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Effect of Recombination Processes and the Experimental Estimation of Ionization State in Laser-Produced-Plasmas

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Abstract

The experimental measurements of the average ionization states of the plasma produced from slab targets of carbon, aluminum, titanium, nickel, molybdenum and tantalum, using a 5ns Nd: YAG laser, at a laser intensity in the vicinity of 7×10^{10} W/cm^2, are reported. The experimental results have been compared with those of the theoretically calculated ones using the steady state collisional radiative (CR) ionization model. It is observed that a significant difference between the two sets exists and is being reported for the first time. From physical considerations one is inclined to consider the possibility of recombination-processes quenching the ionization states faster before detection as one goes towards higher and higher values of the atomic number of the target element.

Keywords:

Ionization state, recombination processes, laser-plasma interaction

1. Introduction

In the hurried quest for laser-fusion and related high-profile physics problems we have not given sufficient and due attention to the experimental investigations of basic plasma properties such as thermodynamic equilibrium, equipartition of energy between electrons and ions and the ionization state of the ions, which depend very significantly on the electron temperature and density. In many investigations on laser-produced plasmas and, specially on the studies of x-ray lasers, one has to know exactly what the ionization states of the plasma under various conditions of plasma temperature and density are. In the investigations related to x-ray lasers many workers [1-5] have theoretically obtained the average ionization states of the plasma taking into account the balance between the ionization rate on the one hand and the radiative, three-body and dielectronic recombination rates on the other, as a function of the plasma temperature and density. As experimental data on the average ionization states of various materials with varying atomic number under conditions of various plasma temperatures and densities are scarcely to be found in the literature, one is not sure how near or how far the theoretically determined average ionization states are form the experimentally estimated ones. One is also curious to know how the three recombination processes, the radiative, the three-body and the dielectronic, influence the ionization state under different situations of the plasma density and the plasma temperature. In the present work we have accurately measured the average ionization states of the plasma produced from slab targets of carbon, aluminum, titanium, nickel, molybdenum and tantalum. We have compared these results with those of the theoretically calculated ones using the CR ionization model and a significant difference between the two sets, hitherto unreported, has been observed for the first time.

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2. Theoretical and Experimental Consideration

Using the steady-state CR ionization model, the ion densities in the consecutive charge states n_{z+1} and n_z were obtained using the relations given by the earlier authors [4,6]. The expressions for ionization coefficient as well as for radiative and three-body recombinations are due to McWhirter [7] and Kolb and McWhirter [8]. Based on the works of Apruzese *et al.* [9], Whitten *et al.* [2] and Hagelstein *et al.* [1] have concluded that the dielectronic recombination coefficient D_{ez+1} can be safely assumed to vary between 1×10^{-12} to $1 \times 10^{-11}\text{cm}^3\cdot\text{s}^{-1}$. Therefore, in our calculations we have considered three values for the dielectronic recombination coefficient as $D_{ez+1} = 1 \times 10^{-11}$, 5×10^{-12} and $2 \times 10^{-12}\text{cm}^3\cdot\text{s}^{-1}$.

A schematic representation of the experimental arrangement is shown in Fig.1. The plasma is created by a Nd: YAG Q-switch pulse ($\tau = 5$ns, $\lambda = 1.06\mu$m) in the TEMoo mode of variable energy incident at a fixed angle of –45° onto flat, rotating targets inside a vacuum chamber. The investigated materials are carbon, aluminum, titanium, nickel, molybdenum and tantalum. The laser energy varied from about 20 mJ to 180 mJ and a flux density variation from approximately 10^{10} to 10^{11} W/cm^2. The freely expanding ions of the plasma were investigated in the angular range from $\theta = -17.5°$ to 60° relative to the target normal and at a distance of 37.5cm from the target. Analysis of the ion velocity distribution and charge was obtained by means of a time of flight retarding potential detector whose transmission function was controlled carefully. Complete details of the experimental arrangement and the measurement technique have been earlier reported by Mann and Rohr [10].

