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Excited atomic state of Li^-

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Abstract. An optical transition of 3489 Å has been shown to arise from Li^- using beam foil spectroscopic technique. The mean life of the state emitting this radiation has been measured to be $2{\cdot}23 \pm 0{\cdot}08$ n sec.

Keywords. Beam foil excitation of Li; excited state of Li^-; lifetime measurement.

1. Introduction

Negative ions of many elements have been produced and studied (Popp 1975; Massey 1976) and in many cases their electron affinities have been calculated and also measured (Moiseiwitsch 1976). In particular, intense Li^- beams have been produced in ion sources and used at several accelerators. The ground state $1s^2\ 2s^2$ of Li^- has an electron affinity of 0·6 eV. Recently Bunge (1980a, b) made a theoretical investigation of the possibility of metastable excited states of Li^-. While the $Li^-(1s^2\ 2p^2)^3P^e$, which is 0·13 eV above the Li $(1s^2\ 2p)\ ^2P^o$, with a width of 0·1 eV, is a resonance, Bunge's calculations show that the core excited states $Li^-(1s\ 2s\ 2p^2)^5P^e$ and $Li^-(1s\ 2p^3)^5S^0$ lie below the corresponding Li $(1s\ 2s\ 2p)^4P^o$ and Li $(1s\ 2p^2)^4P^e$ states and are metastable against auto-ionisation. His calculation also shows that the $^5S^\circ$ decays by an optical transition of wavelength 3489 Å to the $^5P^e$ state with a mean life of $2{\cdot}9\ n$ sec. Such doubly excited states could be populated in beam foil sources and the present investigation was undertaken to study this transition. In the experiments to be described below we have shown that the transition of 3489 Å indeed comes from Li^- ion and have also remeasured the lifetime of the state $^5S^\circ$ from which it decays. During the course of our experiment, Brooks *et al* (1980), Mannervik *et al* (1980), and Denis and Desequelles (1981) also reported experiments to show that the transition comes from a Li^- ion. As discussed below, we have shown that the origin of this transition is from a negative ion by a direct physical separation of the emitting Li^- ion in an external transverse electric field and we believe that this is a more direct verification of the negative ion origin of the transition than the earlier reported experiments.

2. Experimental procedure and results

Since this is our first experiment on beam foil spectroscopy we shall describe the general components of the apparatus in some detail.

2.1 *Accelerator*

The experiments were performed with the 400 kV ion accelerator indigenously built at the Tata Institute of Fundamental Research providing ion beams of practically all elements. The highlights of this machine are (a) extremely good mass resolution so that each isotope of an element is well separated, (b) energy stability of the ion beam within 1%, (c) good focussing arrangement of the beam in the target chamber and (d) beam currents of the order of several μamps can be easily obtained. In the present measurement a few μamps of $^7Li^+$ ion beam was easily obtained in the target chamber. However, most of the experiments utilized only a fraction of a μA to avoid frequent breakage of the foil.

A well collimated near parallel beam was used in practically all the measurements. While the lifetime experiments were made with a 2 mm $\times$ 2 mm rectangular collimator, the charge identification experiment used a collimator of 0·25 mm in the vertical and 3 mm in the horizontal directions. The beam emerging from the foil is collected in a Faraday cup kept at $\sim$15 cm from the target. A permanent magnet was kept on top of the Faraday cup to reduce the error in charge measurement due to secondary electron emission.

2.2 *The vacuum chamber and optical system*

A cylindrical vacuum chamber was mounted on an oil diffusion pump. The top flange of this chamber had several feed throughs. In lifetime measurements, the foil mounted on a micrometer screw could be moved in vacuum, which was $\sim 10^{-5}$ torr, over a distance of $\sim$ 2 cm. Relative positions of the foil could be determined to an accuracy of $\sim$ 0·1 mm. The light emitted from the ion beam after passing through the foil was viewed at right angles to the beam direction. The vacuum chamber had a quartz flange in the direction of observation as shown in figure 1. A quartz lens of focal length 9 cm was used to focus the light on to the slit of a Cerny Turner monochromator with a magnification of unity. This lens could be moved in both the directions perpendicular to the line of incidence of the rays of light. The monochromator consisted of two concave mirrors and a plane grating with 6000 lines per cm. The grating could be rotated about its axis in small steps with the help of a micrometer screw. The dispersed beam of light, after passing through an exit slit was viewed by a 6256 S photomultiplier which had a quartz window. The photomultiplier was cooled to-20°C by a two stage Peltier junction to reduce the dark current. The voltage pulse developing across a 1 kΩ load resistor was amplified and counted after a discriminator. The vacuum chamber and the optical system were made light tight. With this arrangement the dark current was $\sim$ 0·4/sec in the region corresponding to 3500 Å setting of the grating. The monochromator was optically aligned with a mercury pen lamp in the position of the beam. It was mostly operated with an exit slit width corresponding to 30 Å FWHM resolution which was enough for the present experiment. A typical spectrum obtained with a 135 keV Li^+ beam

