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Electron excitation of the lithium 6708-Å resonance line*

David Leep and Alan Gallagher†
Joint Institute for Laboratory Astrophysics, University of Colorado and National Bureau of Standards, Boulder, Colorado 80302
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We have measured the relative optical excitation function and the polarization of the 6708-Å line, using crossed beams of electrons and lithium-6, for electron energies from threshold to 1400 eV. The electron energy resolution was ~0.25 eV, and the lithium-beam optical depth was small and varied. We have normalized our excitation function to Born theory at 1404 eV, where the energy dependence has converged to the theoretical behavior. Between 2 and 6 eV, the measured cross section is (10–45)% smaller than the results of the most recent close-coupling calculations, but the measured polarization P agrees with these theories within 20% of P. The theoretical polarization at threshold is not observed with our energy resolution.

I. INTRODUCTION

There are many theoretical calculations of the electron-excitation cross section for the $2s$-$2p$ transition of the lithium atom[1–15]; several authors have also calculated the polarization of the resulting $2p$-$2s$ radiation.[8,14–17] It is especially important to test the accuracy of the various theoretical approximations in the case of lithium, the simplest of the alkali metals. Previous measurements of this cross section,[18–20] however, disagree on the magnitude and energy dependence of the cross section, and are limited to collision energies below 80 eV. The polarization of electron-excited lithium resonance radiation has also been measured only at low energy.[21] A further measurement of both quantities for collision energy ranging from the excitation threshold into the Born regime is desirable; such data could be accurately normalized to Born theory at high energy, then used to test the various calculations at lower energy.

We have measured the polarization and the relative optical excitation function of the lithium resonance line (6708 Å) over the energy range from threshold (1.85 eV) to 1400 eV. We used low-density crossed beams, thereby minimizing space-charge and optical-depth problems. In the energy range 400–1400 eV, our relative cross section converges to the Born energy dependence, allowing us to normalize the excitation function using the accurately known optical oscillator strength for this transition. This procedure gives us, with about 2% accuracy, the absolute cross section for excitation to the $2p$ level, including contributions from excitation to higher levels which subsequently decay via the $2p$ level. Using calculations[3] and previous measurements[19] of the excitation cross sections of the higher levels, we have estimated the cascade contribution. Subtracting this estimate from the total yields the cross section for the $2s$-$2p$ direct excitation, which we compare with the various theories.

II. MEASUREMENTS

We used the apparatus described in Refs. 22 and 23, in which a beam of atoms from an oven intersects an electron beam at right angles and the resonance radiation is detected in a cone along the third orthogonal axis. The potentials applied to the electron-gun elements are switched to provide a well-focused beam of electrons (divergence half-angle ≈ 0.08 rad) of appropriate current at any value of energy in the range 1.6–10 eV and at discrete values between 10 and 1400 eV. The $f/3$ detection optics uses a lens to make the rays parallel as the light passes through a linear polarization analyzer and an interference filter; then a second lens focuses the light onto the end of a light pipe leading to a cooled photomultiplier tube. Slits in the image plane of the second lens reject light coming from outside the source region, while the light pipe diffuses the signal radiation across a 1-cm² area of the photocathode and provides thermal insulation to the cooled phototube. The polarization analyzer is switched at 6-sec intervals, so that its polarization axis is alternately parallel to and perpendicular to the electron-beam axis, while a pair of gated counters records the detected photoelectrons for the two polarizer orientations.

Using this apparatus to examine the lithium resonance line (unresolved doublet), our procedure was to set the electron-beam energy, and then count the detected 6708-Å photons for 100 sec or longer while averaging the electron-beam current over that interval. The apparent polarization is then $(I_{\parallel} - I_{\perp})/(I_{\parallel} + I_{\perp})$, where $I_{\parallel}$ and $I_{\perp}$ are the two polarization components of the radiation intensity,

given by the corresponding count rates after background subtraction. (Various corrections to the observed quantities will be discussed later.) The cross section for producing 6708-Å photons propagating perpendicular to the electron beam is proportional to $I_{\parallel} + I_{\perp}$ divided by the current; this gives the relative apparent excitation function R_{90} (in the terminology of Moiseiwitsch and Smith,[1] p. 278) provided that the density of the lithium-atom beam, the overlap of the crossed beams, and the optical detection efficiency remain constant while the energy is varied. The total cross section for production of the resonance line R_T (optical excitation function) is proportional to $I_{\parallel} + 2I_{\perp}$ divided by the electron current.

Previous tests of our apparatus[22,23] and similar checks during the present experiment indicated that systematic shifts of the product of beam overlap and detection efficiency were less than 2% throughout our experiment and less than 1% for the data above 5 eV. The energy dependence of the relative optical excitation function was measured for a number of lithium-beam densities. In order to minimize uncertainties due to fluctuations of the lithium-beam density, the count rate divided by current was measured at a reference energy value at 10–20-min intervals. The apparent lithium-beam density, given by the count rate at fixed energy and current, usually changed less than 1% from one such observation to the next. Note that the polarization data, being essentially ratios of intensities at the same energy, were not affected by the systematic uncertainties mentioned above, and were insensitive to slow drifts because the polarization analyzer completed one cycle in about 12 sec.

