# Measurement of the degree of polarization of the spectra from laser produced recombining Al plasmas

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Using a polarization-resolved UV-visible spectrometer, the degree of polarization of the spectra from laser produced Al plasmas was measured. The polarization resolution was achieved by using either a dichroic polarizer or a calcite crystal. The degree of polarization of Al III $4s\,^2S_{1/2}$-$4p\,^2P^o_{3/2}$ transition at 569.66 nm was measured at different positions from a target surface. The degree of polarization was observed to be 2.1 $\pm 0.13\%$ at a distance of 220 $\mu$m from the target and decreased as the distance from the target increased, vanishing at a distance of about 1.3 mm from the target. To avoid the possible error due to the shot-to-shot variation of the line intensity, a calcite crystal was used to simultaneously observe the two polarization components, obtaining a similar result. The electron temperature of about 3 eV and the density of $2 \times 10^{17}$ cm$^{-3}$ measured spectroscopically indicates that the plasma was in the recombining phase. This is a report on the observation of the polarization of a transition in a laser-produced recombining Al plasma.

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The observation of the polarization of emission lines has been a long-standing issue in solar flare physics [1,2]. During the past two decades, polarized emissions have been also observed in tokamak [3], gas-discharge [4,5], and laser-produced plasmas [6–10]. In view of the investigation of the electron distribution function (EDF) in a laser-produced plasma, the study on the polarization of emitted lines in laser-produced plasmas have been pursued. The emissions were observed to be polarized by different causes: spatial anisotropy in EDF [6], laser polarization [8], and the dependence of gain cross section on the reabsorption [9]. These plasmas created by high-power lasers were the high-temperature plasmas in which the collisional excitation and ionization processes are dominant. It has been known that anisotropic collisions of electrons with atoms produce polarized radiations. This fact can, in turn, be used to deduce anisotropy in EDF from the polarization measurement of emissions [11,12].

It is then also interesting to investigate the generation of polarized emission during the recombination processes. In fact, there is little theoretical and experimental work on this issue. In this view, we carried out a series of polarization measurement experiments in low-temperature, high-density, recombining Al plasmas produced by a Nd/glass laser.

In this paper, we report the first observation of the polarization of Al III $4s\,^2S_{1/2}$-$4p\,^2P^o_{3/2}$ transition at 569.66 nm in a laser-produced recombining Al plasma. The experimental setup is shown in Fig. 1. A *Q*-switched Nd/glass laser was used to generate an Al plasma. The full width at half maximum of the laser pulse duration is 3 ns. This laser beam was focused onto an Al target with a focal spot size of 260 $\mu$m diameter. The power density on the target was about $4 \times 10^9$ W/cm$^2$. Two imaging lenses were used to image the plasma on the entrance slit of a Czerny-Turner type UV-visible spectrometer with 1 m focal length. This spectrometer was designed in the near-normal-incidence configuration to minimize an astigmatism. Hence the overall optical system of the spectrometer and the imaging optics could image the plasma in one direction: the imaging direction was the direction of the laser incidence axis ($z$ axis) as shown in Fig. 1. The imaging property of the system was measured using a 0.4-mm-diameter wire as fiducial at the position of a plasma [13]. The measured spatial resolution was about 0.3 mm. All the spatially resolved data, presented below, were taken at

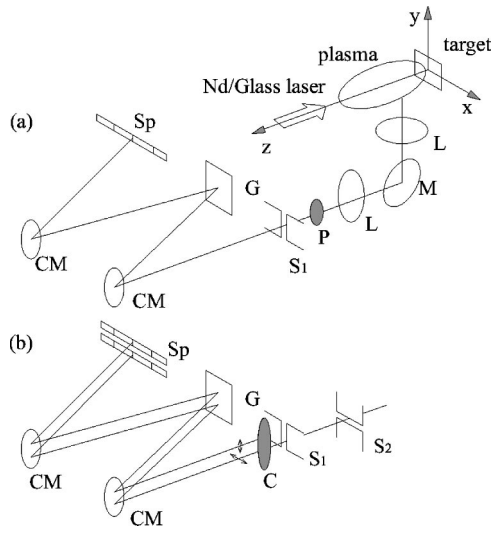


FIG. 1. Experimental setup. When using a dichroic polarizer in front of the entrance slit of the spectrometer (a), only one polarization component is taken. Two spectra are needed to measure the degree of polarization. When using a calcite crystal after the entrance slit of the spectrometer (b), two polarization component of the spectra are taken simultaneously. (L, imaging lens; M, turning mirror; P, dichroic polarizer; $S_1$, spectrometer slit; $S_2$, auxiliary horizontal slit to limit the viewing area; CM, concave mirror; G, plane diffraction grating; Sp, spectrum; C, calcite crystal.)

