that observed for the group-II elements[1] also exists for the group-I elements.

For use in comparisons with other measurements, theories, and applications we will imitate the procedure we have used for the alkaline-earth elements,[1] by suggesting a simple analytic expression which fits this average result as accurately as it can be defined at all energies:

$$(\Delta^2/f)Q_T(\pi a_0^2\ \mathrm{eV}^2) \cong (1 - X^{-1/2})[(620 + 1705 \log_{10} X)/X] , \quad (5)$$

where $X \equiv E/\Delta$. The expression in brackets is very close to the alkali Born cross sections. Although the same factor multiplying the Born cross sections correctly represents the averaged group-II resonance-line cross section[1] the constant term in the Born cross section is larger for the alkalis. Thus the alkali cross sections rise more rapidly above threshold than do those of the group-II elements.

The degree of polarization of the group-I resonance lines is greatly reduced due to the large fine and hyperfine structure. According to the theory of Flower and Seaton,[29] the polarization for the radiation of the complete $^2P \rightarrow {}^2S$ multiplet is

$$P_m = \frac{3(9\alpha - 2)(Q_0 - Q_1)}{12Q_0 + 24Q_1 + (9\alpha - 2)(Q_0 - Q_1)} , \quad (6)$$

and for the radiation of the $^2P_{3/2} \rightarrow {}^2S_{1/2}$ transition is

$$P'_m = \frac{3(9\alpha - 2)(Q_0 - Q_1)}{8Q_0 + 16Q_1 + (9\alpha - 2)(Q_0 - Q_1)} , \quad (7)$$

where Q_0 and Q_1 are the cross section for excitation of the state ^2p to the sublevel $M_L = 0$ and 1, respectively, and the value of α depends on the nuclear spin, hyperfine structure, and natural lifetime of the specific level and species. We have used the values of α for Li and Na resonance levels calculated by Flower and Seaton[29] based on experimental data of Brog *et al.*,[32] Series,[33] and Allen.[34] For K, Rb, and Cs resonance levels, we have used the experimental data of Schmieder *et al.*[35] to calculate the values of α. The results are $\alpha = 0.413$, 0.288, 0.294, 0.276, and 0.271 for ^{6}Li, Na, K, Rb, and Cs, respectively. For H we have used $\alpha = 0.440$, inferred from Percival and Seaton.[36]

It is interesting to define the quantity $P_0 \equiv (Q_0 - Q_1)/(Q_0 + Q_1)$, which is equivalent to the polarization one would observe in the absence of the fine and hyperfine structure. One can invert Eqs. (6) and (7) to obtain P_0 as a function of α and P_m or of α and P'_m, so that the measured polarization yields P_0. Since P_0 represents the results of the electron collision process, we have compared P_0 vs E/Δ for all the alkalis (from our measurements) and H (from Ref. 37) in Fig. 11. As one can see from the figure, all alkali curves are fairly similar, although the curve for Cs shows some departure from the others. (The experimental uncertainty is much larger for Cs since the actual P_m is

smaller.) Furthermore, they are all consistent with a rapid drop from +100% threshold limit to about +80%, and they logarithmically converge to a −100% limit at infinite energy, as expected theoretically. Similar results have also been reported[1] for the alkaline-earth and He resonance transitions. The P_0 for H appears to be quite different than for the alkalis. Near threshold this could be influenced by the $2s$-$2p$ degeneracy and resonance,[3] but the difference at higher E/Δ is rather surprising in view of the agreement of the H total cross sections in Fig. 10.

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