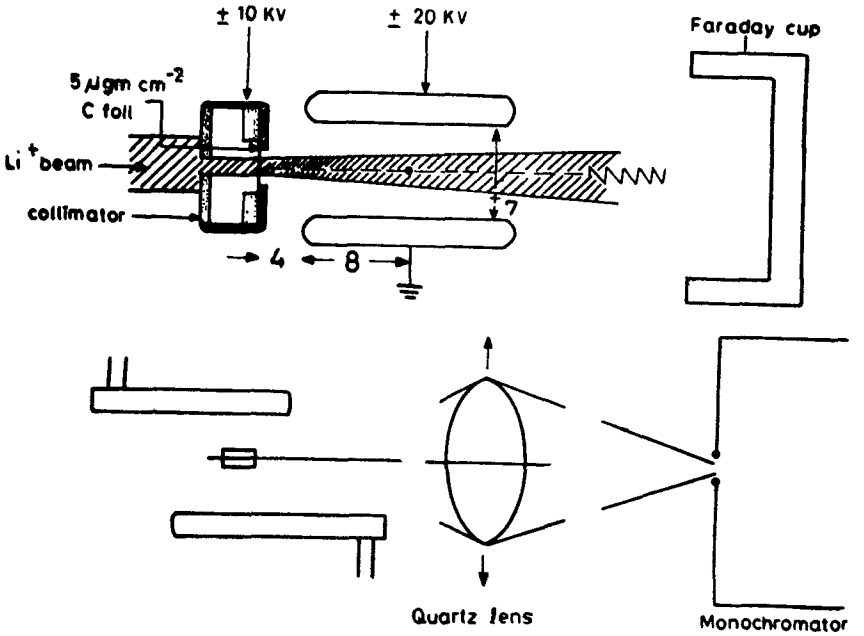

Figure 1. A schematic diagram of the apparatus used. The upper portion shows a side view of the beam. The bottom portion shows the optics.

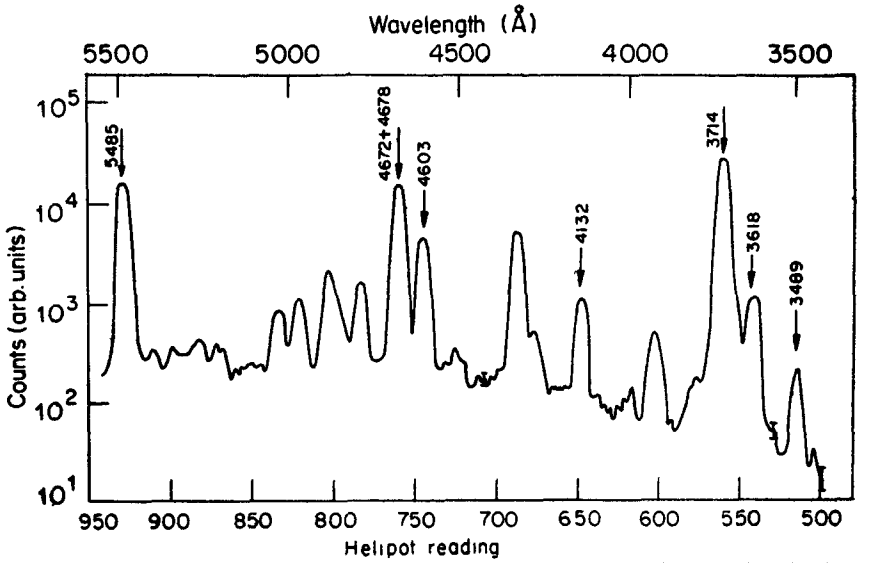

Figure 2. A typical beam foil spectrum of 135 keV Li^+ ions in the visible region. Some of the stronger transitions have their wavelengths (in Å) written above them.

passing through $\sim 5\,\mu g\ cm^{-2}$ foil is shown in figure 2. The counting rate immediately after the foil was $\sim$ 100/sec for an entrance slit width of 1 mm $\times$ 4 mm for a current of 200 nA for the peak of the 3489 Å line.

The carbon foils used in this experiment were made by vacuum evaporation. In some typical cases the thickness of the foil was measured to be $\sim$ 500 Å and in practically all runs the same thickness has been used.