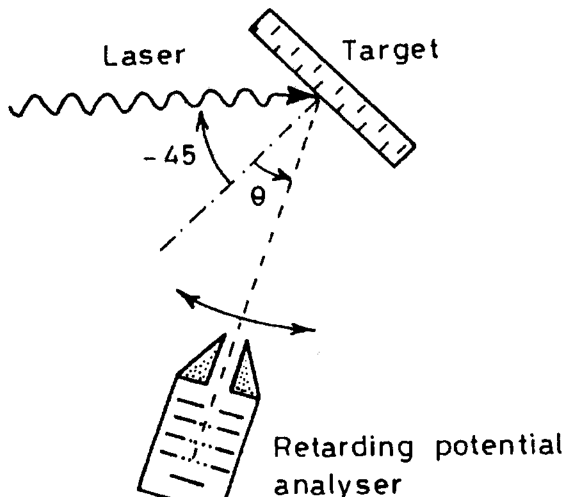

Fig. 1 The scheme of the experimental set up.

3. Results and Discussion

The experimental results of the average ionization Z, which is given by the expression $\Sigma Z^+N^{z+}/\Sigma N^{z+}$, where N^{z+}, represents ions with charge Z^+, are displayed for carbon, aluminum, titanium, nickel, molybdenum and tantalum in Fig.2, respectively. An incident laser energy of 180 mJ corresponds to a laser intensity of about 7×10^{10} W/cm^2. We observe that the average ionization Z is not isotropic with reference to the angle of observation but it is anisotropic. It has the maximum value approximately at the detection angle of 0° and in a narrow cone around it and, then, decreases as θ goes farther from 0° and away. This trend is observed starting from carbon ($Z = 6$) to Ta($Z = 73$).

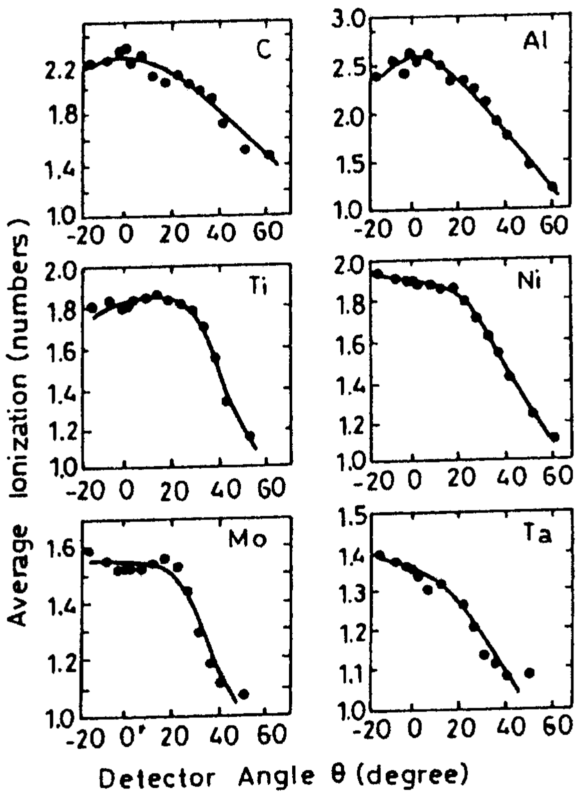

Fig. 2 Average ionization Z as a function of emission angle θ at incident laser energy of 180 mJ for carbon (graphite), aluminum, titanium, nickel, molybdenum and tantalum.

