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Research Article

Mass-Charge and Energy Spectra of Oxygen Ions in a Two-Element Laser-Produced Plasma

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Using a static mass spectrometer, we study the characteristics of multicharge plasma ions generated from solid targets under the action of a 15 nanosecond Nd:YAG laser radiation with maximal intensity 10^{11} W/cm^2. We consider two-element solid targets with a mass of the heavy component ranging from 44.9 (Sc) to 174.9 (Lu) with main attention to the properties of oxygen ions. The time-of-flight measurements show that oxygen ions are obtained in the range of the energy $E = 40$–250 eV with maximal charge $Z_{\max} = 2$. The latter is independent on the target composition for the given intensity of the laser radiation. However, the properties of the energy spectra of oxygen ions strongly depend on the second component of the target, which is explained by the interaction between the light and heavy elements of the target.

1. INTRODUCTION

At present, there is a number of works devoted to the study of laser-produced plasma as a source of ions for the inertial confinement fusion [1–5] together with heavy ion accelerators and the systems on the base of powerful impulse of electrical charge, that is, Z-pinches. Laser ion source (LIS) has been recently designed [6] to load the Heidelberg electron beam ion trap with a pulsed beam of lowly charged ions from solid elements. Due to many characteristics of laser-produced plasmas, LIS takes advantages over, for example, a common metal vapor vacuum arc method [7] as a source of ions.

Most of the studies of laser-matter interaction field have been carried out for the laser intensities ranging from 10^{12} to 10^{19} W/cm^2, where the interests were directed towards investigations of laser-fusion, X-ray lasers, shock-related phenomena, and so on. Not much attention was given to the low intensity part of the laser radiation (10^9–10^{12} W/cm^2). However, this regime was shown to be very useful for the material scientists in the fields of material preparation, for example, of thin films of high-T_c superconductors [8]. The laser pulsed-deposition technique shows considerable promise for the fabrication of such films.

Many theoretical [9, 10] and experimental [11, 12] works have been carried out in order to optimize the performance of the laser ion source and to determine important operating parameters such as the velocity, mass, and charge-state distribution of the generated ion beam and plasma temperature. Authors of [9] considered the case of pulsed laser desorption from planar, binary targets with the ratio of masses of light and heavy particles being 1 : 5 using the Monte Carlo simulations. They have shown that the parameters of plasma generated from two-element targets considerably differ from the ones obtained from single-element targets: the collisions between light and heavy components of the plasma take place and, as a result, the particles move predominantly in the direction normal to the target surface. These particles are more energetic than those hitting the detector at an oblique angle. They further observed that the energy is transferred from the lighter to heavier particles. In addition, lighter species have higher velocity than the heavier particles and focus the heavier particles towards the target normal. However, the mean energy of the heavier species is always higher than that of the lighter ones. The energy exchange between different species of the plasma has been recently shown experimentally by Khaydarov et al. [11]. They investigated time-of-flight (TOF) spectra of two-element PbMg targets, where the

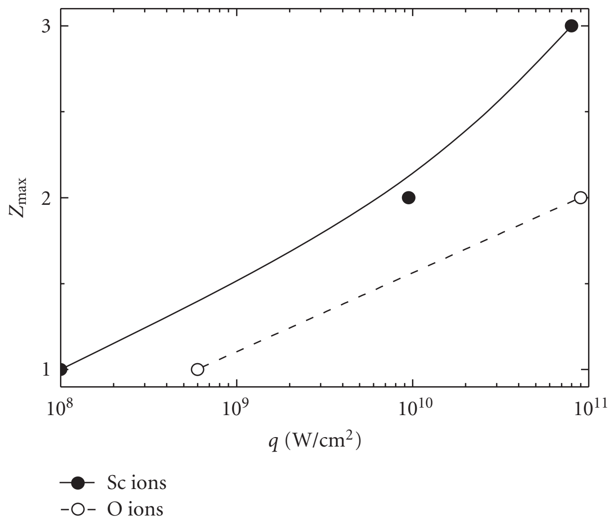

FIGURE 1: Dependence of the maximal charge Z_{max} of Sc (solid curve) and O (dashed curve) ions in the plasma on the intensity of the laser radiation q.

concentration of light element Mg was fluently changed. It was shown that the energy spectra of both light and heavy ions were broadened compared to the spectra of one-element plasma due to the energy exchange between light and heavy ions. For example, the increase of Mg concentration leads to the broadening of energy spectra of Pb ions for two times and the impulse duration for 3 to 10 times compared to one-element targets. Very recently, Srivastava et al. [12] showed that the energy transfers not only among light and heavy ions of the same species but also among different ionization states. They have also shown that the results of [9], which were obtained for neutral particles, are valid for ionized gases as well.