2.3 *Lifetime measurements*

The lifetime of the states emitting the 3489 Å and 3714 Å lines were measured using the apparatus discussed above. A possible correction to the measurement can come due to the spread of the ion-beam after the foil. As the distance from the foil is increased the cross-section of the beam could increase and could result in a reduced collection in the system. This effect was investigated by measuring the lifetime of the long lived 37 nsec 5485 Å line of Li^+ and was found to be absent at a displacement of ~ 2 cm. The measured values reproduce the correct lifetime for this state. The intensity of the line as a function of distance downstream from the foil is shown in figures 5 and 6. From the known energies and hence velocities of the ion beam the mean lifetimes of these states could be determined and are found to be 2·3 nsec and 6·1 nsec respectively. The uncertainties mainly come from $\sim 1\%$ in the velocity, $\sim 1\%$ in the distance, $\sim 3\%$ in the statistical counts. These lifetimes (table 1) have been measured by several workers (Berry *et al* 1971; Bromander 1979, Harde 1975). Our values are in agreement with the recent results of Mannervik (1981). It was also assumed that there is no side feed to the 3714 Å line. This was done on the basis of the measurements of Mannervik *et al* (1981).

2.4 *Charge state identification*

The identification of the charge state of the ion from which a given optical transition originates is carried out by spatially separating the beam in an external electric field. The arrangement used is shown in figure 1. An electric field of ~ 30 kV/cm in the vertical direction was produced by two electrodes separated by 7 mm. The foil was kept at a distance of ~ 4 mm upstream from the end of the plates. There was another electrode with a central hole of ~ 1 mm diameter in front of the target to protect it from sparking. The beam was collimated to $\sim 0{\cdot}25$ mm in the vertical ~ 3 mm in the horizontal directions. Since the mean life of the state emitting the 3489 Å line in 2·23 n sec (Berry *et al* 1971; Mannervik 1981) corresponds to a distance of ~ 4 mm, it is necessary to effect the deflection as near the foil as possible. The light from the beam 11·0 mm to 14·0 mm upstream corresponding to a decay of 4 half lives was focussed on the spectrometer slit which had an opening of 0·5 mm and 3 mm in the vertical and horizontal directions. For this experiment, the monochromator was aligned with the lines of the grating in the horizontal direction. Since the magnification was unity, the entrance slit width viewed a region of the beam which was 0·5 mm in the vertical direction. By moving the lens now in the vertical direction

Table 1. Mean lifetimes (n sec)

Reference	3714 Å	3489 Å
Berry *et al* 1971	$6{\cdot}5 \pm 0{\cdot}3$	
Buchet *et al* 1969	7 ± 2	
Bickel *et al* 1969	$6{\cdot}4 \pm 0{\cdot}3$	
Gaillard *et al* 1969	$5{\cdot}8 \pm 0{\cdot}7$	
Mannervik 1981	$5{\cdot}86 \pm 0{\cdot}15$	$2{\cdot}3 \pm 0{\cdot}1$
Present work	$5{\cdot}78 \pm 0{\cdot}15$	$2{\cdot}23 \pm 00{\cdot}8$

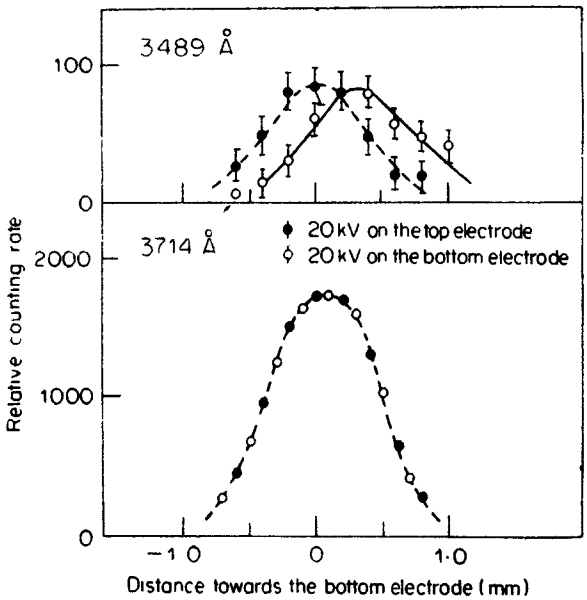

Figure 3. Vertical intensity profiles of the 3489 Å and 3714 Å transitions with electric field applied in opposite directions.

