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Absolute total cross sections for the scattering of low-energy electrons by lithium atoms

B. Jaduszliwer, A. Tino, and B. Bederson
Department of Physics, New York University, New York, New York 10003

T. M. Miller
Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma 73019

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Absolute (i.e., unnormalized) total cross sections for the scattering of electrons by lithium atoms between 2 and 10 eV have been measured, using the atomic-recoil technique in the scattering-out mode. In this energy range, elastic scattering and impact excitation of the 2*P* state are the dominant processes. The results best fit the sum of the modified polarized-orbitals elastic scattering cross-section calculations of Bhatia, Temkin, Silver, and Sullivan [Phys. Rev. A 18, 1935 (1978)], and the close-coupling impact-excitation cross-section results of Burke and Taylor [J. Phys. B 2, 869 (1969)]. Agreement over the entire energy range is at the 10% level or better.

I. INTRODUCTION

In the field of low-energy electron-atom collisions, all the alkali elements, particularly sodium and potassium, have been extensively studied. The exception is lithium. Indeed, very few such measurements have been reported for lithium, despite its attractiveness as a testing ground for collision theory. This sparcity of experimental work can doubtlessly be attributed to its generally less tractable nature, as compared to the other alkalis. Its lower vapor pressure requires hotter sources, the hot lithium vapor is very corrosive, and lithium atoms are more difficult to detect than the other alkalis. Perel *et al.*[1] measured electron-lithium total cross sections between 0.25 and 10.0 eV, relative to those of potassium. An attempt to measure the absolute total scattering cross sections by the recoil technique at the New York University Atomic Beams laboratory yielded some preliminary results,[2,3] but the lack of a direct measurement of the average atomic-beam velocity (essential for the recoil technique) cast some doubt on the validity of those results. Elastic and impact-excitation differential cross sections have been reported by Williams *et al.*,[4] and optical excitation-function measurements for the 2*S*-2*P* transition have been performed by Hughes and Hendrickson,[5] Aleksakhin and Zapesochnyi,[6] Hafner and Kleinpoppen,[7] and Leep and Gallagher.[8]

Several approaches have been followed by theorists to study the electron-lithium system. Inokuti and McDowell[9] (Born approximation), Sarkar *et al.*[10] (polarized Glauber) and Walters[11] (frozen-core Glauber) have extended their total cross-section calculations to fairly low energies, where such high-energy approximations cannot be expected to yield reliable results. Sinfailam and Nesbet[12] calculated variational phase shifts below the 2*P* threshold.

The few-state close-coupling method has been very successful in describing low-energy electron collisions with potassium and sodium atoms. Lithium is, of course, quite similar to sodium and potassium from the point of view of electron configuration, but on the other hand there are enough differences to leave the extension of the close-coupling approach to lithium a tantalizing open question. (As an example of those differences, while the oscillator strength of the resonant transition for all the heavier alkalis is near unity, it is only 0.75 for lithium.) Two-state close-coupling calculations for the electron-lithium system have been performed by Karule and Peterkop[13] (below and above the 2*P* threshold, respectively), by Burke and Taylor,[14] and, at very low energies, by Norcross.[15]

The other approach that has been followed to study electron-lithium collisions is the polarized-orbitals method. Burke[16] has shown that this method, in its original form,[17] where the polarization potential is determined using perturbation theory, breaks down for highly polarizable systems like the alkali atoms, giving an overly attractive potential. Bui and Stauffer[18] studied the elastic scattering of electrons by lithium following the "classic" polarized-orbitals method, with not quite satisfactory results. Stone[19] determined the polarization potential variationally, rather than by perturbation theory, and Vo Ky Lan[20] used Stone's method in an otherwise conventional polarized-orbitals calculation. Bhatia *et al.*[21] modified the polarized-orbitals method by demanding that the polarized orbital yield the correct value of atomic polarizability, the correct electron affinity of lithium, and the proper number of nodes of the zero-energy scattered wave. In this way, they obtained phase shifts for elastic electron-lithium scattering which are qualitatively similar to, but still differing from, the close-coupling calculations.[14]

This paper reports new measurements of the total electron-lithium scattering cross sections between 2 and 10 eV. The experimental technique is discussed in Sec. II. The results are presented, and compared with close-coupling[14] and polarized-orbitals[21] calculations in Sec. III.

II. EXPERIMENTAL METHOD

Rubin, Perel, and Bederson[22] developed the atomic-recoil technique for the study of low-energy electron-atom collisions. The main difference between this and other experimental techniques is that observations are made on the scattered atoms downstream from the collision region, rather than on the electrons. The atomic-recoil angles are much smaller than the electron scattering angles, but because the angular resolving power for the atomic beam is quite high, they are sufficiently large to allow not only the determination of total cross sections by measuring the attenuation of the atomic beam when cross fired by electrons ("scattering-out" experiment), but also the study of differential scattering by selectively collecting atoms recoiled away from the beam axis ("scattering-in" experiment).

