Interaction of laser radiation with two-element Sc$_2$O$_3$, Ce$_2$O$_3$, Eu$_2$O$_3$ and Lu$_2$O$_3$ targets

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Abstract. Multi-charge plasma ions generated on the surface of solid targets under the action of the laser radiation are studied using a static mass-spectrometric. We consider two-element Sc$_2$O$_3$, Ce$_2$O$_3$, Eu$_2$O$_3$ and Lu$_2$O$_3$ targets 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 $Z_{\text{max}}=2$. Although the maximal charge of O ions is independent on the target composition for the given intensity of the laser radiation, the other properties the ions (e.g. maximal energy, intensity) depend on the second component of the target, which is explained by the interaction between the light (O) and heavy (Sc, Ce, Eu, Lu) component of the target.

1. Introduction
It is known that intense beams of multi-charged ions are widely used in many different areas of physics as well as in the inertial confinement fusion program [1]. Such an interest to charged heavy ions is due to a number of important advantages, as energy carrier, over laser radiation and electron beams. Laser source of ions is capable to supply highest intensity in a single cycle injection of multi-charge ions practically in any element of accelerators. For its practical application one should have possibility to extend ions impulse keeping the intensity and charge of ions unchanged. One way to achieve this effect is to use composite targets. In Ref. [2] two-element PbMg targets were investigated where the concentration of light element Mg was fluently changed. It was shown that the energy spectra of both light and heavy ions were enlarged compared to the spectra of one-element plasma due to the energy exchange between light and heavy ions. Laser-produced plasma ions generated from porous Ho$_2$O$_3$ target were studied in Ref. [3] depending on the target density. It was experimentally shown that at low energy part of the spectra ($E \leq 50$ eV) maximal charge for oxygen ions is reached at low densities, while maximal charge of Ho ions is obtained at higher target densities. This effect was related to non-equilibrium ionization processes in the plasma due to the changing of the volume, which absorbs laser radiation.

In this work we investigate the properties of plasma ions generated from the surface of two-element (Sc$_2$O$_3$, Ce$_2$O$_3$, Eu$_2$O$_3$, and Lu$_2$O$_3$) targets under the action of the laser radiation. As oxygen atoms are present in most of the targets used in such experiments, we mainly focus on the properties of oxygen ions. We find that mass-charge and energy distribution of O ions strongly depend on the mass of the
second component of the target, which is due to the mutual interaction between different target components.

2. Experimental setup
Experiments were carried out on a static laser mass-spectrometer with mass resolution of \( m/\Delta m \approx 100 \) and time-of-flight distance \( L=100 \) cm. The Nd:YAG laser beam was directed normal to the surface of the target. The duration of the laser impulse is 15 ns and the power density of the maximal laser radiation at the target surface is \( q=10^{11} \) W/cm\(^2\). All measurements were carried out at the same inertial conditions (vacuum 10\(^{-6}\) Tor., focusing condition of laser radiation, parameters of electrostatic mass-spectrometer, etc.). We repeated each measurement several times in order to remove residual contaminations (e.g. carbon, hydrogen) from the target surface. The following targets (in the form of thick disks of diameter 10 mm) have been used in the experiments: Sc\(_2\)O\(_3\), Ce\(_2\)O\(_3\), Eu\(_2\)O\(_3\) and Lu\(_2\)O\(_3\).

3. Results and discussion
Experimentally we obtained mass-charge spectra, i.e. time-of-flight (TOF) spectra of ions in two-component laser-produced plasma. Oxygen ions with maximal charge \( Z_{\text{max}}=2 \) are observed at low energies of the ions and these peaks disappear from the TOF spectra at higher energies. The ions of the second component of the target with maximal charge \( Z_{\text{max}}=3 \) are obtained in higher energy part of the spectra. The intensity of O ions strongly depends on the target composition (especially in low energy part of the spectra), e.g. it decreases with increasing the mass of the second component of the target. We note that the maximal charge of both light and heavy component of ions does not depend on the nature of two-element targets for a given intensity of the laser radiation.

