Electron excitation of thallium $7\,^2S_{1/2}$ and $6\,^2D_{3/2,5/2}$ levels*

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We have measured the relative optical excitation functions of the 3776-Å ($7^2S_{1/2}\rightarrow 6^2P_{1/2}$), 2768-Å ($6^2D_{3/2}\rightarrow 6^2P_{1/2}$), 3529-Å ($6^2D_{3/2}\rightarrow 6^2P_{3/2}$), and 3519-Å ($6^2D_{5/2}\rightarrow 6^2P_{3/2}$) lines, and the polarization function of the 2768-Å line, using crossed beams of electrons and thallium atoms, for electron energies from thresholds to 1500 eV. The electron energy resolution was ~ 0.3 eV for energies below 13 eV, and the atom beam was optically thin. By normalizing the resonance-line excitation functions to Born theory in the high-energy limit the $7^2S_{1/2}$, $6^2D_{3/2}$, and $6^2D_{5/2}$ level-excitation cross sections are obtained. The $7^2S_{1/2}$-level excitation function rises very rapidly immediately above threshold, while the $6^2D_{3/2}$ level rises much more slowly. The 2768-Å polarization function shows strong resonance at a few electron volts above the threshold. The $6^2D_{5/2}$ level excitation function peaks at lower energy as expected for a dipole-forbidden transition, but shows a small $E^{-1}\log_{10}E$ behavior at the high-energy limit.

I. INTRODUCTION

Thallium (Tl) has some interesting and unusual properties as a target for studies of electron impact excitation. It behaves predominately as a single electron atom, but with a P ground state and a very large fine structure. We have measured the electron excitation of the Tl resonance lines to see how these cross sections fit into a general behavior observed for the group I and II elements, to investigate fine-structure effects, $P\rightarrow S$ and $P\rightarrow D$ transitions, and provide necessary data for modeling potential Tl-based lasers and the behavior of Tl in metal vapor lamps. Some aspects of the resonance-line excitations we observe fit into the systematic picture found for the group I and II elements, but we also find some unusual fine-structure effects as well as some major differences between the $P\rightarrow S$ and $P\rightarrow D$ resonance-line excitation cross sections.

The absolute excitation cross sections of the Tl atom by electron impact have previously been measured by Zapesohnyi and co-workers.[1,2] They reported the absolute cross sections, with ±40% error, for several atomic transitions of Tl. Born approximation calculations of the level-excitation cross sections and polarization functions for several transitions have recently been performed,[3] and are used here for normalization. Here we report the normalized level excitation cross sections for the Tl $7\,^2S_{1/2}$, $6\,^2D_{3/2}$, and $6\,^2D_{5/2}$ levels, and the polarization function for the 2768-Å resonance line ($6\,^2D_{3/2}\rightarrow 6\,^2P_{1/2}$) excited by electron impact on thallium $6\,^2P_{1/2}$ ground-state atoms. Figure 1 shows a Tl-energy-level and wavelength diagram.

Our measurements covered the energy range from thresholds to 1500 eV. We used crossed low-density beams of electrons and thallium atoms, thereby minimizing space-charge and optical-depth problems.

The apparatus used for the present experiment, the method of measurement and possible minor corrections, such as finite electron-beam and optical solid angles, imperfect polarization analyzer, and possible radiation entrapment, have been described in detail in previous papers[4-6] reported

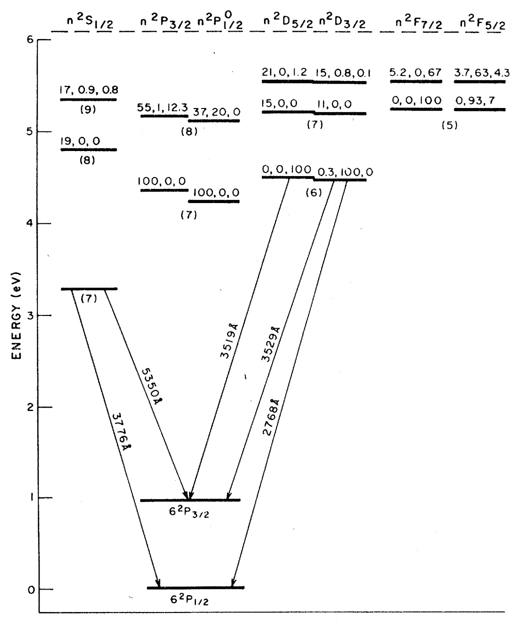

FIG. 1. Energy-level diagram for low-lying doublet levels of thallium. The number in parenthesis represents the principal quantum number of the term above it, and the numbers above each level specify, in order, the percent of atoms in that level which cascade to the $7\,^2S_{1/2}$, $6\,^2D_{3/2}$, and $6\,^2D_{5/2}$ levels.