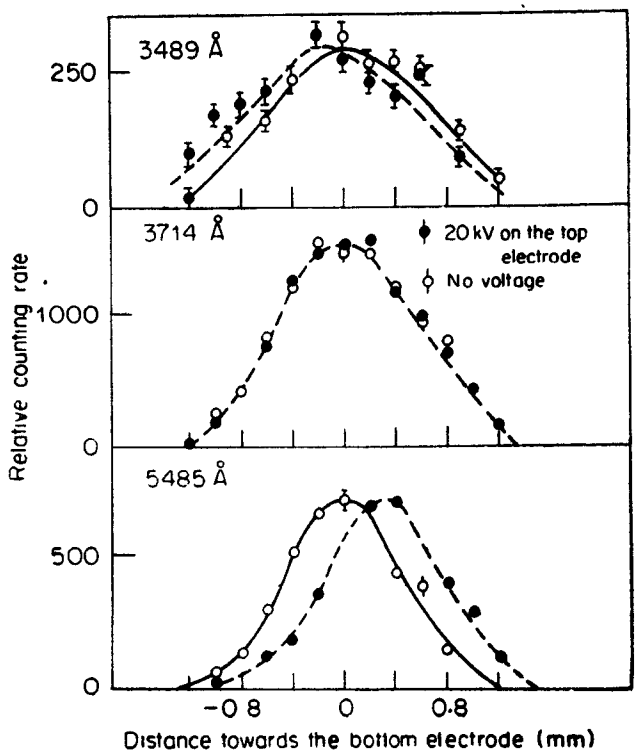

Figure 4. Vertical intensity profiles of 3489 Å, 3714 Å and 5485 Å transitions with and without electric fields.

different portions of the beam of 0·5 mm width in the vertical direction could be viewed. Thus it was possible to scan the intensity profile and hence the beam profile in the vertical direction. Even though the collimator was only 0·25 mm wide in the vertical direction, the beam observed 12 mm after the foil had a height profile width 0·8 — 1·0 mm. This could be understood in terms of the spreading of the beam due to small angle scattering in the foil. The height profile with an electric field at the electrode would thus alter according to the charge of the ion from which a given radiation is emitted. For a negative ion the peak of the intensity profile would shift towards the electrode with a positive potential, while for a neutral ion it should be unaffected. Figure 3 shows such height profiles for the 3489 Å and 3714 Å lines for two directions of the field. The 3714 Å line is known to be $(1s\ 2p^2)^4P^e$ to $(1s\ 2s\ 2p)^4P^0$ transition in the core excited neutral lithium and hence no height shift is expected with the application of an electric field as seen in figure 3. The ion emitting the 3489 Å line, on the other hand moves towards the electrode with a positive potential as

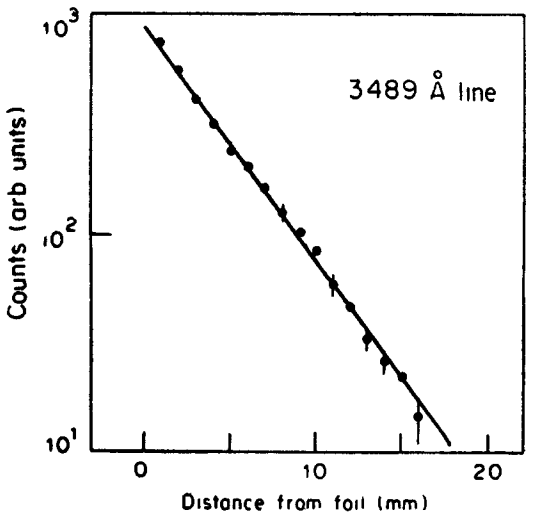

Figure 5. Beam foil lifetime spectrum of the 3489 Å transition.

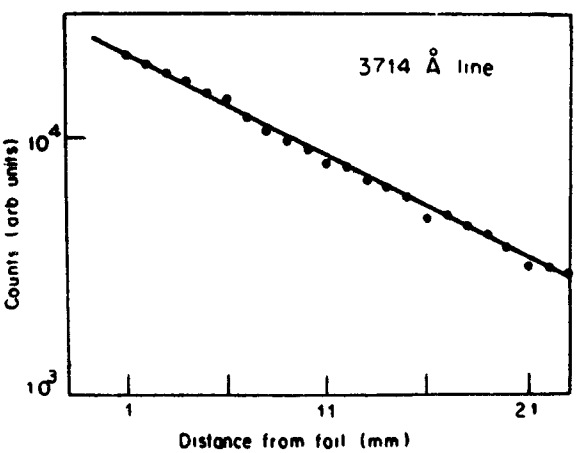

Figure 6. Beam foil lifetime spectrum of the 3714 Å transition.

evident in figure 3. Later, the experiment was repeated for the 5485 Å line also which is a well-known (Li II) Li^+ line. The result is shown in figure 4. It can again be seen that the ions emitting the 3489 Å line and those emitting the 5485 Å line shift in opposite directions and hence are oppositely charged.

The above experiments thus conclusively prove that the 3489 Å line originates from a negatively charged ion. The value of the shift is consistent with that expected for the field.

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