In Fig.3 we have displayed the values of maximum average ionization as a function of laser energy for the elements carbon, aluminum, titanium, nickel, molybdenum and tantalum. The maximum ionization has been plotted for all the elements as a standard reference. Here we find a trend which has an element of consistency. For low Z values like those of carbon $Z = 6$ and aluminum ($Z = 13$) the average ionization increases with energy. For elements like Ti($Z = 22$) and Ni($Z = 28$) the average ionization increases up to an incident laser energy of 40 mJ and then decreases as the energy increases from 40 mJ to 180 mJ. For elements like molybdenum ($Z = 42$) and tantalum ($Z = 73$) the average ionization is maximum at an incident laser energy of 20 mJ and slowly decreases as the energy increases up to 180 mJ. Moreover, one more trend is clearly discernible. As the value of Z, the atomic number, increases, the experimentally determined values of maximum average ionization, or, in a sense, the values of average ionization decreases for a given incident laser energy. From Fig.4 it is observed that as the density increases, the average ionization, at estimated electron temperature of Te = 30eV, slowly falls and the fall is sharper between a density of 10^{20} to 5×10^{20}cm^{-3}. Between densities of 10^{17}cm^{-3} to 10^{19}cm^{-3} the fall is very slow.

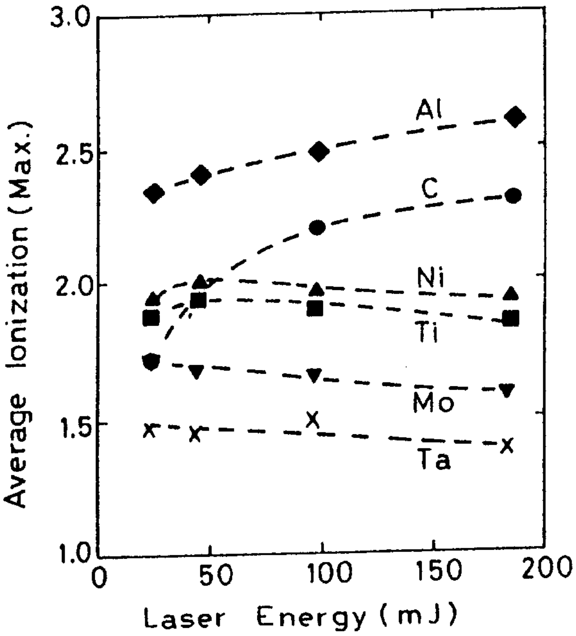

Fig. 3 Maximum value of average ionization in the vicinity of emission angle $\theta = 0°$ as a function of incident laser energy for carbon, aluminium, titanium, nickel, molybdenum and tantalum.

That is to say, the effect of the three recombination processes is profound at a density higher than 10^{20} cm^{-3}. The effect of dielectronic recombination coefficient does not seem to vary much with the density. In the density range of 10^{17}cm^{-3} to 5×10^{20}cm^{-3}, as we vary the dielectronic recombination coefficient from 1×10^{-11} cm^{3}·s^{-1} to 2×10^{-12}cm^{3}·s^{-1}, the variation in average ionization state is of the order of 10% or less for all the three elements. This point should be noted, because, as mentioned earlier, the exact values for dielectronic