We will discuss the theory of the recoil method very briefly. A more complete analysis is given by Rubin *et al.*[23] Although our data were taken in the scattering-out mode, which is appropriate for studying total cross sections, differential scattering data were taken to measure the lithium beam speed, so that a discussion of scattering in is appropriate here. In Fig. 1, θ and ϕ are the electron-polar and azimuthal scattering angles, ψ is the atomic-recoil angle in the horizontal plane containing the electron and atomic beams, and χ is the atomic-recoil angle in the vertical plane. In the present experiment the detector is capable of translation in the horizontal, i.e., ψ direction. It is easy to show that

$$\psi = \alpha - \beta \cos\theta \ , \tag{1}$$

$$\chi = \beta \sin\theta \sin\phi \ , \tag{2}$$

where $\alpha = mv/MV$ and $\beta = mv'/MV$. mv and mv' are the magnitudes of the electron momenta before and after the collision, respectively, and MV is the magnitude of the atomic momentum, assumed unchanged in the collision. It is assumed that α and β are small, although this restriction is not relevant to the case of scattering-out experiments.

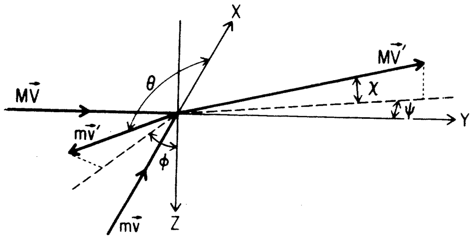

FIG. 1. Atomic-recoil and scattering angles. The electron and atom beams define the x and y axes, the z axis completes a right-hand set. $M\vec{V}$ and $m\vec{v}$ are the atomic and electron momenta before the collision; $M\vec{V}'$ and $m\vec{v}'$ are the respective momenta after the collision. The usual electron-polar and azimuthal scattering angles θ and ϕ are defined with respect to the x and z axes, respectively. The atomic-recoil angles are ψ and χ. ψ is defined in the xy (horizontal) plane and χ in the vertical plane containing $M\vec{V}'$.

Equation (1) gives a relationship between the electron scattering angle θ and the atomic-recoil angle ψ, independent of χ. However, different values of ϕ will lead to different values of χ, as described in Eq. (2). If the angle subtended by the detector height, as seen from the interaction region, is larger than 2α, then the detector will collect all atoms recoiled by a given ψ regardless of χ, thus effectively integrating over ϕ. But if that angle is smaller than 2α, then only a fraction of the atoms recoiled by a given ψ will be collected, and, furthermore, that fraction will be strongly dependent on θ, as shown by Eq. (2). Because of this, an "azimuthal form factor[23]" will be folded in the observed angular distribution of recoiled atoms as a function of ψ. This azimuthal form factor, as discussed by Rubin *et al.*,[23] peaks very strongly in the forward (that is to say, $\theta = 0$) direction.

Figure 2 schematically shows our experimental arrangement. The lithium-beam source is an effusive oven constructed from standard stainless-steel pipe fixtures and surrounded by a helical tantalum filament mounted on insulating posts. It reaches a temperature of about 700 °C by a combination of radiative and electron bombardment heating. The oven is normally offset from the

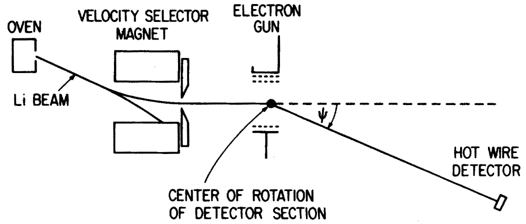

FIG. 2. Schematics of the experimental arrangement.

beam axis; a Stern-Gerlach magnet selects, in high fields, one of the two m_J states present in the lithium beam, acting in this experiment as a velocity filter ($\Delta V/V \cong 0.08$).[24]

The electron gun is similar to the one described by Collins *et al.*[25] The electron beam is shaped like a ribbon, about 25 mm in width and 0.8 mm in height. The energy width of the electron beam is 0.43-eV full width at half maximum (FWHM). The mean electron energy is corrected for space charge and contact potentials. The electron current through the interaction region is monitored by a digital microammeter. In this experiment we have used currents between 150 and 500 μA.