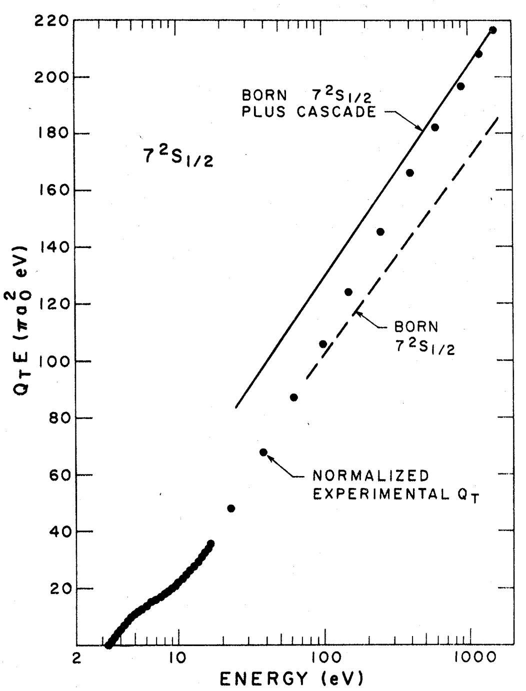

FIG. 2. Method of normalizing the relative cross section for the $7\,^2S_{1/2}$ level. The Born-approximation calculations by Leep and Leep (Ref. 3) have been used for the $7\,^2S_{1/2}$ level and for the cascade contributions $n\,^2S_{1/2}$ ($n=8, 9$), $n\,^2P$ ($n=7, 8$), $n\,^2D$ ($n=6$–8), and $n\,^2F$ ($n=5, 6$) (see Sec. II). The present total cross section Q_T (dots) is normalized to the sum of the Born $7\,^2S_{1/2}$ plus estimated total cascade cross sections.

from this laboratory. In the present paper we will describe the normalization procedure in Sec. II, and experimental results in Sec. III.

II. NORMALIZATION AND CASCADE

To obtain the absolute excitation cross sections for the $7^2S_{1/2}$ and $6\,^2D_{3/2}$ atomic resonance levels, we normalize the measured 3776- and 2768-Å relative line-emission cross sections at high energy to the Born-direct cross sections plus cascade contributions, all from Ref. 3. Figures 2 and 3 illustrate the normalization method. The high-energy behavior of the total cross section Q_T for a dipole-allowed transition can be expressed as[7]

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

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 approximation, and $O(\Delta_n/E)$ represents higher-order terms that are neglected in the Bethe approximation and partly included in the Born approximation.

The Born cross sections calculated by Leep and Leep[3] for Tl $6\,^2P_{1/2}\to 7\,^2S_{1/2}$ and $6\,^2P_{1/2}\to 6\,^2D_{3/2}$ excitation approach at high energy

$$Q_BE(\pi a_0^2\ \text{Ry}) = 4\left(\frac{0.1383}{0.2412}\right)\ln(4\times 1.0050E)\ \text{for}\ 7\,^2S_{1/2}$$

$$\quad (2)$$

$$Q_BE(\pi a_0^2\ \text{Ry}) = 4\left(\frac{0.4022}{0.3291}\right)\ln(4\times 0.6138E)\ \text{for}\ 6\,^2D_{3/2}\ ,$$

corresponding to $f_n = 0.1383$ and 0.4022 for $6\,^2P_{1/2}\to 7\,^2S_{1/2}$ and $6\,^2P_{1/2}\to 6\,^2D_{3/2}$, respectively. The experimental oscillator strengths measured by Gallagher and Lurio[8] are 0.133 ± 0.007 and 0.29 ± 0.022 for these transitions, respectively. To obtain a more accurate Born cross section for the purpose of normalization, we replace the theoretical f_n in Eq. (2) by the experimental values of Ref. 8. Thus we are using the Born cross sections of Ref. 3 to obtain only the constants C_n in Eq. (1). The sensitivity of C_n to various changes in Tl wave functions has been tested in Ref. 3, and found to be relatively minor. The resulting normalization uncertainty is discussed below. The Born cross sections for the $7\,^2S_{1/2}$ and $6\,^2D_{3/2}$ direct excitation cross sections are then

$$Q_BE(\pi a_0^2\ \text{eV}) = -36.567 + 69.06\log_{10}E\ \text{for}\ 7\,^2S_{1/2}\ ,$$

$$\quad (3)$$

$$Q_BE(\pi a_0^2\ \text{eV}) = -82.009 + 110.28\log_{10}E\ \text{for}\ 6^2D_{3/2}\ ,$$

with the electron impact energy E in units of eV. In Eq. (3), the constant term and the logarithmic