In this work, we study parameters of the plasma ions generated from the surface of two-element targets (i.e., oxides of elements), where the mass of the main component of the targets changes from 44.9 (Sc) to 174.9 (Lu), under the action of pulsed laser radiation using a 15 nanoseconds Nd:YAG laser, at the laser intensity 10^{11} W/cm^2. As oxygen atoms are present in most of the targets used in such experiments, we mainly focus on the properties of oxygen ions. We show that mass-charge and energy distribution of O ions strongly depend on the nature of the second component of the target, which is related to the mutual interaction of the target components.

2. EXPERIMENTAL SETUP

Experiments were carried out on a static laser mass spectrometer with mass resolution of $m/\Delta m \sim 100$ and time-of-flight distance $L = 100$ cm. The latter helps to separate ions of different mass away from the plasma region. The Nd:YAG laser beam was directed normal to the surface of the target. The duration of the laser impulse was 15 nanoseconds and the power density of the maximal laser radiation at the target surface is q = 10^{11} W/cm^2. The peak power of laser radiation varied within 5% and each experimental data is averaged over five impulses of the laser radiation. The applied extraction voltage enables us to select ions with given energy. All experiments were carried out at the same inertial conditions (vacuum (10^{-6} Torr), focusing condition of laser radiation, parameters of electrostatic mass spectrometer, etc.). The following targets (in the form of thick disks of diameter 10 mm) have been used in the experiments: Sc_2O_3 (m = 44.955), Y_2O_3 (m = 88.905), Ce_2O_3 (m = 140.11), Eu_2O_3 (m = 151.96), Dy_2O_3 (m = 162.50), Tm_2O_3 (m = 168.93), Yb_2O_3 (m = 173.05), and Lu_2O_3 (m = 174.96). Although the properties of plasma ions show nonlinear dependence on the intensity of the laser radiation (see Figure 1), we present here experimental results obtained for the maximal intensity of the laser radiation q = 10^{11} W/cm^2.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Experimentally, we obtained mass-charge spectra, that is TOF spectra of ions, in two-component laser-produced plasma. Figure 2 shows typical TOF spectra (i.e., the intensity of ions current as a function of time) of ions in Ce_2O_3 (Figures 2(a), 2(b)) and Lu_2O_3 (Figures 2(c), 2(d)) plasmas for two values of the ions energy: E/Z = 25 eV (Figures 2(a), 2(c)) and E/Z = 150 eV (Figures 2(b), 2(d)). It is seen from this figure that the O ions with maximal charge Z_{max} = 2 are observed at low energies of the ions and these peaks in the spectra disappear at higher energies. The ions of the second component of the target with maximal charge (Z_{max} = 3) are clearly seen in higher energy part of the spectra. We note that maximal charge of both light and heavy components of ions does not depend on the nature of two-element targets for a given intensity of the laser radiation. The intensity of O ions strongly depends on the target composition (especially in low energy part of the spectra). For example, for the energy of ions 25 eV, the intensity decreases with increasing the mass of the second component of the target (see Figures 2(a) and 2(c)). The latter may be explained as follows: as both species acquire the same temperature under the laser irradiation, lighter particles are desorbed with a higher velocity than the heavy species. Monte Carlo simulations show that in the latter particles move predominantly in the direction normal to the surface, where heavy particles are more strongly focused than the lighter ones [9]. Then the energy is transferred from the light to the heavy species due to the collisions. To our understanding, as the mass of the heavy species increases the total number of collisions also increase leading to higher probability of the light particles to go away from the direction of the detection, as well as to scatter back towards the target surface. However, this explanation is very crude keeping in mind very complex physical processes during the plasma formation and expansion, and more theoretical investigations are needed for this issue.

From the obtained mass-charge spectra, we constructed energy distribution of the ions, which allows us to study the effect of target composition on the parameters of plasma ions. As an example, we plotted in Figure 3 the energy spectra of ions from (a) Sc_2O_3 and (b) Lu_2O_3 plasmas. As seen from this figure, plasma ions have a broad energy spectrum with a single maximum of the distributions. The spectrum