In our experiment the lithium-atom beam was optically thin (density $\lesssim 5\times10^{9}$ atoms/cm^3), and the electron-beam current was small enough so that space-charge depression of the electron energy was negligible (less than $0.005E$). Despite the low densities of both beams, typical signals from the photomultiplier were 10^3–10^4 counts/sec for electron energies above 5 eV, while the background was about 40 counts/sec. Thus the data obtained by counting for 100 sec generally had less than 1% statistical uncertainty. Longer times were spent in the threshold region where the signal diminished because of the smaller cross section and less available current. For energy values above 2.1 eV, the data obtained by repeated measurements on one day had statistical uncertainties (1σ) of 0.5% or less. (This value applies both for the fractional uncertainty of the cross-section data and for the absolute uncertainty of the polarization data.) The observed fluctuations of data taken on different days, after different assemblies of the apparatus, and using different values of electron-beam current and atom-beam intensity, had a standard deviation of 0.8% or less. This was about 1.5 times the standard deviation that would be expected from the number of photoelectron counts in each data set, and reflects contributions from the other sources of uncertainty. Our results given in Table I are averages of data from four or more different days. For collision energies above 10 eV we took data only at the energy values given in the table; no structure was observed in the cross section or polarization in this region. Below 10 eV, where more rapid variations occurred, we took data at more than 100 different energy values, combining the results graphically.

The energy spread of the electron beam used in this experiment was about 0.25-eV full width at half-maximum at energies below 10 eV; it increased to 0.7 eV at energies above 60 eV, where the slow energy dependence of the data makes this energy spread inconsequential. The electron energy distribution at 1.8 eV is shown in Fig. 1. The energy of the electrons was measured by a retarding-potential energy analyzer.[22] This does not allow for contact-potential differences between the interaction chamber and the analyzer, so the results were checked by observing the $2p$ excitation threshold. The uncertainty of identifying the threshold was ±0.035 eV as explained in Sec. IV and Fig. 1. The electron energy inferred from threshold observation was typically 0.2 eV greater than that measured by the analyzer. This difference depended on the history of the apparatus but did not vary during a given data run. During previous work using our apparatus[22] it was noted that the contact-potential difference increased steadily with exposure of the interaction chamber to the alkali-metal beam. In the present experiment this time variation was prevented by heating the chamber walls to about 100 °C throughout the measurements. This temperature difference between interaction chamber and analyzer may have contributed to the observed 0.2-eV contact-potential difference.

The lithium oven was operated at about 500 °C, with the beam-forming effuser at a higher temperature to prevent clogging and to reduce the concentration of the lithium dimer in the beam. Using data from Lapp and Harris,[24] we estimated this dimer concentration to be less than 0.3% and therefore neglected it.

A. Corrections

Corrections to our data arising from instrumental effects will now be discussed. These correc-

TABLE I. Experimental results.

Energy (eV) [a]	Lithium-6 polarization (%)	R_{90} [b]	$Q_T(\pi a_0^2)$ [c]	$Q_D(\pi a_0^2)$ [d]
2.10(1) [e]	28.2(6)	1.12(2)	14.8(3)	14.8
2.30(1)	26.8(4)	1.49(3)	20.0(4)	20.0
2.70(2)	24.4(4)	2.27(4)	30.6(6)	30.6
3.10(2)	22.1(4)	2.72(4)	37.1(6)	37.1
3.50(2)	17.8(3)	2.94(5)	40.6(7)	40.6
4.00(3)	15.4(3)	3.18(5)	44.3(7)	44.1
5.00(3)	12.7(3)	3.42(4)	48.0(6)	46.7
6.60(5)	9.6(2)	3.45(3)	48.9(5)	46.8
8.40(5)	7.2(3)	3.35(3)	47.9(5)	45.8
10.81(12)	4.8(2)	3.20(3)	46.1(4)	44.3
15.64(12)	1.85(20)	2.87(2)	41.7(3)	40.2
23.78(12)	−1.19(16)	2.43(2)	35.7(3)	34.5
38.60(12)	−4.02(14)	1.880(11)	27.84(16)	26.93
63.56(12)	−6.46(14)	1.372(7)	20.46(11)	19.79
99.15(15)	−8.22(14)	1.000(5)	14.99(8)	14.51
149.4(2)	−9.56(21)	0.7322(42)	11.025(64)	10.67
249.9(2)	−10.93(25)	0.4851(28)	7.334(43)	7.089
400.5(3)	−11.96(25)	0.3282(19)	4.978(29)	4.808
601.4(3)	−12.71(25)	0.2331(14)	3.543(21)	3.421
802.3(4)	−13.13(25)	0.1817(11)	2.765(16)	2.669
1102.8(6)	−13.54(26)	0.1381(8)	2.104(12)	2.030
1404.2(8)	−13.89(26)	0.1119(6)	1.706(10)	1.645

[a] Besides the given uncertainties, an additive uncertainty of ±0.035 eV affects the entire energy scale; see Fig. 1.