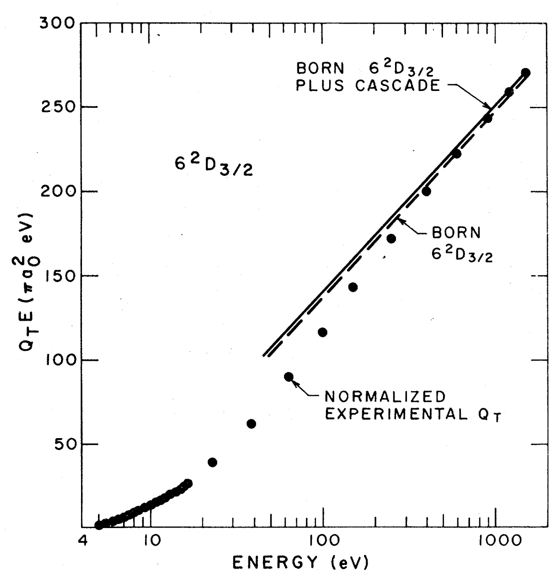

FIG. 3. Same as Fig. 2, but for $6\,^2D_{3/2}$ level.

term are separated, which is more convenient when we have to add the cascade contribution to the direct level-excitation cross section.

We make a first estimate of cascades into $7\,^2S_{1/2}$ and $6\,^2D_{3/2}$ using Born cross sections from Ref. 3. This yields 19% into $7\,^2S_{1/2}$ and ~1% into $6\,^2D_{3/2}$ at 1500 eV. The cascade contributions are from $n\,^2S_{1/2}$ ($n=8,9$), $n\,^2P$ ($n=7,8$), $n\,^2D$ ($n=6$–8), and $n\,^2F$ ($n=5,6$). The branching ratios for these levels to decay, mainly via $7\,^2P$, $8\,^2P$, $5\,^2F$, to the $7\,^2S_{1/2}$ and $6\,^2D_{3/2}$ are obtained from transition probabilities given in Ref. 8, or from the Coulomb approximation[9] for those that are not given in Ref. 8. We can improve the accuracy of the Born cross sections for these $8\,^2S$, $9\,^2S$, $7\,^2D$ and $8\,^2D$ terms by replacing theoretical f_n values in the Born cross-section calculation[3] with the experimental values from Ref. 8. The result is 16% cascade into $7\,^2S_{1/2}$ and still ~1% into $6\,^2D_{3/2}$. We thus obtain total theoretical excitation cross sections for $7\,^2S_{1/2}$ and $6\,^2D_{3/2}$, including the cascade contributions from the levels mentioned above:

$$Q_T E(\pi a_0^2\ \text{eV}) = -20.83 + 74.87\ \log_{10}E \text{ for } 7\,^2S_{1/2}\ ,$$
$$Q_T E(\pi a_0^2\ \text{eV}) = -78.99 + 110.37\ \log_{10}E \text{ for } 6\,^2D_{3/2}\ . \quad (4)$$

Our measured relative 3376- and 2768-Å excitation functions are normalized to converge to the cross sections in Eq. (4) in the high-energy limits. (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 $7\,^2S_{1/2}$, due to the 5% uncertainty in $7\,^2S_{1/2}$ optical oscillator strength, a 2% uncertainty in C_n, plus a 3% uncertainty in cascade contributions. The total uncertainty is about ±9% for $6\,^2D_{3/2}$, primarily due to the 8% uncertainty in the $6\,^2D_{3/2}$ optical oscillator strength, and the 4% uncertainty in C_n.

The relative intensities of the 3776- and 2768-Å radiation could, in principle, be used to test the accuracy of these two independent normalizations. However, uncertainties in branching ratios from the $7\,^2S_{1/2}$ and $6\,^2D_{3/2}$ states and in experimental sensitivies at the different wavelengths, are much greater than the above normalization uncertainties. The observed relative radiative intensities were consistent with expectations, but with large uncertainties.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The present results are given in Table I and in Figs. 4–10. The corrections described in Refs. 4–6 have been taken into account. The causes of the uncertainties quoted in Table I have been described in more detail in Refs. 4–6; they do not include the normalization uncertainty.

The data were obtained at energy intervals of less than 0.1 eV below 17 eV, and at 11 energy values between 23 and 1500 eV. All of the data above 23 eV and a representative set below are given in Table I. The original data at low-energy regions can be seen in Figs. 5, 7, and 9. Because of the smooth behavior of the high-energy Q_T data shown for every case, we have represented our high-energy data as a continuous curve in Figs. 4, 6, 8, and 10.