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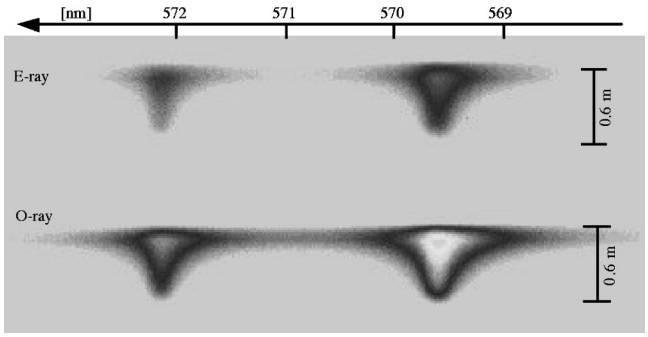


FIG. 2. The image of polarization-resolved spectra on the CCD detector in the case of using a calcite crystal. The upper part of the spectra is an extraordinary (E) ray of the calcite crystal, which corresponds to the perpendicular polarization to the laser incidence axis, and the lower part is an ordinary (O) ray, which is the polarization parallel to the laser incidence axis.

the positions which were at least 0.3 mm apart.

To measure the degree of polarization of an emission line, two methods were employed. The first one is to use a dichroic polarizer in front of the entrance slit of the spectrometer. The spectrometer system has a large view of observation of a plasma: it views a region of about 1.5 mm from a target surface with a spatial resolution of 0.3 mm. The disadvantage of this setup is that for the measurement of the degree of polarization, two spectra need to be obtained independently with a polarizer set for the perpendicular ($x$ axis) and parallel ($z$ axis) polarization to the laser incidence axis respectively. Hence the shot-to-shot variation can affect the measurement of the degree of polarization.

The second one is to use a calcite crystal after the entrance slit. The birefringent property of a properly-cut calcite crystal separates two perpendicular polarizations and allows one to observe two polarizations simultaneously. Hence the possible error due to the shot-to-shot variation can be avoided. This second method was also employed to check the variation of the spectral line intensity in the measurements using the dichroic polarizer. In our experiment, two polarizations were separated by 1.6 mm vertically with a 19 mm long calcite crystal, dispersed by the grating of the spectrometer, and imaged by imaging concave mirrors on a CCD detector. On the detector, then, we had two horizontal lines, one spectrum per each polarization as shown in Fig. 2. Since the optical set up in our experiment did imaging in the $z$ direction, the two spectra overlapped each other without the proper limitation of the viewing area. To avoid this, we placed a 1-mm-wide horizontal slit in front of the entrance slit of the spectrometer.

The direction of polarization is defined as follows: one polarization is parallel to the laser incidence axis ($z$ axis) and the other polarization is perpendicular to the laser incidence axis ($x$ axis). The degree of polarization is then defined by $P=(I_{\parallel}-I_{\perp})/(I_{\parallel}+I_{\perp})$, where $I_{\parallel}$ is the intensity of the light whose direction of polarization is parallel to the laser incidence axis, and $I_{\perp}$ the intensity of the perpendicular polarization.

The optical system consisted of many optical elements such as mirrors, grating, lenses, and windows. It's important