[b] R_{90} is the measured relative apparent excitation function. (See Ref. 1, p. 278 for an explanation of terminology.)

[c] Q_T is the corrected normalized optical excitation function (cascade included). The uncertainty in this column does not include ~±2% uncertainty in the normalization of the cross-section scale.

[d] Q_D is the direct excitation cross section obtained from Q_T using measurements of Ref. 19 to estimate cascade.

[e] Number in parentheses gives the uncertainty in the last places of the preceding number. The uncertainties represent roughly 2σ including estimated systematic uncertainties.

tions are small and introduce little uncertainty beyond that of the primary data.

The principal transmittances of our polarization analyzer had the ratio $k_{\parallel}/k_{\perp} \approx 4000$ for 6708-Å light; no correction was made for the nonzero $k_{\perp}$. Immediately behind this polarizer was a quarter-wave retarder which circularly polarized the emerging light so that the efficiency of the rest of the detection system did not vary with orientation of the polarizer. The instrumental polarization was $(0.1 \pm 0.1)\%$; this amount has been subtracted from our polarization data.

We wish to know the polarization of electron-excited atomic radiation emitted at right angles to the path of the incident electron, whereas the trajectories in our electron beam fill a finite solid angle, and the detection system, placed at right angles to the electron-beam axis, subtends a finite solid angle also. In our apparatus the half-angles of the optical detection cone and of the electron-beam divergence were $\psi_m = 0.165$ rad and $\theta_m = 0.08 \pm 0.02$ rad, respectively. Because these angles are small, the correction can be made,[23] to a good approximation, by multiplying the observed polarization fractions P by

$$1 + \tfrac{1}{4}\psi_m^2(1-P) + \tfrac{1}{4}\theta_m^2(3-P).$$

The correction terms amount to 0.014 at most, with 0.003 uncertainty.

The relative apparent excitation function $R_{90} \propto I_{\parallel} + I_{\perp}$ has a different energy dependence from the total optical excitation function $R_T \propto I_{\parallel} + 2I_{\perp}$ because the radiation distribution is anisotropic. The correction factor for this effect has been obtained by Percival and Seaton[25] and previously evaluated for the geometry of our apparatus in terms of the polarization P.[23] Using that result, we obtain the relative optical excitation function R_T (including cascade contribution) from R_{90} as follows:

$$R_T = R_{90}(1 - \tfrac{1}{3}P)/[1 - \tfrac{1}{4}(\psi_m^2 + \theta_m^2)P], \quad (1)$$

where P is the polarization including only the corrections mentioned above. The uncertainty of P at this stage is typically less than 0.003, so the uncertainty of R_T is almost entirely due to uncertainty of the measured R_{90}.

A further correction to the polarization arises because of radiation entrapment. When lithium-6 atoms absorb and reradiate the resonance line, about 75% of the initial polarization is lost in each successive scattering event.[26] We worked at low optical depth to minimize this radiation entrapment effect. (The lithium-beam density, estimated from the cross section and signals, was typically 5×10^9 cm^{-3}.) When we increased the density of the lithium beam from ~2×10^9 to ~9×10^9 cm^{-3} we observed about a 3% fractional decrease of the polarization, which was attributed to radiation entrapment. (No density dependence was found in the cross-section data.) Previous investigations[22] have verified the expectation that a small fractional depolarization depends linearly on the density, so we have corrected our polarization data for radiation entrapment by extrapolating linearly to zero atom-beam density. This correction amounted to 2% of the polarization for the typical density of 5×10^9 cm^{-3}, and introduced an uncertainty of about 0.8% of the polarization ($\pm0.008P$).

Finally, we must take into account the isotopic composition of our lithium sample, since the resonance lines of ^{6}Li, ^{7}Li have different polarizations P_6, P_7 when excited by electron impact.[25] From the theory of Flower and Seaton[27] we find that the ratio of these polarizations is nearly independent of energy:

$$P_7/P_6=\beta[(3-P_7)/(3-P_6)], \tag{2}$$

where the factor in brackets, which ranges from 1.06 to 0.97, contains the only energy dependence. Here we have defined $\beta\equiv[9\alpha(^7\mathrm{Li})-2]/[9\alpha(^6\mathrm{Li})-2]$, where the values of α are dependent on the hyperfine structure and natural lifetime of the $2p$ level, and were calculated by Flower and Seaton.[27] Their results, based on experimental data of Brog, Eck, and Weider,[28] are $\alpha(^6\mathrm{Li})=0.413$, $\alpha(^7\mathrm{Li})=0.326$, yielding $\beta=0.544$. Next, using Percival and Seaton's expression for the anisotropy of the radiation,[25] we find that P_6 can be obtained from our data as follows:

$$P_6=\frac{P[1+C(3-P_6)/(3-P_7)]}{1+C\beta}=P(1.022\pm0.002). \tag{3}$$

Here $C=0.045$ is the ratio of number density of ^{7}Li to ^{6}Li in our enriched isotope sample and in the atom beam, P is the measured polarization, and the ±0.2% variation of the correction factor, due to the variation of P, can be taken into account by one iteration if desired. Note that one could also derive the polarization for ^{7}Li from our corrected results, using Eq. (2), with accuracy depending on β as well as our data.