The convolution procedure described in Ref. 6 has been used to find the threshold energies and adjust the energy scale for each individual level (typically by 0–0.10 eV relative to the analyzer). This yields about ±0.05 eV uncertainty in our energy scale, in addition to the uncertainties given for individual energy points in Table I. The results for each level will be discussed separately below.

A. $7\,^2S_{1/2} \rightarrow 6\,^2P_{1/2}$ line

The normalized cross sections for the $7\,^2S_{1/2}$ level are listed in column 2 of Table I, and also shown in Figs. 4 and 5. The present results are compared in the figures with Born theory[3] and earlier measurements by Zapesochnyi *et al.*[2] Our results and the Born theory include cascade contributions while results from Ref. 2 have been plotted for both the directly measured $7\,^2S_{1/2}$-level excitation cross section including cascades (denoted by $Z1$), and the reported $7\,^2S_{1/2}$-level direct-excitations cross section (denoted by $Z2$). Zapesochnyi *et al.* used a crossed-beam apparatus and spectrometer to carry out their measurements for the excitation function and quoted ±40% for their experimental uncertainty. The discrepancies between the shape and normalizations of the present results versus Ref. 2 are much greater than can be accounted for on the basis of reported uncertainties or cascade corrections. Radiation entrapment, as indicated by an anomalous 5350/3776-Å line intensity ratio compared to the known branching ratio in Ref. 8, might account for part of the discrepancy. We used a density of $\lesssim 10^8$ atoms/cm^3, and possible effects of radiation entrapment were checked by varying the beam density and were found to be negligible.

Cascade contribution to the $7\,^2S_{1/2}$ level begins at 4.23 eV and may cause the structure discernible in the data of Fig. 5. According to the previous measurements,[2] the dominant cascade contributions are from the $7\,^2P$ and $8\,^2P$ terms. The maximum cascade contribution was measured[2] to be about

TABLE I. Normalized cross sections for electron-impact excitation of the Tl $7\,^2S_{1/2}$, $6\,^2D_{3/2}$, and $6\,^2D_{5/2}$ levels and the polarization of the 2768-Å resonance line.

Energy [a] (eV)	$7\,^2S_{1/2}$	Q_T [b] (πa_0^2) $6\,^2D_{3/2}$	$6\,^2D_{5/2}$	Polarization (%) 2768 Å
3.50(1) [c]	0.477(16) [c]			
4.00(1)	1.415(32)			
4.50(1)	1.969(40)			
5.00(1)	2.149(25)	0.257(10)	0.343(8) [c]	14.0(16) [c]
5.50(2)	2.229(29)	0.480(18)	0.414(10)	13.8(13)
6.00(2)	2.268(31)	0.657(24)	0.450(11)	15.0(13)
6.50(2)	2.369(26)	0.803(30)	0.470(12)	16.7(10)
7.00(2)	2.299(24)	0.976(32)	0.473(12)	18.5(10)
7.50(2)	2.253(24)	1.052(34)	0.412(12)	20.0(10)
8.00(2)	2.285(24)	1.152(22)	0.438(13)	22.5(7)
8.50(2)	2.224(23)	1.237(24)	0.410(12)	23.8(6)
10.00(3)	2.237(23)	1.360(26)	0.324(13)	25.3(6)
12.00(3)	2.206(23)	1.480(30)	0.248(12)	24.6(5)
16.70(5)	2.122(19)	1.600(32)	0.179(9)	18.6(3)
23.11(6)	2.080(15)	1.671(32)	0.127(7)	12.4(3)
37.9(2)	1.784(13)	1.635(30)	0.084(7)	+5.7(3)
62.7(2)	1.387(10)	1.439(28)	0.056(6)	+1.8(2)
98.6(2)	1.068(8)	1.187(20)	0.041(5)	−1.0(2)
149.2(2)	0.831(6)	0.959(17)	0.029(4)	−3.1(2)
248.2(2)	0.584(5)	0.696(12)	0.020(3)	−5.7(3)
399.8(3)	0.414(3)	0.502(9)	0.014(2)	−7.1(3)
600.7(3)	0.301(2)	0.371(7)	0.0094(14)	−8.7(4)
897.9(6)	0.218(2)	0.271(5)	0.0073(11)	−9.5(4)
1198.6(8)	0.173(1)	0.216(3)	0.0057(9)	−11.1(4)
1497.6(10)	0.144(1)	0.181(3)	0.0046(7)	−11.9(4)

[a] The mean energy of the incident electrons, corrected by reference to the $7\,^2S_{1/2}$ and $6\,^2D_{3/2}$ excitation energies, which are 3.282 and 4.476, respectively. The electron energy resolution was 0.3-eV FWHM for energies below 13 eV. Besides the uncertainty given for each point, there is an additional uncertainty of ±0.05 eV in the calibration of the energy scale (see Sec. III).

