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# Effect of a transverse magnetic field on the plume emission in laser-produced plasma: An atomic analysis

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ABSTRACT

We have investigated the effect of varying transverse magnetic field on the plasma plume emission of laser-produced lithium plasma. Two atomic transitions for lithium neutral Li (I) and two for Li ion LI (II) are taken for the study. It has been found that for Li (I), the emission from 670.8 nm transition ($2s^2S_{1/2} \leftarrow 2p^2P_{3/2'1/2}$) shows initial enhancement and then subsequent decrease for higher fields. Of course, the overall intensity is increased for all the fields when compared to the case of without field. On the other hand, for 610.3 nm ($2p^2P_{1/2} \leftarrow 3d^2P_{3/2'5/2}$), there is continuous decrease in intensity. Interestingly, for Li (II) transitions also, after an initial increase in intensity up to 0.08 Ta decrease is observed. From the atomic analysis, we find that for 670.8 nm line, the cause of initial enhancement is increase in electron impact excitation whereas for decreased intensity, increased field-induced ionization appears to be responsible mechanism. However, for 610.3 nm line, decrease in intensity appears to be due to decreased recombination. For Li (II), 478.8 nm ($3p^1P_1 \leftarrow 4d^1D_2$) and 548.4 nm ($2s^3S_1 \leftarrow 2p^3P_{2,1,0}$) transitions, initial increase appears to be due to increased confinement (increase in plasma density) and subsequent decrease in intensity with increase in field due to decreased recombination.

## 1. Introduction

The presence of magnetic field during the expansion of a laser-produced plasma (LPP) may initiate several interesting physical phenomena, which include conversion of kinetic energy into plasma thermal energy, plume confinement, ion acceleration/deceleration, emission enhancement, plasma instabilities, control of debris mitigation for EUV source, increase in the detection sensitivity of laser-induced breakdown spectroscopy (LIBS) etc. [1–15]. In an earlier work, the limits of detection for Mn and Mg have been found to be improved by a factor of two in the presence of 0.5 T magnetic field [10].

Plasma changes its physical properties during expansion across a magnetic field, and this ultimately affects its emission characteristics. An enhancement in optical emission under the influence of a pulsed magnetic field has been reported in most of the earlier reports [1,2,4–13]. Optical emission spectroscopy and/or imaging techniques have been used as diagnostics for studying the dynamics of these plasma plumes. Kim et al. have found that in the presence of magnetic field, there is decrease in Zn (I) emission but enhancement in case of Zn (II), which they have ascribed to increased ionization [1]. Temporal evolution of aluminum plasma plumes traveling through a transverse magnetic field (0.61 T) has been studied by Harilal [4]. They have found enhancement for Al (III) emission but a decrease in Al (II) and Al (I) emissions. García et al. [5] have studied the ablation of $SrFe_{12}O_{19}$ in the presence of inhomogeneous transverse magnetic field and found enhancement in Sr emission, which they have attributed to electron confinement. Shen at al. [6] have studied the effect of magnetic field on the plasma produced by the ablation of Al, Cu and Co targets. Enhancement in emission has been observed in case of Al and Cu whereas for Co a decrease in emission was observed. They have attributed this behavior to effective increase/decrease in plasma density. Li et al. [7] have studied the effect of magnetic field on copper plasma plume and the enhancement has been attributed to increased radiative recombination. Pant et al. [8] applied a uniform transverse magnetic field of 0.6 T for studying X-ray emission from laser-produced plasma and have found enhancement in intensity, which has been attributed to confinement and radiative recombination. Neogi and Thareja [9] applied a magnetic field of 0.5 T (non-uniform) along the direction of expansion in the carbon plasma and have found enhancement in ionic as well as neutral lines. Optical emission spectroscopy has been used by Rai et al. [10] to study the effect of fixed magnetic field on laser-produced plasmas of Mn, Mg, Cr, and Ti and have found enhancement in emission, which has been attributed to enhanced radiative recombination. Moreover, ion recombination effects have also been suggested to be significant in the presence of the magnetic field [11]. Optical emission of laser-ablated graphite has been studied by Kokai and the changes in the emission of various species have been attributed to electron impact ionization [12]. In a recent work [13,14] we had observed enhancement

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in Li (I) emission in presence of magnetic field in the laser-blow-off (LBO) study and found that enhancement is due to increased electron impact excitation. Appearance of structures due to instabilities in the presence of magnetic field has also been observed in some works [9,15].

To explain enhancement/decrease in line emission, various mechanisms like increase in ionization, electron confinement, increase/decrease in effective plasma density, increased radiative recombination and increase in both confinement and radiative recombination have been proposed. However, no study considering the role of atomic processes from the intensity variation of different transitions as well as systematic variation of magnetic field was done in case of laser-produced plasma (LPP). In the present work we report a systematic study of the effect of the magnetic field in case of LPP from solid lithium target for two characteristic emissions from Li (I) and two from Li (II) by varying the field. It can be mentioned that first and second ionization potentials for lithium are 5.39 eV and 76.64 eV respectively. A simplified energy level diagram depicting these transitions is shown in Fig. 1. We explain the behavior of these transitions in the presence of magnetic field by considering the role of atomic processes.