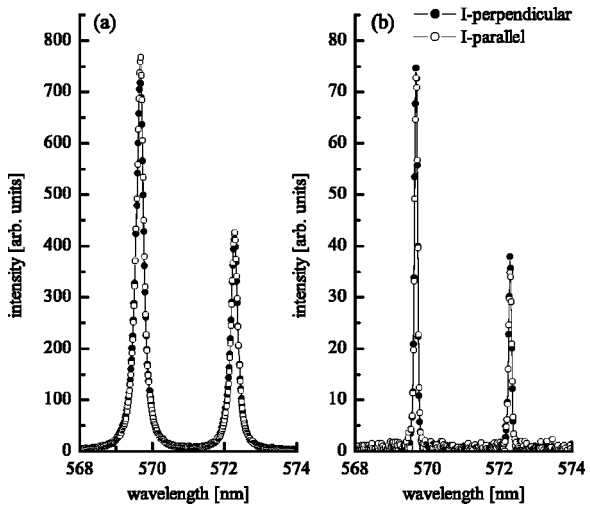


FIG. 3. Polarization-resolved spectra using a dichroic polarizer. The laser energy is 6 mJ. (a) is taken 220 $\mu$m from the target surface and (b) 1.3 mm from the target surface. Open circles are the spectrum of the parallel polarization and dots are the spectrum of the perpendicular polarization. The polarization was measured for Al III $4s\,^2S_{1/2}$-$4p\,^2P^o_{3/2}$ at 569.66 nm. Al III $4s\,^2S_{1/2}$-$4p\,^2P^o_{1/2}$ at 572.27 nm was used as a reference for the polarization calibration of the measuring system.

to calibrate the sensitivity of the optical system to different polarization components. In this work, Al III ($4s\,^2S_{1/2}$-$4p\,^2P^o_{1/2}$) transition line at 572.27 nm was selected to calibrate the polarization sensitivity of the system because this line can never be polarized. Both the upper and lower levels of this transition have two magnetic sublevels ($m_J=+1/2$ and $-1/2$). This transition has four multiplets, two of which have $\sigma$ polarizations and the other two $\pi$ polarizations. Each polarization has contributions from the two magnetic sublevels with equal strength. Hence the degree of the polarization of the transition always vanishes regardless of any possible difference in the populations of the magnetic sublevels [14]. The transitions from $J=1/2$ levels to $J=1/2$ levels, similar to the Al III transition, have been used as reference lines in other polarization spectroscopy experiments [3].

The intensities of this Al III 572.27 nm line were measured for the two different polarization in the region of 0.4 mm to 1.5 mm away from a target surface for the polarization sensitivity measurement. The region very close to a target was avoided because the continuum radiation from such a high density plasma region contaminated the line emission. The ratio of intensities of two different polarizations, $R=I_{\parallel}/I_{\perp}$, was measured to be about 0.544 in the above region with a standard deviation of 0.002.

Figure 3 shows the polarization-resolved Al III ($4s\,^2S_{1/2}$-$4p\,^2P^o_{1/2,3/2}$) lines obtained with a dichroic polarizer. The polarization sensitivity was taken into account using the reference line Al III ($4s\,^2S_{1/2}$-$4p\,^2P^o_{1/2}$) as mentioned above. The transition lines were fitted by Voigt profile to find the intensities. Figure 4(a) shows the variation of the degree of polarization with respect to the distance from the target surface. The degree of polarization was measured to be 2.1

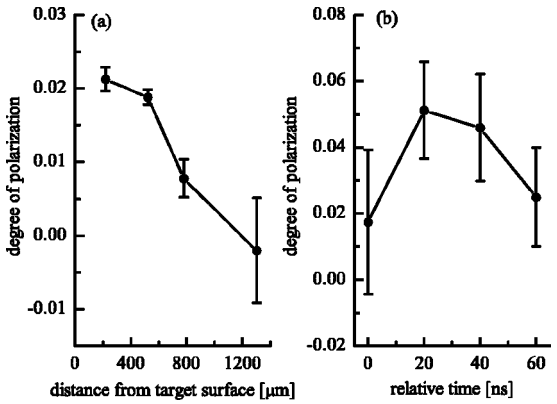


FIG. 4. (a) The degree of polarization as a function of the distance from the target surface. (b) Preliminary time resolved degree of polarization measurement. $t=0$ ns point is defined when the intensity of the line is reasonably high.

$\pm 0.13\%$ at a distance of 220 $\mu$m from the target, and decreased with the distance, vanishing at 1.3 mm. To make sure that this degree of polarization was not due to the shot-to-shot variation of the intensities of spectral lines, another series of experiments were performed with a calcite crystal, by which two polarization component was simultaneously observed. The similar result was observed, confirming that the measured polarization was not an experimental error by the shot-to-shot variation of spectral intensities, but real. The observation of degree of polarization in time-integrated measurement implies the existence of a larger degree of polarization in reality, because the time-integration diminishes the degree of polarization. The preliminary time-resolved experiments for the same spectral lines were performed at a laser energy of 120 mJ, as shown in Fig. 4(b) [15]. As expected, the stronger degree of the polarization was observed, providing the further support to the observation of the polarization of the transition under interest in the time-integrated spectrum