[b] Q_T is the normalized level-excitation cross section including cascade contributions. The uncertainties given in the columns do not include uncertainties in the normalization of the cross section scale, i.e., ±6% for $7\,^2S_{1/2}$ and ±9% for $6\,^2D_{3/2}$, and ±16% for $6\,^2D_{5/2}$.

[c] The number in parentheses gives the uncertainty in the last places of the previous number. In columns 2–5, the quoted uncertainties include the observed statistical uncertainties (roughly 2σ) and estimated systematic uncertainties.

25% near 7 eV. As mentioned in Sec. II, Born calculation predicts a 16% cascade contributions to the $7\,^2S_{1/2}$-level total cross section at high energy. It is also interesting to note that the $7\,^2S_{1/2}$-level excitation function rises very rapidly immediately above threshold, similar to the previously measured excitation function for sodium resonance lines but not for the Li and alkaline-earth resonance lines.[4]

B. $6\,^2D_{3/2} \rightarrow 6\,^2P_{1/2}$ line

The normalized $6\,^2D_{3/2}$-level excitation cross section and the 2768-Å line ($6\,^2D_{3/2} \rightarrow 6\,^2P_{1/2}$) polarization function have been listed in columns 3 and 5 of Table I, and shown in Figs. 6 and 7. In Fig. 6(a) the present normalized results are compared with Born theory[3] and earlier absolute measurements by Shimon *et al.*[1] Shimon *et al.* used an apparatus similar to that described in Ref. 2. Both experimental results are relatively structureless, and in good agreement below 20 eV. However, the present excitation function has a peak in the 20–30-eV region, while their results show a relatively broad peak in the 60–100-eV region.

The present measured polarization function for the 2768-Å line, including cascades, is compared with Born calculation,[3] without cascades, in Fig. 6(b). One notes that the present polarization function behaves smoothly and agrees with Born theory at energies above 15 eV, but decreases below 10 eV. Similar resonance effects have been observed in polarization curves for He $3\,^{1,3}P \rightarrow 2\,^{1,3}S$ and

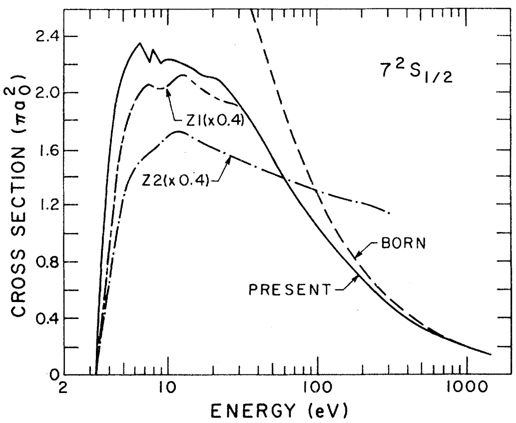

FIG. 4. Normalized total excitation cross section for the Tl $7\,^2S_{1/2}$ level. The present cross section is compared with Born theory (Ref. 3) and previous measurements by Zapesochnyi *et al.* (Ref. 2). Our data include cascade contributions as does the Born cross section to which the present data are normalized. Data from Ref. 2 multiplied by a factor of 0.4, are shown in this figure for both the total excitation cross section including cascade contributions ($Z1$), and the direct excitation cross section for the $7\,^2S_{1/2}$ level ($Z2$).

$4\,^{1,3}D \rightarrow 2\,^{1,3}P$ transitions[10] and for a series of Hg $n\,^{1,3}D \rightarrow n'\,^{1,3}P$ transitions.[11,12] There is a traditional explanation[10] for these types of low-energy results based on resonances slightly above threshold. No other experimental measurements for the 2768-Å polarization function are available for comparison.

The detailed low-energy data near the threshold are shown in Fig. 7. Possible cascade contribution begins at 5.13 eV. As described in Sec. II

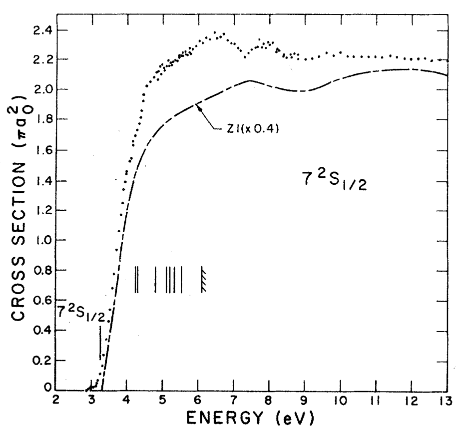

FIG. 5. Present low-energy data (dots) for the $7\,^2S_{1/2}$ level including cascade contributions and Ref. 2 data as described in Fig. 4. Excitation thresholds for some cascade-producing terms are indicated by bars.