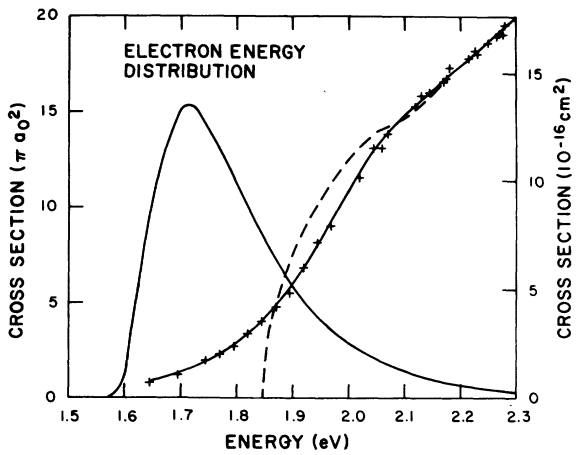

FIG. 1. Normalized total-cross-section data (plus symbols) near threshold, and the experimental electron energy distribution shown with centroid at 1.8 eV. Our best estimate of the actual cross section is given by the dashed curve which, when convolved with the electron energy distribution, yields the solid line through the data. The point identified as the threshold, which defines the value 1.847 eV on our energy scale, has an uncertainty of ±0.035 eV because of uncertainty in the energy-distribution and cross-section data.

III. RESULTS

Table I gives the results of our measurements. In column 1 we list the mean energy of the electrons, ascertained by the energy analyzer and by the appearance of the excitation threshold. The analyzer was used only intermittently, so variations of the cathode-potential drop and of the power-supply voltages caused the listed energy uncertainties. An additive uncertainty of ±0.035 eV to the entire energy scale, due to the uncertainty of identifying the threshold (see Fig. 1), is not included in the table.

Column 2 contains the polarization of the lithium-6 resonance doublet excited by electron impact and observed at right angles to the collision axis. The values are corrected for radiation entrapment, instrumental polarization, isotope mixture, and solid angles of observation, as described in Sec. II, but we have not attempted to remove the cascade contribution to the polarization. The uncertainties represent roughly $2\sigma_{\mathrm{mean}}$ for the statistical scatter, combined with the uncertainties of the corrections.

Column 3 gives the relative apparent excitation function (including cascade) observed at right angles to the electron beam. The uncertainty in this

column is primarily due to systematic uncertainty of the beam overlap and detection uniformity, but includes $2\sigma_{mean}$ for the statistical scatter. The absolute values for the optical excitation function, given in column 4, were obtained by correcting the apparent excitation function for radiation anisotropy using the observed polarization [Eq. (1)] and by normalizing to Born theory at high energy.

A. Normalization and cascade

The normalization will now be discussed; Fig. 2 illustrates the method. The high-energy form of the Born cross section Q_B for an optically allowed transition[29] can be written

$$Q_B E \to A + 1705(f/\Delta)\log_{10}(\tfrac{1}{10}E) \qquad (4)$$

if Q_B is expressed in units of πa_0^2, E is the impact energy in eV, $\Delta = 1.847$ is the excitation energy in eV, and f the optical oscillator strength. From Refs. 28, 30, 31, and references cited in the latter, we take $f = 0.750 \pm 1\%$. Three independent Born calculations of the lithium $2s$-$2p$ direct excitation[2,4,10] indicate that the high-energy form is already reached at 10 eV and that the Born cross section at 10 eV is $(82.3 \pm 2)\pi a_0^2$. This fixes $A = 823$ in Eq. (4), and $Q_B = 1.645 \pm 1\%$ at $E = 1404$.

Next, we must estimate the cascade contribution to our experimental total cross section. Using transition probabilities from Wiese *et al.*[31] we find that the following amounts of higher-level populations will decay via the $2p$ level: $3s$ and $3d$ (100%), $3p$ (76%), $4s$ (90%), $4p$ (46%), $4d$ (94%), $5s$ (80%), $5p$ (40%), and $5d$ (90%). Born cross sections for excitation of these levels are available for $E < 200$ eV.[3,10] Contributions from higher levels should be less than 1% of the $2p$ cross section and are neglected. Extrapolating the s, d cross sections of Ref. 3 as E^{-1} and the p's as was done for the resonance transition above, we find that the total cascade Q_{BC} in Born's approximation is

$$Q_{BC}E \approx 110 + 3.2\log_{10}E \quad \text{for } E > 100 \text{ eV}.$$

This is plotted in Fig. 2. These calculations imply that at 1404 eV the cascade is $0.085\pi a_0^2$ or 5% of the $2p$ cross section, and that 40% of this cascade is due to the $3d$ and 25% due to the $3s$ excitation.