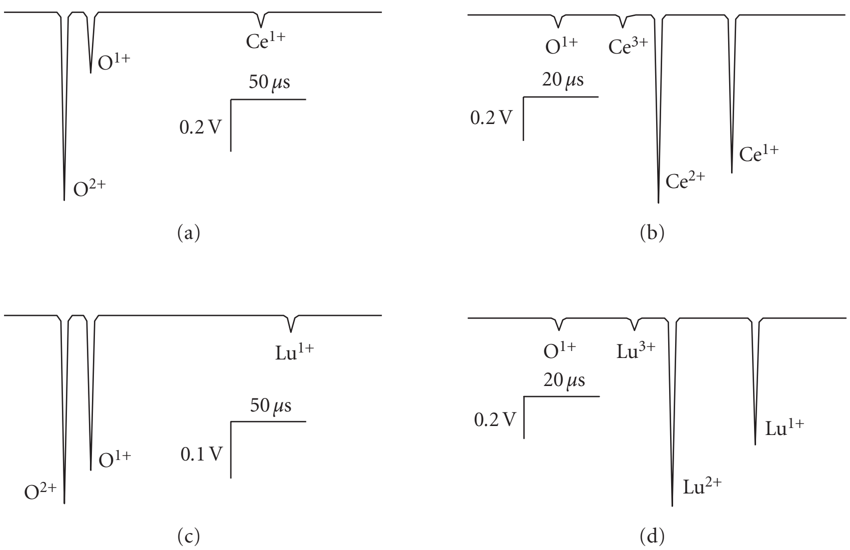

Figure 2: Typical mass-charge spectra of ions in two-element plasma, generated by the laser radiation from (a), (b) Ce_2O_3 and (c), (d) Lu_2O_3 at energies (a), (c) E/Z = 25 eV, and (b), (d) E/Z = 150 eV.

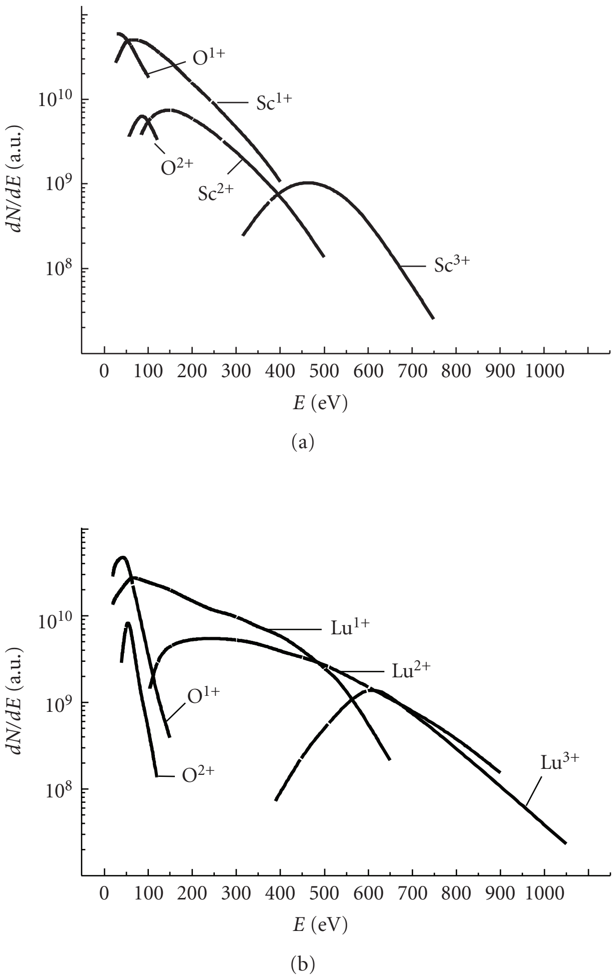

Figure 3: Energy spectra of ions in two-element (a) Sc_2O_3 and (b) Lu_2O_3 plasmas, obtained at $q = 10^{11}$ W/cm^2.

consists of different species of ions located in different energy ranges. It is also possible to observe that by increasing the charge-state the energetic distribution is shifted towards higher energy, according to the Coulomb-Boltzmann-shifted model proposed by Torrisi et al. [13]. But the decrease of the ion yields does not follow the exponential low predicted by Shirko-Lotz theory of the ionization cross-sections [14]. O ions with two ionization states are located in low energy part of the spectra, while Sc and Lu ions are located in higher energy part. As expected, the maximal energies of the second component of the target for all charge multiplicity of ions increase with increasing the mass of the ions as illustrated in Figure 4 for the cases of Sc, Ce, and Lu elements. The latter is in agreement with the previous theoretical studies [9].