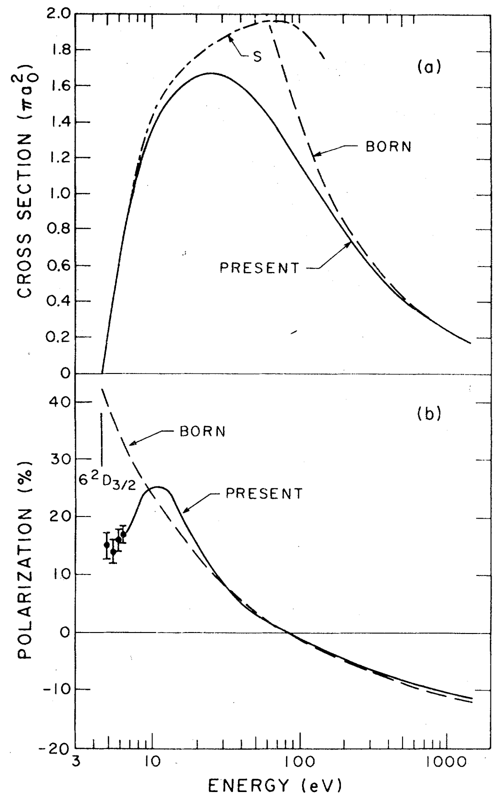

FIG. 6. Normalized total excitation cross section for the Tl $6\,^2D_{3/2}$ level and polarization of the 2768-Å resonance line ($6\,^2D_{3/2} \rightarrow 6\,^2P_{1/2}$). The present $6\,^2D_{3/2}$-level excitation cross sections and polarization is compared with Born theory (---, Ref. 3) and with previous absolute measurements for the sum of the 2768- and 3529-Å lines from this level by Shimon *et al.* (——, Ref. 1). All the experimental data include cascades, as does the Born cross section to which the present data are normalized. However, the Born polarization is given for direct excitation only.

the cascade contributions play a less important role for the excitation of the $6\,^2D_{3/2}$ level due to small branching functions (Fig. 1). This is also explicitly supported by the relatively structureless excitation function shown in Fig. 7(a). Comparings Figs. 5 and 7 one should also note that the $6\,^2D_{3/2}$-resonance-level excitation function rises much more slowly than the $7\,^2S_{1/2}$-level excitation function. This difference in the threshold behavior is important to the excitation efficiency in discharges since it has a major effect on the rate constants.

C. $6\,^2D_{5/2} \rightarrow 6\,^2P_{3/2}$ (3519-Å) line

We have measured the relative optical excitation function $R_T(E)$ of the unresolved 3519- and 3529-Å lines using a broadband interference filter

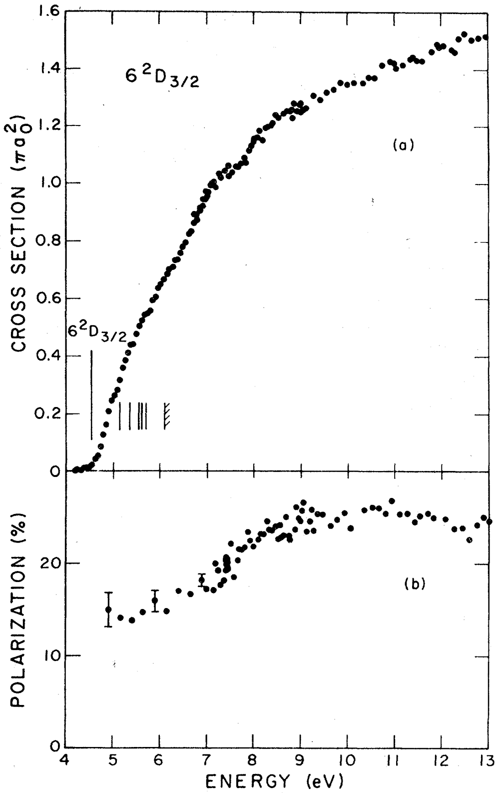

FIG. 7. Low-energy data (dots) for the $6^2D_{3/2}$ level including cascade contributions. Excitation thresholds for some possible cascade-producing terms are indicated by bars.