Excitation cross sections for most of these levels, with estimated uncertainties of (35–40)%, have been given by Aleksakhin and Zapesochnyi,[19] based on absolute measurements of spectral-line intensities in a crossed-beam experiment. Their results were given up to 30 eV; we have plotted the resulting total cascade in Fig. 2 and have extrapolated it as a straight line up to 1404 eV. This extrapolation is somewhat arbitrary but cannot go too far wrong if we assume that the Born values at high energy constitute an upper limit (actually, we extrapolated separately for each level; only the $3d$ approached its Born value near 1404 eV). Our experimental total cross section has been normalized to the sum of this extrapolated experimental cascade plus the Born $2p$ cross section. As shown in Fig. 2, our data converge to the Born energy dependence above 400 eV. If we had used the Born cross sections for the cascade, our final cross-section scale would have been 1.4% larger and the convergence of our data to Born theory would have been slower. In view of this and the uncertainty of the direct Born cross section, we estimate that the uncertainty of the normalization is about 2%; this generally exceeds the uncertainty of our relative optical excitation function, and is not included in the uncertainties given for Q_T in Table I, since it is a correlated uncertainty which scales all points equally.

The last column of Table I gives the estimated cross section Q_D for $2s$-$2p$ direct excitation, obtained from Q_T by subtracting the experimental

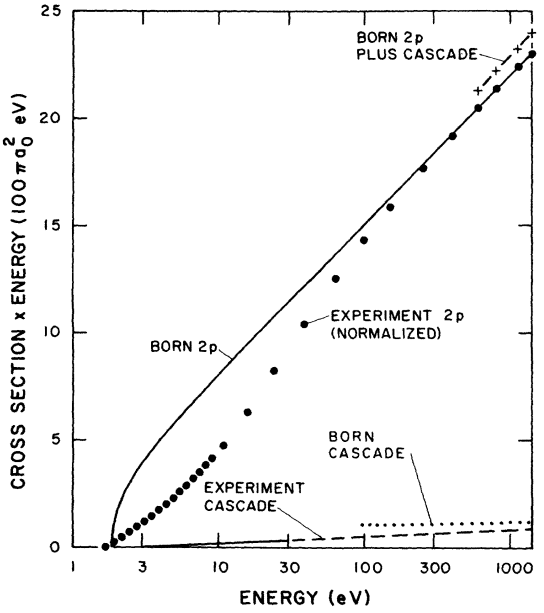

FIG. 2. Method of normalizing the relative cross-section measurement. The Born $2p$ excitation cross section is constructed using Refs. 2, 4, 10, 28, 30, and 31. The cascade cross section is estimated from measurements by Aleksakhin and Zapesochnyi (Ref. 19), extrapolated above 30 eV. (The cascade value calculated from Born cross sections of Refs. 3 and 10 is also shown for comparison.) The total cross section Q_T of the present experiment (plus symbols) is normalized to the sum of the direct Born plus experimental cascade cross sections at 1404 eV. The experimental direct excitation cross section (dots), obtained by subtracting cascade from Q_T, is thereby normalized to Born theory at 1404 eV.

cascade values of Ref. 19, extrapolated as described above. Below 3.3 eV, the uncertainty of Q_D is the same as that of Q_T; above, it is primarily due to uncertainty of the cascade. Note that the same cascade estimate subtracted here was added during the normalization procedure, so Q_D at 1404 eV is defined to be equal to the Born value regardless of the cascade. It is only the difference in energy dependence of the total versus cascade portion that contributes a net uncertainty to Q_D at lower energy.[32]

IV. DISCUSSION

The purpose of this experiment was to measure the relative optical excitation function and the polarization of the unresolved resonance doublet of lithium. Using data from another experiment to estimate cascade contributions and normalizing to the Born cross section at 750 times the threshold energy, we determined the absolute cross sections shown in Figs. 1 and 3. The threshold behavior of the cross section is obscured by the tail of the electron energy distribution, as shown in Fig. 1. Because of uncertainty in the energy-distribution and cross-section data, there was no unique deconvolution; several possible forms for the threshold behavior were found which, when convolved with the electron energy distribution, were seen to be compatible with our cross-section data. The most plausible of these, shown in Fig. 1, has energy dependence $(E-E_0)^{1/2}$ for 0.15 eV above threshold (E_0), in agreement with the theoretical threshold behavior.[33] This form is our best estimate of the cross section below 2.1 eV. The other possibilities consistent with our data reached zero cross section at different points along the energy axis, indicating the ±0.035-eV range of uncertainty in our energy scale.