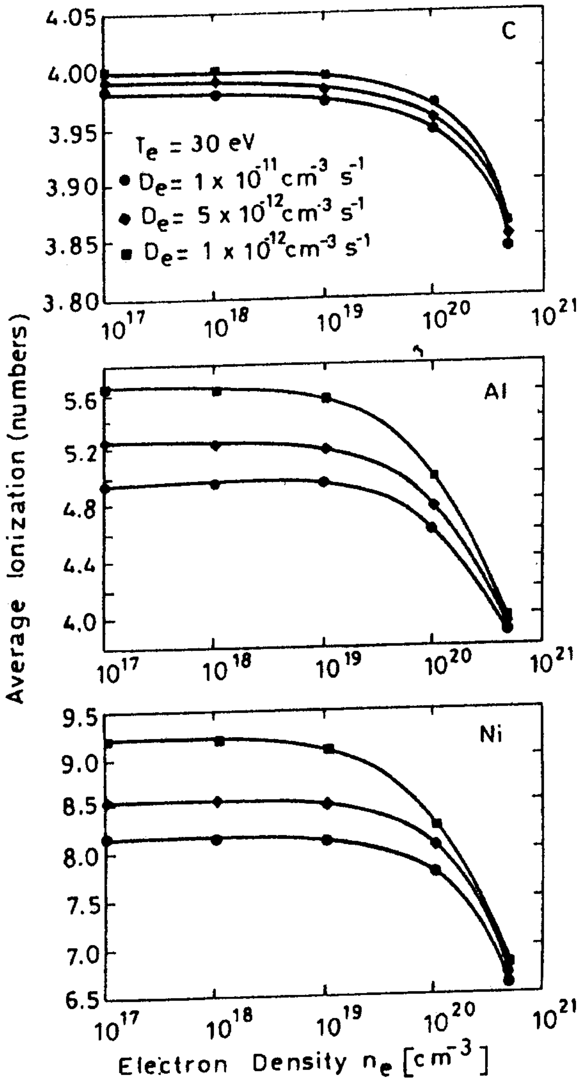

Fig. 4 Theoretically estimated average ionization for carbon, aluminum and nickel as a function of electron density and at an electron temperature of T_e = 30 eV for three different values of dielectronic recombination coefficients which are given by D_e = 1×10^{-11}, 5×10^{-12} and 2×10^{-12}cm^{3}·s^{-1}.

recombinaion coefficient are difficult to obtain.

The most significant results of the present investigation, hitherto unknown and hitherto unreported, are contained in Fig.3 and 4. Figure 3 itself is derived from Fig.2. We keenly observe that as the laser enegy increases from 20 mJ to 180 mJ, the average ionization of carbon ($Z = 6$) and aluminum ($Z = 13$) increases from 1.72 and 2.35 to 2.3 and 2.6, respectively. This seems to be in order as with the increase in laser energy, the plasma temperature increases and hence, the ionization state. But for the second set of elements titanium ($Z = 22$) and nickel ($Z = 28$) average ionization increases slightly from values of 1.88 for Ti and 1.94 for Ni up to an incident laser energy of 40 mJ and then slowly decreases as the laser energy increases up to 180 mJ. In the third set of the elements molybdenum ($Z = 41$) and tantalum ($Z = 73$) the picture is completely different. Here as the laser energy is increased from 20 mJ to 180 mJ, the average ionization (1.48 for Ta and 1.72 for Mo at 20 mJ) slowly decreases instead of increasing. Moreover, from Fig.4 one notes that theoretically calculated average ionizations are in the vicinity of 4.0, 5.2 and 8.6 for carbon, aluminum and nickel. For tantalum it has been separately calculated to be in the vicinity of 12.

From the physical considerations it seems that the recombination effects are fast and profound as one goes to elements with higher atomic number. At the initial stage of plasma production it is possible that the plasma is produced with a higher value of ionization state, which gets quenched to lower values due to possibly faster recombination processes. One also notes that the values of ionization energy of different ionization stages gets smaller and smaller as one goes towards higher values of Z. As a result, for a given laser energy, for ions of higher Z-values, ionization states are higher and, hence, the electron densities enhance the recombination rate before the detection-system is in a position to detect them.

It is important to note that during the adiabatic expansion of the plasma the three recombination processes (1) the radiative, (2) the three-body and (3) the dielectronic ones come into play. But after the laser action has terminated, the ion-composition of the plasma mainly changes due to the effect of the three-body recombination which predominates over the radiative and dielectronic ones due to a large drop in the plasma temperature as the plasma expands into vacuum. Three-body recombination has a strong influence throughout the entire duration of the plasma expansion, right up to the time when it enters the detectors [11]. The ions located at the front of the expanding plasma acquire the largest energy during the hydrodynamic acceleration and rapidly fly apart. As a result, their charge composition is considerably less influenced by recombination and the average-charge of the ions in the high-energy part of the spectrum roughly corresponds to that in the heating phase. But the ions located in the inner plasma layers are accelerated much less during the expansion and remain much longer in the denser state, which results in being subjected to strong recombination [11]. As the mass of high Z-elements is much higher than those of low-Z elements, the high-Z ions are likely to stay still longer in the denser state. This explains the higher recombination quenching of the ionization state of the high-Z elements.

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