corrected for measured polarization of the unresolved lines. The intensity ratio of the total light emitted in the direction perpendicular to the electron beam for these two lines was then measured at 100 eV using a monochromator. Using the calculated Born polarization[3] to make a few percent polarization correction, this measured intensity ratio yields $D \equiv Q_{5/2}(100\text{ eV})/Q_{3/2}(100\text{ eV}) = 0.23(\pm 10\%)$. The inteference filter used for this measurement leaked ~0.3% of the 3776-Å line; this accounts for ~3% of the total signal at 16.7 eV. We have corrected for this leakage as shown in Figs. 8 and 9. The total excitation cross section $Q_{5/2}(E)$ of the 3519-Å line, was obtained using the formula

$$Q_{5/2}(E) = BQ_{3/2}(100)\left(\frac{R_T(E)}{R_T(100)}(1+D) - \frac{Q_{3/2}(E)}{Q_{3/2}(100)}\right) , \quad (5)$$

where $Q_{3/2}(E)$ is the $6^2D_{3/2}$-level cross section from Sec. III B, and $B = 0.149 \pm 0.020$ is the $6^2D_{3/2}$-level branching ratio to the 3529-Å line from Ref. 8. Here we have utilized the fact that the 2768- and 3529-Å line cross sections are related by a constant. Aside from the uncertainty in B, Eq. (5) yields about ±3%–5% uncertainty for the 3519-Å relative cross section at energies below 23 eV, increasing to ±16% uncertainty at 1500 eV where the 3529-Å line is the major portion of the unresolved lines. The ±10% uncertainty in D is the dominant cause of this increased uncertainty at the higher energies. The 3529-Å line excitation cross sections in Figs. 8 and 9 are $BQ_{3/2}(E)$. Note that uncertainty in B or $Q_{3/2}$ (100) does not affect the ratio of $Q(3529)$ to $Q_{5/2}$ in Figs. 8 and 9. We have estimated the branching ratio for $6^2D_{5/2} \to 6^2P_{3/2}$ vs $6^2D_{5/2} \to 7^2P_{3/2}$ using the known optical oscillator strength[8] for the former and the Coulomb approximation for the latter.[9] We conclude that the transition rate from the $6^2D_{5/2}$ to the $7^2P_{3/2}$ level is less than 0.1% of that to the $6^2P_{3/2}$ level. The 3519-Å ($6^2D_{5/2} \to 6^2P_{3/2}$)-line emission cross section is thus effectively identical to the $6^2D_{5/2}$-level excitation cross section, including cascade contribution. The $R_T(E)/R_T(100)$ and $Q_{3/2}(E)/Q_{3/2}(100)$ ratios in Eq. (5) are accurate to ≤2% so that the major uncertainty in the shape of $Q_{5/2}(E)$ comes from the 10% uncertainty in D. The magnitude of the $6^2D_{5/2}$-level excitation cross section is uncertain by an additional 16%, due to the 13% uncertainty in B and 9% uncertainty in $Q_{3/2}(100)$ from Sec. II (added to quadrature).

The present results were compared (in Fig. 10)

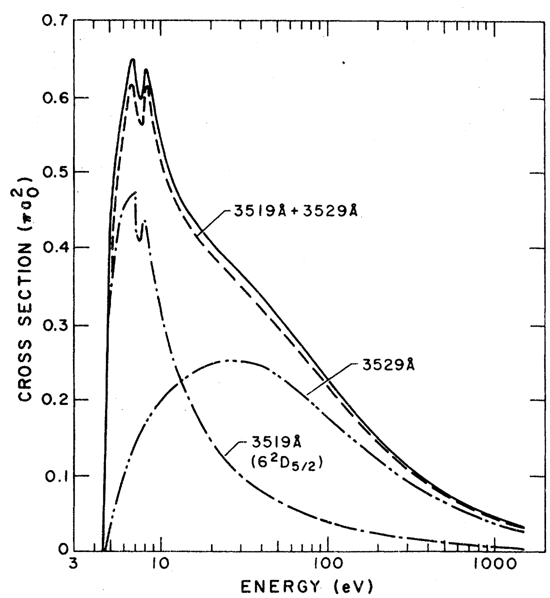

FIG. 8. Normalized total cross section for excitation of the 3519-Å line or $6^2D_{5/2}$ level. Minor leakage of the 3776-Å line was subtracted from the raw data (solid curves), yielding the corrected cross sections for the unresolved 3519- and 3529-Å lines (dashed curves). The 2529-Å line-emission cross section is 0.149 times $Q(6^2D_{3/2})$. The separation into the two lines is described in Sec. IIIC.

with Born theory[3] and earlier measurements by Shimon *et al.*[1] Both experimental results include cascade contributions as does the Born cross section. The excitation function reported in Ref. 1 was different from ours in shape, as well as in magnitude, although both observed similar structures in the 6–9-eV region. The present $Q_T E$ vs $\log_{10} E$ of the $6\,^2D_{5/2}$ level is also plotted in Fig. 10 compared with the corresponding plot of the Born cross section. The present $6\,^2D_{5/2}$ excitation function tends to show a small $E^{-1}\log_{10}E$ behavior in the high-energy limit.