Let us now consider the effect of the second component of the target to the energy distribution of O ions in more detail. Figure 5(a) shows the energy spectra of O^{1+} ions in the two-element Se_2O_3, Ce_2O_3, and Lu_2O_3 plasmas. As we mentioned above, the character of the energy spectra, for example, the width and the maximal energy, of O ions depends on the nature of the target. Single charged O^{1+} ions have a narrow energy interval ($E_{max} \leq 100$ eV) for small mass ratio (i.e., Sc ions) (solid curve in Figure 5(a)). With increasing the mass of the second component (Ce ions) the maximal energy increases more than two times (dashed curve in Figure 5(a)). Although E_{max} of O^{1+} ions slightly decreases with further increasing the mass of the second component of the target, it is still larger than the case of Sc ions. The energy spectra of O^{2+} ions for different mass of the second component of the target are shown in Figure 5(b). O^{2+} ions are mostly located in the interval of the energy between 40 eV and 120 eV and the energy range of the ions in this case does not strongly depend on the target composition.

It is noticeable that the increase of the mass of the second component of the target leads to considerable changes

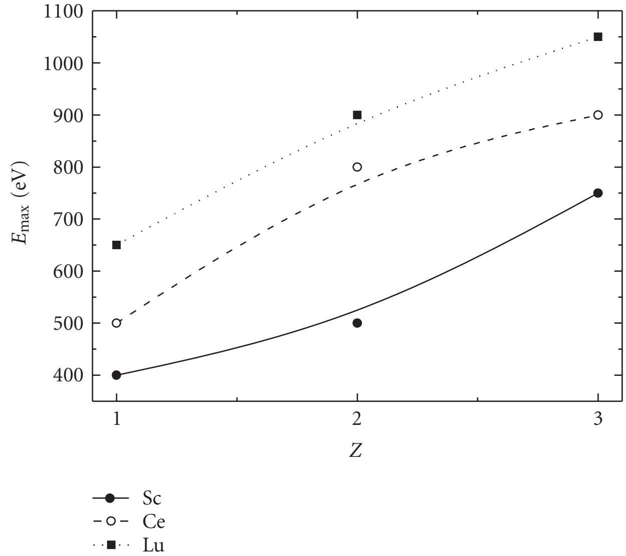

FIGURE 4: Dependence of the maximal energy of Sc, Ce, and Lu ions on the charge multiplicity of ions.

in the spectrum of O ions. For example, the intensity and the maximal energy of O ions increase with increasing the mass of the second component of the target, which we relate to energy exchange between heavy and light components of the plasma. As we mentioned above, this energy transfer was already shown both theoretically [9] and experimentally [11, 12]. However, in these studies the mass ratio of the plasma particles was fixed. In what follows, we have performed our experiment for large number target composition. Figure 6 shows the maximal energies of O^{1+} (solid curves) and O^{2+} (dashed curves) ions as a function of the mass of the second component of the target. It is seen from this figure that the maximal energy of single charged oxygen ions increases with increasing m, which is in good agreement with the recent experiments [12]. This may indicate that even light species of the plasma also can gain from the collisions. With further increasing m, the energy decreases and starts to saturate after $m > 160$ amu. However, we could not explain this dependence of the maximal energy of the O^{1+} ions on the mass of the heavier species. The maximal energy of doubly charged oxygen ions does not strongly depend on m.

Figure 7 shows the dependence of the total number of oxygen ions on m for both charge multiplicities. As expected, the intensity of single charged O^{1+} ions is always larger than the one for doubly charged O^{2+} ions. The latter considerably decreases with increasing m, whereas the intensity of O^{1+} ions increases first for $m < 140$ amu and only after that it decreases for larger mass m. This behavior of light ions is difficult to explain only in the framework of energy transfer between the ions, but the complex thermal desorption mechanisms should be taken into account.

Comparative study of O ions and Sc (Ce, Lu) ions shows that the process of formation and expansion of O ions of all charge multiplicity is determined by the composition of the target. In spite of their different thermophysical parameters,