The normalized optical excitation function and the direct $2p$ excitation cross section are shown in Fig. 3. The data points plotted below 4.5 eV in Fig. 3(b) represent averages of several days measurements. Some degree of structure is found near the $n=3$ excitation thresholds and below 2.5 eV, although the interpretation of the data below 2.1 eV is uncertain to the extent indicated earlier. Close-coupling calculations by Moores and Norcross[34] have shown an inflection point about 0.25 eV above the threshold of the sodium $3s$-$3p$ excitation function, and Hafner[35] has observed that feature using 50-meV energy resolution. Thus it appears plausible that a similar feature may occur in the lithium $2s$-$2p$ excitation function, which could explain the slight upward curvature discernible in our data between 2.1 and 2.5 eV. Our allowance for cascade below 5 eV was no doubt in-

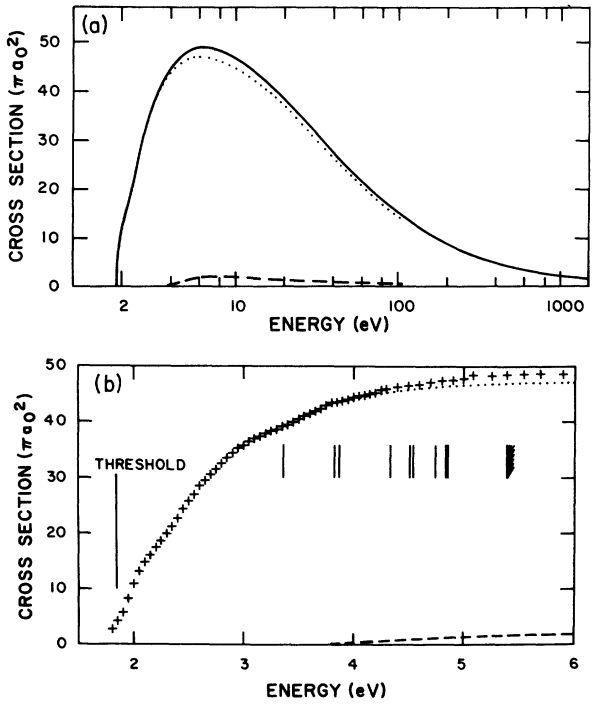

FIG. 3. Normalized total cross section Q_T for excitation of the lithium 6708-Å line as a function of incident electron energy [(solid line in 3a, data points in 3b)]. The total cascade contribution to the cross section (dashes) is estimated from measurements of Ref. 19 and an appropriate extrapolation described in the text. Subtracting the cascade estimate from Q_T yields the direct excitation cross section Q_D (dotted line) for the $2p$ level. Vertical lines indicate excitation thresholds of the higher levels which produce most of the cascade.

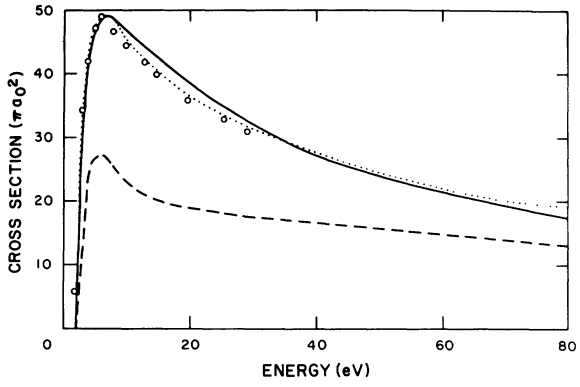

FIG. 4. Normalized optical excitation function Q_T (solid line) compared with previous experimental results. Hughes and Hendrickson (Ref. 18), open circles; Aleksakhin, Zapesochnyi, and Shpenik (Refs. 19 and 20), dashed curve. The dotted curve shows relative data of Hafner and Kleinpoppen (Ref. 21) which we have normalized to our results at the peak of the cross section for comparison of shape. All of these measurements include cascade.

adequate since the cross sections of Ref. 19 for the higher levels were measured with energy resolution of 1.0–1.5 eV and therefore show slow onsets. According to the latter measurements the peak of the cascade is about $2.2\pi a_0^2$ at 7.0 eV, which gives 4.5% of our measured total $2p$-$2s$ fluorescence. This is much smaller than the peak cascade contribution to the sodium resonance line, estimated at 16% in Ref. 22.

Our normalized optical excitation function is compared with previous experimental results in Fig. 4. Hughes and Hendrickson[18] measured a relative optical excitation function and normalized it using a theoretical approximation and sodium cross sections. From the data given by Hafner and Kleinpoppen[21] in connection with their polarization measurements, one can also construct a relative optical excitation function (see Fig. 93 of Ref. 1). For the comparison in Fig. 4 we have normalized this to our data at the peak. The absolute optical excitation function measured by Aleksakhin, Zapesochnyi, and Shpenik[19,20] has markedly different energy dependence as well as over-all magnitude; its value is 55% of ours at the peak and 75% at 80 eV. The uncertainty of their result was estimated at (35–40)%, but the disagreement with our data is larger than that over most of the energy range. One can only speculate on possible causes of the discrepancy. Their experiment, like all the others, used crossed beams, but the density of their atom beam was about 100 times larger than ours. If the atom beam was optically thick, one might suspect systematic distortions due to energy dependence of the electron-beam geometry, but details concerning this were not given. Our data and those of Ref. 21 have been corrected for anisotropy of the radiation distribution as explained in Sec. II. For the data of Refs. 18 and 20 this was not done, but the appropriate correction would have been within ±2% for energies above 6 eV.