After passing through the interaction region the atoms are surface ionized on a hot wire (92 at.% Pt and 8 at.% W).[26] The ions are mass analyzed by a 60° sector magnet and detected by a Channeltron electron multiplier operated in the current mode.

The distance between the interaction region and detector is $L = 81.3$ cm. This portion of the apparatus can rotate about the center of the interaction region in the horizontal plane. The angular distribution of recoiled atoms as a function of ψ can be determined by performing a scattering-in experiment. This is accomplished by chopping the electron beam at 4 Hz and measuring the magnitude of the 4-Hz modulation in the recoiled-atom current, using phase-sensitive techniques.

To measure a total cross section, the detector is kept on the beam axis, and a scattering-out experiment is performed, measuring the difference between the atom current I_0, which reaches the detector when the electron beam is turned off, and I, which reaches the detector when the electron beam is turned on. The total cross section σ_0 is related to the other parameters of the experiment by

$$\sigma_0 = \frac{I_0 - I}{I_0} \frac{Vh}{I_e} , \tag{3}$$

where h is the height of the atomic beam, V is the mean speed of the atoms, and I_e is the electron current through the interaction region (electrons/sec). It is important to stress that in this technique it is not necessary to measure absolute atomic-beam densities or fluxes. The only requirements that must be satisfied for the method to yield absolute cross sections are that the atomic detector signal must be linear with beam intensity, and that the measurement of the electron current passing through the interaction volume must be absolute. This, in turn, means that the height of the electron beam must be smaller than the height of the atomic beam. The angular resolving power of this experiment is briefly discussed in Sec. III.

Scattering-out experiments are performed by connecting the detector output to an electrometer; the electrometer output is fed to the analog-to-digital converter of a DECLAB-03 computer which is programmed to sample repetitively the beam signal with the electron gun off, turn the gun on and sample again, then turn the gun off and start the cycle anew. At the end of a preset number of cycles the data accumulation is stopped, and the computer performs a least-squares linear fit to both halves of the data, the first half with the electron gun off and the second half with the electron gun on. From the results of these fits $(I_0 - I)/I_0$ is computed, and a value for σ_0 is obtained using Eq. (3).

The use of Eq. (3) explicitly requires the measurement of the atomic-beam mean speed. This is accomplished by a technique described by Rubin *et al.*[23] Electrons which are inelastically scattered in the forward direction ($\theta = 0$) result in recoiled atoms for which $\psi = \alpha - \beta$ and $\chi = 0$. These atoms have a high azimuthal form factor, that is to say, they are detected with much greater efficiency than those for which $\theta > 0$, where χ is not necessarily zero. Thus, these $\theta = 0$ inelastically scattered electrons give rise to a peak in the observed atomic angular distribution, as shown in Fig. 3. The displacement s of the forward inelastic scattering peak relative to the atomic-beam axis is

$$s = \frac{(2m)^{1/2}}{M} \frac{L}{V} [E^{1/2} - (E - E^*)^{1/2}] , \tag{4}$$

where E is the electron energy, and E^* is the ex-

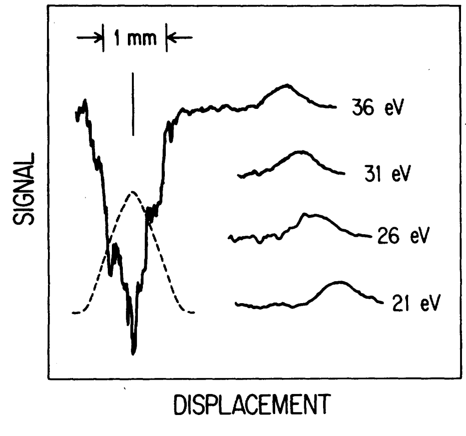

FIG. 3. Atomic-beam ac-modulated signal with the detector moving parallel to the electron beam at four different electron energies. The positive peaks are the forward inelastic scattering peaks. The negative peak indicates scattering off the atomic beam. The line of dashes shows the atomic-beam profile with the electron beam turned off. The vertical line above it marks the beam axis.

citation energy of the atom. Thus, by measuring the displacement of the forward inelastic scattering peak, the mean speed of the atomic beam V can be determined, usually to an accuracy of better than ± 3%.

III. RESULTS

We have used the technique described in Sec. II to measure total cross sections for the scattering of electrons by lithium atoms between 2 and 10 eV. Since the $2P$ threshold is 1.85 eV, inelastic processes will contribute to the cross sections over the whole energy range investigated in this experiment.