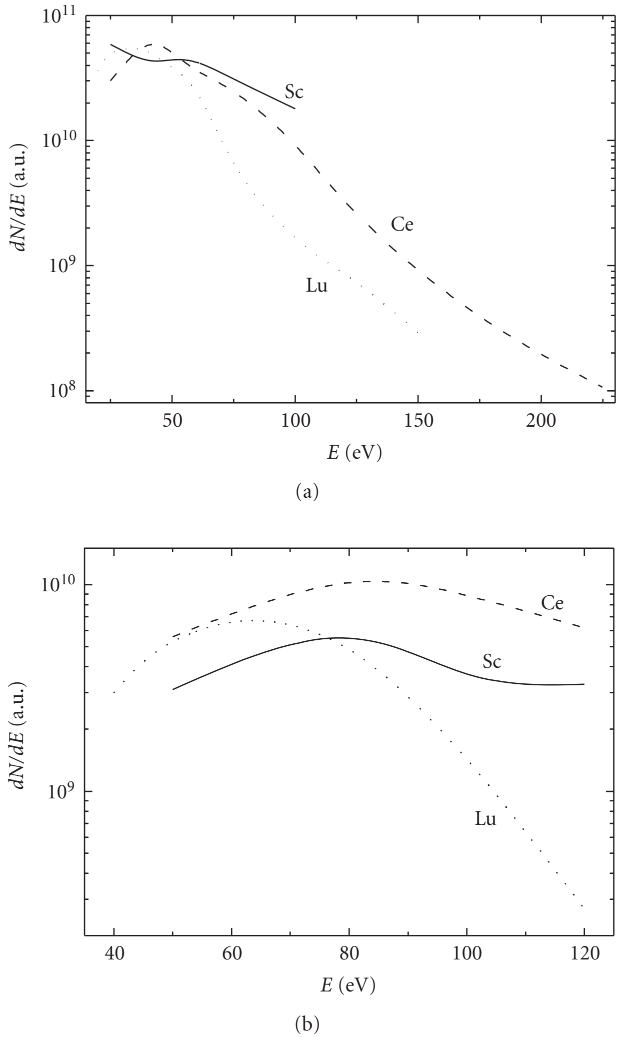

FIGURE 5: Typical energy spectra of (a) O^{1+} and (b) O^{2+} ions in two-element Sc_2O_3 (solid curves), Ce_2O_3 (dashed curves), and Lu_2O_3 (dotted curves) plasmas.

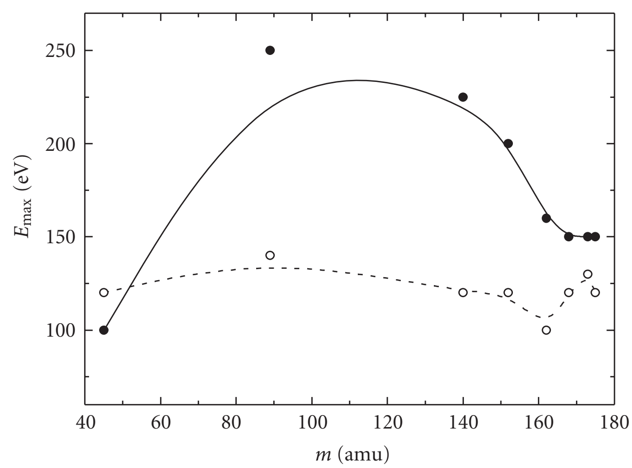

FIGURE 6: Dependence of maximal energy E_{max} of O^{1+} (solid lines) and O^{2+} (dashed lines) ions on the mass of the second component of the plasma.

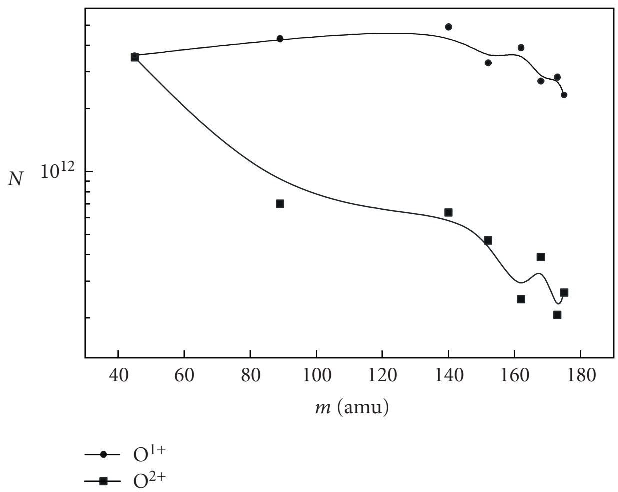

FIGURE 7: Total number of O^{1+} (circles) and O^{2+} (squares) ions as a function of the mass of the second component of the target.

these elements differ with the mass and it is much larger than the mass of oxygen (mass of Sc, Ce, and Lu atoms are 3, 9, and 11 times larger than the mass of oxygen atoms). This difference in mass plays a considerable role in the formation of two-element plasma, and consequently, to the energy exchange between the ions. Due to the lack of the experimental results for pure Sc, Ce, and Lu targets, it is difficult to conclude about the effect of the oxygen ions to the properties of the ions of the second component of the target.

4. SUMMARY

We have reported time-of-flight measurements of ions produced by laser radiation from solid targets consisting of light (oxygen) and heavy components of different atomic mass *m*. We found out that the maximum charge of plasma ions does not depend on the nature of the target for considered low intensity of the laser radiation. However, the maximal energy and intensity of light elements of all charge state strongly depend on the mass of the heavy component of the target, which we related to the energy-exchange between different kinds of ions.

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