Our normalized direct excitation cross section for the $2s$-$2p$ transition is compared with theoretical calculations in Fig. 5. The first Born approximation is known to overestimate cross sections near threshold; for this transition we find that at 34 times the threshold energy the Born cross section is still 10% too large, and 2% accuracy is reached only for energies more than 100 times threshold. Similarly slow convergence has been observed for excitation of the Na and Ca resonance lines[22,23] and of the Ca^+ and Ba^+ resonance lines.[36,37]

Several of the theories in Fig. 5 are basically modifications of the Born approximation. Felden and Felden calculated that the Born results between 5 and 30 eV are reduced (1–9)% when exchange is included via Ochkur's approximation.[10] Tripathi, Mathur, and Joshi achieved a greater improvement of the Born cross section below 50 eV by using polarized atomic wave functions as well as the Ochkur approximation.[6] McCavert and Rudge have pursued an approximation both simpler and apparently more accurate than the Born-Oppenheimer approximation, giving several versions of results.[8,9] The one plotted in Fig. 5 is from Table I of the more recent paper; its value is only 20% larger than our data from 5 to 9 eV but grows worse at lower energy, as do the other versions.

Two calculations using the Glauber approximation[7,12] have given conflicting results; Walters[12]

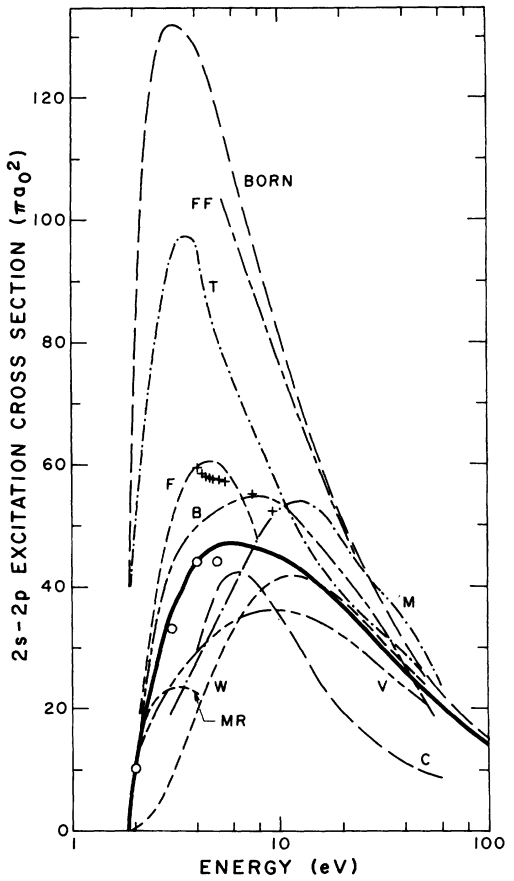

FIG. 5. Comparison of normalized direct $2s$-$2p$ excitation cross section (heavy solid line) with results of theoretical calculations; the approximations used are given in Sec. IV. Calculation by Vainshtein *et al.* (Ref. 2), V; Mathur *et al.* (Ref. 5), C; Tripathi *et al.* (Ref. 6), T; Mathur *et al.* (Ref. 7), M; McCavert and Rudge (Ref. 9), plus symbols; Felden and Felden (Ref. 10), FF; Walters (Ref. 12), W; Karule and Peterkop (Ref. 4), open circles; Marriott and Rotenberg (Ref. 13), MR; Burke and Taylor (Ref. 14), B; Feautrier (Ref. 15), F. The results of Refs. 13–15 are reproduced here less accurately than the others because of uncertainty of retrieving information from the original graphs.

has cast doubt on the former calculation. According to both calculations the cross section has a peak near 12 eV and becomes much smaller than our data at lower energy, but the cross section due to Walters agrees with our data above 15 eV. For the calculation in Ref. 5, Mathur, Tripathi, and Joshi used a classical impulse approximation. The results we have taken from Ref. 2 were obtained using the Vainshtein-Presnyakov-Sobelman approximation, which is discussed in Ref. 1, p. 253.

The remaining calculations shown in Fig. 5 are $2s$-$2p$ close-coupling calculations. The earliest of these, due to Karule and Peterkop,[4] agrees best with our low-energy data: two of the four calculated points lie on our curve, two are (5–8)% lower. The authors used Hartree-Fock wave functions and included exchange with the optical electron but not with the core. Marriott and Rotenberg[13] calculated wave functions for the valence electron in a scaled Thomas-Fermi core potential. Exchange with the optical electron was included. Burke and Taylor,[14] using Hartree-Fock wave functions and including exchange, obtained a cross section larger than our data by (10–25)% in the range 2–5 eV with the agreement improving somewhat at higher energy. The Feautrier[15] modification of this approach, attempting to take into account the full dipole polarizability of the atomic states, yields an even larger cross section, (30–45)% above our data in the range 2–5 eV. We see here a sequence in which agreement with experiment grows worse as the calculations become more sophisticated.