Our results are presented in Table I. The errors incorporate standard statistical errors and an allowance for systematic errors to a 68% confidence level. Possible sources of systematic errors in our measurements have been discussed extensively elsewhere.[27, 28] We will briefly present some of them. The correct overlap of the electron and atomic beams is ensured by the geometry of the interaction region and the careful alignment of the atomic beam. Since the atomic-beam density in the interaction region is about 10^7 cm^{-3}, the electron mean free path is of the order of 10^7 cm, and atomic-density effects in the cross-section measurement can be neglected. On the other hand, electron-density effects could be significant because of changes in the energy scale due to space charge in the interaction volume.[29] Space-charge corrections are applied routinely to our energy scale, as mentioned in Sec. II, and Jaduszliwer *et al.*[28] have investigated in detail the validity of these corrections. If they are not incorporated properly, the measured values of the cross section will appear to depend on the value of the electron current, if the total cross section varies fast enough with energy. In this experiment we have measured the total cross section at 2 eV (which, from this point of view, is the worst case) at two different values of electron current, and were unable to detect any variation in the results.

TABLE I. Total cross sections for the scattering of electrons by lithium.

Energy (eV)	Cross section (10^{-16} cm^2)	Standard error (10^{-16} cm^2)
2	115	6
3	110	7
4	88	5
5	83	5
7	76	4
10	72	3

Incomplete suppression of secondary electrons produced at the anode and reentering the collision region could lead to anomalous scattering, resulting in measured cross sections which are too high. This can be avoided by operating at the anode at a sufficiently high potential.[27, 28] The effective electron path length across the atomic beam could be slightly larger than the beam width, thus leading to an underestimation of the cross section.

A detailed discussion of angular resolution of total cross-section measurements in crossed-beam experiments is given by Bederson and Kieffer[30] and by Kasdan *et al.*[27] Forward scattering events within a cone determined by the angular resolution of the apparatus will not be counted, thus leading to measured values which are smaller than the correct total cross sections. The maximum possible error due to the finite angular resolution of the apparatus is estimated to be 2% in the energy range that we have investigated. In summary, we expect that the combination of systematic errors will affect our results at most by ± 3%.

These data are to be compared with theoretical calculations for the quantity $\sigma = \sigma_{el} + \sigma_{2S-2P}$, where σ_{el} is the elastic scattering contribution to the total cross section and σ_{2S-2P} is the contribution

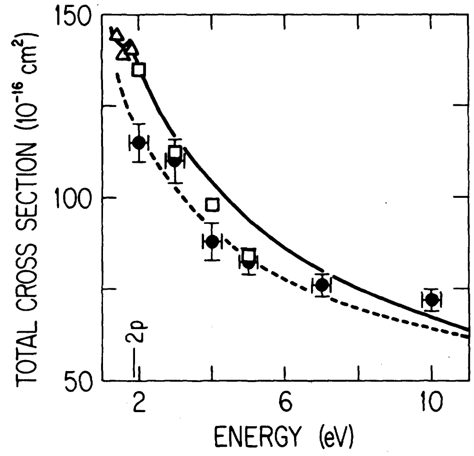

FIG. 4. Total cross sections for the scattering of electrons by lithium atoms. The black dots represent the results of the present work. Horizontal error bars define the energy spread; vertical bars incorporate statistical errors and an allowance for systematic error, to a 68% confidence level. The triangles and squares are the close-coupling results of Karule (Ref. 13), and Karule and Peterkop (Ref. 13). The full line shows the close-coupling results of Burke and Taylor (Ref. 14). The dashed line is the sum of the integral elastic scattering cross section of Bhatia *et al.* (Ref. 21) and the integral impact-excitation cross section of Burke and Taylor (Ref. 14).

from the excitation of the 2P state. We are assuming here that the total cross section is overwhelmingly dominated by these two processes, and that the sum of contributions from other channels is smaller than the errors present in the experiment.

Figure 4 shows our data together with the values of σ obtained from the results of two-state close-coupling calculations of Karule and Peterkop[13] (squares) and Burke and Taylor[14] (full line). The dashed line is a hybrid curve showing the values of σ obtained by adding σ_{el} results from the modified polarized-orbitals calculation of Bhatia *et al.*[21] and the σ_{2S-2P} results of the close-coupling calculations by Burke and Taylor. The differences between the elastic contributions to the total cross section calculated by the modified polarized orbitals and the close-coupling methods are of the order of 20% in the energy range we have explored. Of course, adding the same 2P impact-excitation contribution to both of them makes the difference between the total cross sections appear smaller, especially at higher energies, where the impact-excitation contribution is dominant.

Our results seem to fit better the hybrid curve obtained using the elastic cross sections of Bhatia *et al.* At the higher energies they become larger than both theoretical curves, probably reflecting the increasing importance of contributions from channels other than the elastic and 2S-2P excitation.

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