IV. CONCLUSIONS

(i) The present measured $7\,^2S_{1/2}$-level excitation function rises very rapidly immediately above threshold, similar to the previously measured excitation function for sodium resonance line, while the $6\,^2D_{3/2}$ level and previously measured Li and alkaline-earth resonance lines excitation functions rise much more slowly. Such rapid onsets are sometimes due to resonances in the threshold region.

(ii) The 2768-Å line ($6\,^2D_{3/2} \to 6\,^2P_{1/2}$) polarization decreases in the first few eV above the threshold and does not approach the theoretical threshold value for the present energy resolution.

(iii) The $6\,^2D_{5/2}$ excitation function exhibits typical dipole forbidden excitation behavior, in that it rises rapidly and peaks at low energy. In addition it agrees rather well with the Born cross section at all energies. However, we observe a component of $E^{-1}\log_{10}E$ behavior in the high-energy limit (Fig. 10), which is predicted to be zero in the Bethe and Born theories due to the absence of an optical oscillator strength for the transition from $6\,^2P_{1/2}$ to $6\,^2D_{5/2}$. It cannot be attributed to experimental uncertainty in the enclosure of Eq. (5), or to cascading terms. From the known Tl oscillator strengths and Born cross sections we can evaluate the size of the cascade contributing to this $E^{-1}\log_{10}E$ term in the $6\,^2D_{5/2}$ cross section as less than 0.1% of the direct excitation. This comes from $n^2S_{1/2}(n \geq 9)$ and $n'^2D_{3/2}(n' \geq 8)$ excitations (primarily $n = 9$ and $n' = 8$), and is very small because these branch only slightly ($\beta < 0.01$) into the $6\,^2D_{5/2}$ level. On the other hand, it would seem that if the $6\,^2D$ term fine structure were very small there might be some long-range mixing of the $6\,^2D_{3/2}$ and $6\,^2D_{5/2}$ levels. This is the first test of such a fine-structure dependence of which we are aware.

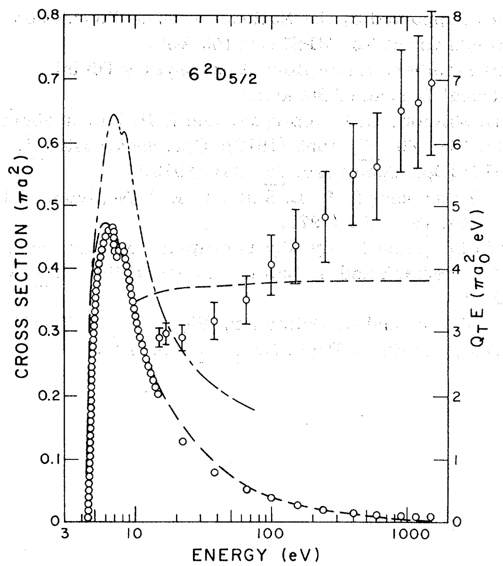

FIG. 10. Normalized total cross section Q_T for excitation of the $6\,^2D_{5/2}$ level. The present $6\,^2D_{5/2}$-level excitation cross section (OOO) is compared with Born theory (---, Ref. 3), and earlier absolute measurements by Shimon *et al.* (——, Ref. 1). All experimental data include cascades, as does the Born cross section. The $6\,^2D_{5/2}$-level excitation cross section times electron energy is also plotted against the $Q_T E$ scale on the right (Φ present; horizontal dashed line is Born theory). The error bar represents the uncertainty in the relative cross section not including the ±16% uncertainty in normalization scale.

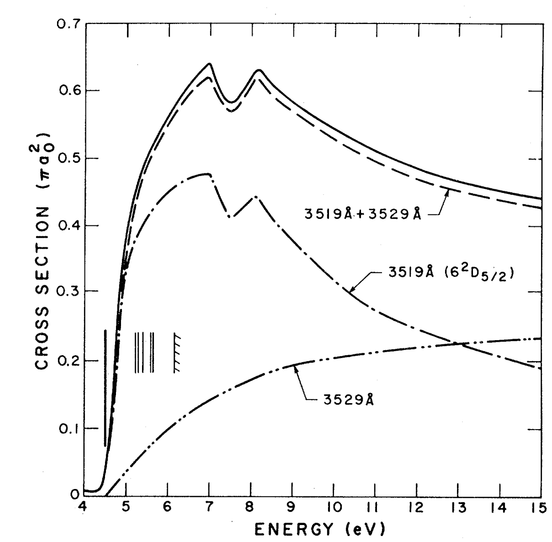

FIG. 9. Low-energy data for the $6\,^2D_{5/2}$-level excitation cross section. All symbols are the same as in Fig. 8. Excitation thresholds for some cascade-producing terms are indicated by bars.

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