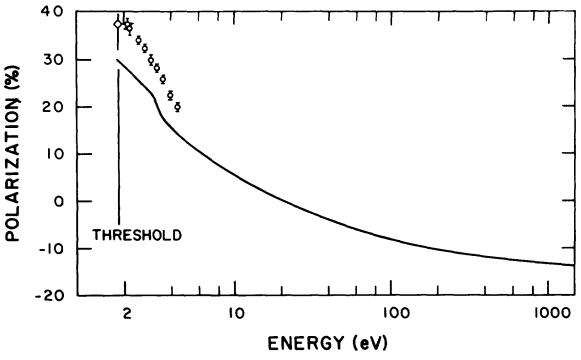

FIG. 6. Measured polarization of electron-excited 6708-Å radiation from lithium-6 atoms (solid line). The data are corrected for instrumental effects, but cascade contributions have not been removed. The diamond at 37.5% polarization marks the theoretical threshold limit calculated by Flower and Seaton (Ref. 27) which is not observed because of the experimental electron energy spread (given in Fig. 1). Open circles represent measurements by Hafner and Kleinpoppen (Ref. 21), whose data we have treated as follows: Energy values have been reckoned from the cross-section threshold given (since the numerical scale given is shifted as the authors point out), and the polarizations have been corrected for the given isotopic composition by the same method (Sec. II, last paragraph) used in the present work.

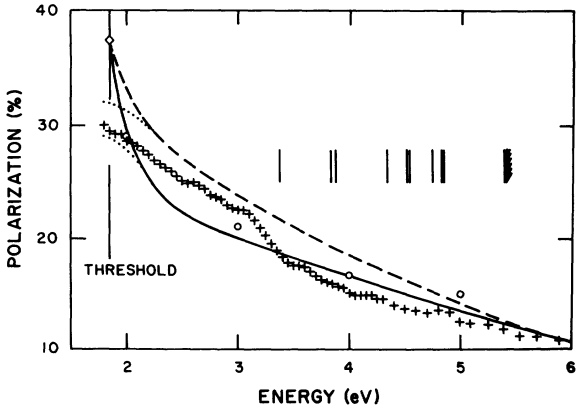

FIG. 7. Comparison of experimental polarization data (plus symbols) with results of $2s$-$2p$ close-coupling calculations. Karule (Ref. 16), open circles; Burke and Taylor (Ref. 14), solid curve; Feautrier (Ref. 15), dashed curve. The theoretical polarization limit at threshold, calculated by Flower and Seaton (Ref. 27), is marked with a diamond. The dotted lines merging with two theoretical curves near threshold represent convolutions of the theoretical results with the energy distribution of the experimental electron beam (see Fig. 1). The experimental data have not been corrected for cascade contributions. The energies of cascade-producing states are indicated.

Our measured polarizations are shown in Fig. 6, where they are compared with the previously measured values.[21] In Fig. 7 our low-energy polarization data are compared with results of close-cou-

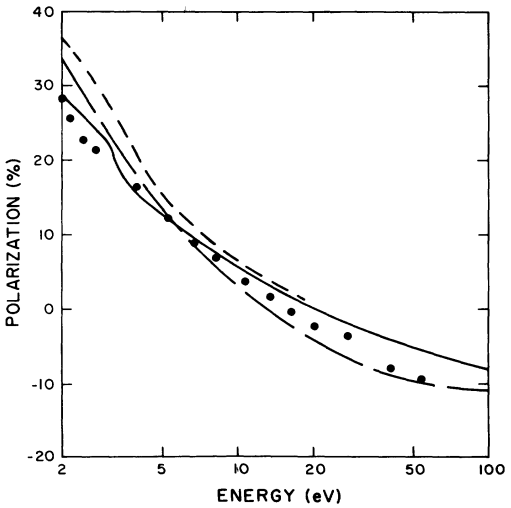

FIG. 8. Comparison of measured polarization (solid line) with theoretical results by McCavert and Rudge (Ref. 8), short dashed curve; Tripathi *et al.* (Ref. 17), long dashed curve; Burke and Taylor (Ref. 14 and private communication), dots.

pling calculations.[14-16] All three calculations indicate that the polarization decreases sharply within 0.15 eV above threshold. The results of convolving the experimental energy distribution with the theoretical polarizations from Refs. 14 and 15, using the measured apparent cross section R_{90} as a weight function, are given by dotted curves in Fig. 7. These indicate that our 0.25-eV energy resolution (see Fig. 1) was insufficient to observe the threshold polarization value calculated by Flower and Seaton.[27] The scatter in the data above 4.5 eV in Fig. 7 is considered to be statistical, since individual data are plotted. Below 4.5 eV each plotted point is an average of several days measurements and the resulting scatter is less. Because of the uncertainty of the cascade cross sections we have not estimated the cascade contribution to the polarization. The polarization calculations which have been carried out to higher energies are compared with our data in Fig. 8.

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†Staff member, Laboratory Astrophysics Division, National Bureau of Standards, and Professor Adjoint, Department of Physics and Astrophysics, University of Colorado, Boulder, Colo.

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