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. Fig. 1 shows the energy spectra of ions from Sc\(_2\)O\(_3\) (a), Ce\(_2\)O\(_3\) (b), Eu\(_2\)O\(_3\) (c) and Lu\(_2\)O\(_3\) (d) plasma. As seen from this figure plasma ions have a wide energy spectrum with a single maximum of the distributions. The latter indicates that the process taking place in two-element plasma can be divided into to stages: at the first stage (before the maximum) intense ionization takes place, which is accompanied by the formation of multi-charged ions of both O and Sc (Ce, Eu, Lu); the second stage (after the maximum) is characterized by the increase of recombination process as well as by the energy exchange between light (O) and heavy (Sc, Ce, Eu, Lu) ions of two-component plasma, which qualitatively agrees with the theoretical results for the expansion of two-component plasma in vacuum [4]. It is also seen that the spectrum consists of two packages of ions located in different ranges of the energy. O ions with charge \( Z=1,2 \) are located in low energy part of the spectra, while heavy ions are located in higher energy part. There is also an overlap of energy spectrum of O ions and Sc (Ce, Eu, Lu) ions. The maximal energy of the second component of the target for all charge multiplicity of ions increases with increasing the mass of the ions. It is noticeable that the increase of the mass of the second component of the target leads to considerable changes 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 is due to the energy exchange between heavy and light components of the plasma.
Figure 1. Energy spectra of ions in two element Sc$_2$O$_3$ (a), Ce$_2$O$_3$ (b), Eu$_2$O$_3$ (c) and Lu$_2$O$_3$ (d) plasma, obtained at $q=10^{11}$ W/cm$^2$.

Figure 2. Typical energy spectra of O$^{1+}$ (a) and O$^{2+}$ (b) ions in two element Sc$_2$O$_3$, Ce$_2$O$_3$, Eu$_2$O$_3$, and Lu$_2$O$_3$ plasma.
Let us now consider the effect of the second component of the target to the energy distribution of O ions in more detail. Fig.2 (a) shows the energy spectra of O$^{1+}$ ions in the two-element Se$_2$O$_3$, Ce$_2$O$_3$, Eu$_2$O$_3$, and Lu$_2$O$_3$ plasma. As we mentioned above character and the width of the energy spectra of O ions and the maximal energy depends on the nature of the target. Single charged O$^{1+}$ ions have a narrow energy interval ($E_{\text{max}} \leq 100$ eV) for small mass ratio (i.e., Sc ions) (filled circles in Fig. 2 (a)). With increasing the mass of the second component (Ce ions) the maximal energy increases more than two times (open circles in Fig. 2 (a)) due to the energy exchange between the ions of different mass. However, with further increasing the mass of the second component (filled and solid squares) the energy spectrum of O$^{1+}$ ions again decreases. This nonlinearity indicates to the complex processes taking place in the highly charged plasmas. The energy spectra of O$^{2+}$ ions for different mass of the second component of the target are shown in Fig. 2 (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. However, the number of ions per energy unit ($dN/dE$) is affected by the mass of the second component of the target. The latter again show the nonlinear behaviour.

4. Conclusions
Using the mass-spectrometric method we studied mass-charge and energy spectra of two-element laser produced plasma ions generated from the surface of solid targets consisting of oxygen atoms and atoms of rear-earth materials. We found out that the maximum charge of plasma ions does not depend on the nature of the target for a given intensity of the laser radiation. The energy spectra of plasma ions consist of two packages of ions located in different energy ranges. Oxygen ions with charge $Z=1,2$ are located in low energy part of the spectra, while the second component of the plasma has larger energy diapason. We also found that the formation of mass-charge and energy spectra of multi-charge ions in two component plasma are described not only by the ionization and recombination processes, but also by the mutual interaction between the ions of different mass.

Acknowledgments
This work is supported by IAEA (contract UZB- No: 13738)

References
[1] H. Hora, Laser and Part. Beams 22, 439-450 (2004).
[2] R.T. Khaydarov, G.R. Berdiyorov, U.S. Kunishev, M.G. Khalmuratov, E. Tojikhanov, M. Kanapathipillai, Laser and Particles Beams 23, 521-526 (2005).
[3] R.T. Khaydarov, AIP Conference Proceedings Series, 875, 2006, Plasma and Fusion Science, ISBN 978-0-7354-0375-8, ISSN 0094-243X.
[4] S.I. Anisimov, Plasma Phys 8, 1045 (1982).