## 2. Experimental

The experimental technique of time of flight emission spectroscopy used in the present work has been described elsewhere [13]. Briefly, the plasma plume is generated inside a multi-port stainless steel chamber, which is evacuated to a base pressure better than $5\times10^{-6}$ mbar. The target is composed of solid lithium (99.9%) rod of 12 mm diameter, which is mounted on a motorized *x*–*y* translator stage so as to expose a fresh region of the target for every successive shot. An Nd:YAG laser ($\lambda = 1.064$ µm, pulse width: 8 ns and repetition rate: 30 Hz but operating in single shot mode) was used to generate the plasma plume. The laser beam was focused on the target surface (angle of incidence ~6°). The spot size of the laser beam was set to about 1 mm diameter at the target to achieve average power density of $\sim10^{9}$ W/cm$^{2}$. For time and space-resolved spectroscopy, the plasma plume is viewed, using 1:1 imaging optics, normal to the direction of expansion and imaged at the entrance slit of a monochromator ($\Delta\lambda = 12.5$ Å for slit width of 250 µm).

The monochromator with photomultiplier tube was mounted on a single-stage translator system, which enabled space-resolved scan of the plume along its expansion axis. The output of the PMT was directly fed to a 1 GHz digital oscilloscope. The time resolution in the present experiment was about 4 ns. A small fraction of the light reflected from the laser-focusing lens was detected by a photodiode and was used as time-reference. Overall maximum uncertainty in our measurement is less than 8%.

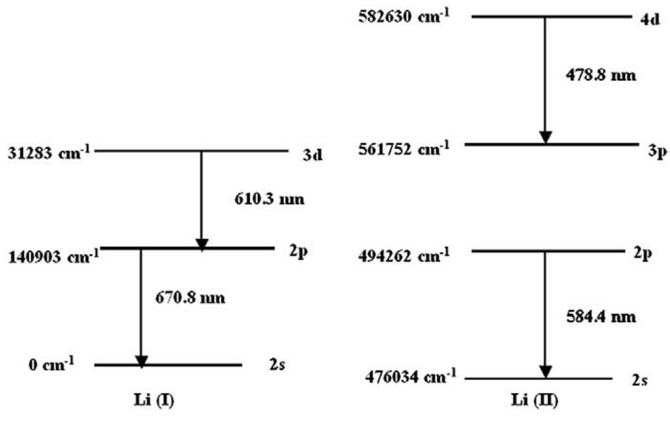

**Fig. 1.** Simple energy level diagram depicting transitions taken in the study.

A pulsed power system consisting of capacitor bank and a wire wound solenoid was used to produce the magnetic field, 0.04–0.2 T (flat-top duration of the magnetic field profile is 40 µs; much larger than the plume duration of few µs) [13] in the transverse direction to the plume propagation. It has been found that magnetic field is almost uniform in the region of ~20 mm both along and perpendicular to the plume expansion, which ensures that the plume propagates in uniform field in the considered range. A time sequencing circuit is developed to synchronize the flat temporal profile of the field with the formation of the plume.

## 3. Results and discussion

Fig. 2a shows the temporal evolution of Li (I) 670.8 nm line with different magnetic fields. The measurements were done at a distance *z* of 6 mm from the target. Here it can be mentioned that the bandwidth (12.5 Å) of the detection system was sufficient enough to detect the integrated emission intensity including the Stark shifted components which is (~1 Å). Moreover, we checked for the contribution from the background also both in the presence and absence of the field and found that it was insignificant (at $z = 6$ mm) as compared to the signal from the line emission. It can be seen that enhancement in the emission takes place when the field is just introduced (0.04 T), which remain more or less same up to 0.08 T and then there is decrease with further increase in field. Of course, the overall intensity is increased for all the fields when compared to the case of without field. Moreover, the profile becomes broadened with some small structures. It can be mentioned here that structures are not prominent as in the case of laser-blow-off plasma plume [13,14], which will be discussed latter. However, unlike 670.8 nm, for 610.3 nm line a decrease in emission is observed even for 0.04 T although the profile is relatively broadened (Fig. 2b).

Fig. 3 shows the temporal evolution of Li (II) 548.4 nm line with increase in magnetic field. Interestingly, initially there is an increase in emission up to 0.08 T, which subsequently decreases with further increase in the field. It can be mentioned here that similar behavior is observed for Li (II) 478.8 nm line.

To explain the behavior in emission intensity, we discuss it by using computed photoemissivity coefficients (PEC) described latter from atomic data and analysis structure (ADAS) database [16,17] (considering all the possible processes of excitation/emission for these lines).

The intensity of a particular line can be expressed in terms of PEC. In ADAS it is assumed that the collisional and radiative processes between all excited levels redistribute the populations and the excited levels are in quasi-static equilibrium with the metastables. The emissivity of an individual line between states *j* and *k* for electron impact excitation is given by

$$\varepsilon_{j\to k}(exc) = A_{j\to k}\sum_{\sigma=1}^{M} F_{j\sigma}^{(exc)} N_{\mathrm{e}} N_{\sigma} \tag{1}$$

and emissivity of an individual line due to recombination is given by

$$\varepsilon_{j\to k}(rec) = A_{j\to k}\sum_{\upsilon=1}^{M} F_{j\upsilon}^{(rec)} N_{\mathrm{e}} N_{\upsilon} \tag{2}$$

where $A_{j\to k}$ is the transition probability for transition between *j* and *k* levels, $F_{\sigma}^{exc}$ and $F_{\upsilon}^{rec}$ are the effective contributions to the populations of the excited state from metastable $\sigma$ of the atom and $\nu$ of the ion for electron impact excitation and recombination respectively (electron density and temperature dependent) and $N_{\mathrm{e}}$, $N_{\nu}$ and $N_{\sigma}$ are electron density, density of ions in metastable $\nu$ and density of atoms in metastable $\sigma$ respectively. Here it can be noted that recombination