The electron temperature was estimated by the intensity ratios of three spectral lines, Al III $3d\,^2S$-$4p\,^2P^o$, Al III $4p\,^2P^o$-$4d\,^2D$, and Al III $4f\,^2F^o$-$5g\,^2G$ [16]. The electron temperature was measured to be about 3 eV for a laser energy of 6 mJ. The Stark broadenings of Al III $4p\,^2P^o$-$4d\,^2D$ and Al III $4s\,^2S$-$4p\,^2P^o$ were used for the estimation of electron density. The spectral line was fitted using Voigt profile and the Lorentzian width was used to measure the electron density. Electron-impact broadening parameter was taken from Ref. [17]. The averaged electron density was measured to be $2.2\times10^{17}$ cm$^{-3}$ at a place of 220 $\mu$m from the target and decreased to $4\times10^{16}$ cm$^{-3}$ at a place of 1300 $\mu$m from the target for a laser energy of 6 mJ. Because the spectral lines used for the measurement of $T_e$ and $N_e$ are emitted from the same ionization stage as the one from which the spectral line under interest for the polarization measurement is emitted, the measured $T_e$ and $N_e$ provide the plasma status averaged over a period during which the spectral line under interest was emitted, even though they are obtained from time-integrated measurements.

The previous studies with respect to the polarization of emitted lines using laser-produced plasmas attributed the origin of the observed polarizations to the spatial anisotropy of EDF [6], laser polarization [8] and the dependence of gain cross section of a transition on the reabsorption of a spectral line originating from the lower level of the transition [9].

The polarization due to the laser polarization is ruled out in our case because the laser was incident normally to the target and Kieffer *et al.* [6] has already observed that their observation of polarization was independent of the laser polarization in the case of normal incidence of a laser to a target.

The radiation trapping does not seem to be the cause for the polarization observation in our case. In Kawachi *et al.*'s experiment [9], the observed spectral lines were under lasing action. A gain cross section is also affected by the population of the lower level of a lasing transition. Hence the absorption of the spectral line, whose upper level is the lower level of a lasing transition, affects the magnitude of the gain cross section, which in turn changes the spectral intensities of a lasing transition. Our situation is different from their case, because (1) the spectral lines in our observation were not under lasing action and (2) hence their intensities were independent of the population of the lower level. Considering the structure of the magnetic sublevel and the relative strength of the multiplets of Al III $J=3/2$–$J=1/2$ transition, the self-absorption tends to destroy the degree of polarization. Hence the observation of polarization even in a situation of a large opacity means that there would exist the higher population imbalance between the magnetic sublevels.

We may consider the anisotropy in EDF as a cause for the observed polarization. However, the estimated electron temperature and density tells us that the electron-electron collision time is in the order of a few ps and the ion-ion collision time is in the order of a few hundreds of ps, which are much shorter than the laser pulse and the observation time. Hence the consideration of collision times rules out the possibility of anisotropy in EDF as a cause.

The ionization balance estimated by the Saha equation indicates the abundance of neutrals is about 7 orders of magnitude smaller than that of Al III for the measured values of $T_e$ and $N_e$. The estimated collision time between an electron and neutrals is in the order of a few tens microseconds. Hence the possibility of anisotropy in EDF being induced by collision of neutrals is also ruled out.

The estimated electron density and temperature are too low for collisional excitation to be the dominant process to the upper level population. The Saha equation indicates that Al IV ions are more abundant than Al III ions. This means that the upper level of the transition was populated by recombination processes from Al IV ion, indicating that recombination might create the population imbalance between the magnetic sublevels; in other words, the polarization of the spectral line. The detailed mechanism is not clear. There has been little work on this effect. This experimental observation should motivate theorists to carry out related investigation in this unexplored area. Quantitative calculations including the recombination processes are needed.

In conclusion, the degree of polarization of Al III $(4s\,^2S_{1/2}$-$4p\,^2P^o_{3/2})$ transition from laser-produced Al plas-

mas was measured using a polarization-resolved UV/visible spectrometer. The degree of polarization was measured along the laser incidence direction. This emitted line was polarized to a degree of $2.1 \pm 0.13\%$ near the target and unpolarized far from the target. The spatial anisotropy in EDF, laser polarization, and radiation trapping as possible origins of the polarization were ruled out by physical argument related to the current experimental situation. The electron temperature and density estimated by the spectroscopic method indicate that our plasma was in the recombination phase. The recombination might be considered as a cause, although the detailed mechanism is not yet clear. Since there has been little work in this area, further study is needed to understand the behavior of polarization characteristics of emitted lines in a recombining plasma.

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