FORMATION OF THE ENERGY SPECTRUM OF THE IONS OF A LASER PLASMA

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Plasma produced by laser irradiation of solid targets has recently become an important research subject.

In [1, 2] the behavior of the energy spectra of the ions is attributed to ion acceleration and recombination. The influence of these processes on the angular distributions of the ions of a laser plasma was noted in [3]. An analysis of the results of these investigations shows that with increasing radiation flux density (q) a change takes place mainly in that part of the spectrum in which there are highly charged ions (energy $\sim E_{max}$), whereas the low-energy region of the spectrum changes little and saturation with respect to the number of registered ions is observed in this part of the spectrum. In the high-energy region of the spectrum there are also singly-charged ions, the appearance of which has been attributed to recombination of more highly charged ions accelerated to a higher energy. Such a process leads to the appearance of "recombination" maxima on the distributions of the ions with the lower charges. It is assumed that the dependence of the energy of the registered ions E on the charge z is determined by acceleration in a self-consistent electrostatic field. The field is due to the fact that the electrons, having essentially higher thermal velocities, tend to leave the plasma. The greatest loss of neutrality occurs on the periphery of the plasmoid, at a distance on the order of the Debye radius r_D. The ions moving in the resultant field are accelerated to velocities much higher than thermal, and then the maximum kinetic energy E_{max} of the ions should depend on the charge z and should change little with the mass M of the ion.

The purpose of the present investigation was to separate experimentally the influences of acceleration and recombination on the ion energy spectra. To this end, we investigated mixtures of two elements, one of which produces only

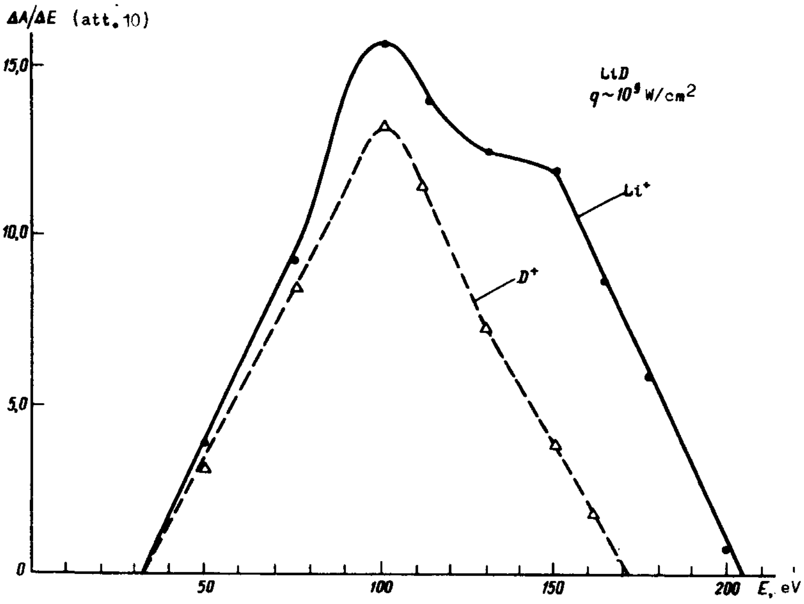

Fig. 1. LiD target, $q \sim 10^9$ W/cm^2: Δ - D^+, ● - Li^+.

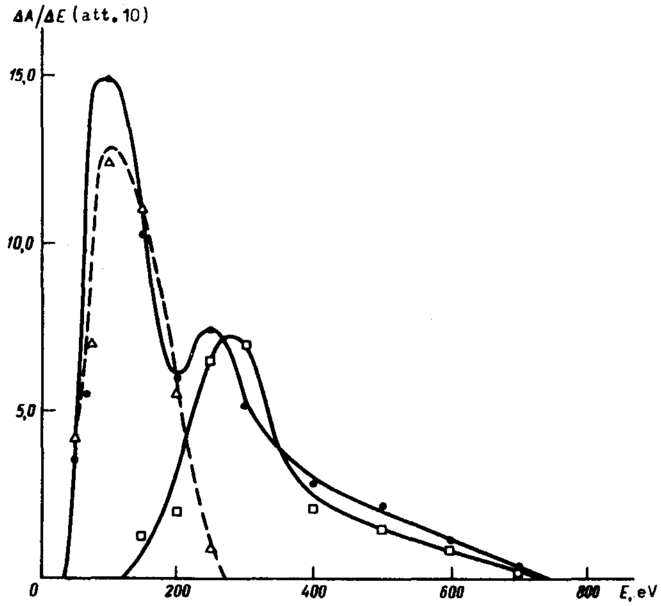

Fig. 2. LiD target, $q \sim 10^{10}$ W/cm^2: Δ - D^+, ● - Li^+, □ - Li^{2+}.

singly-charged ions and the other also multiply charged ions. A detailed study was made of the energy distributions of hydrogen and zirconium ions (zirconium hydride) and deuterium and lithium ions (LiD) at different flux densities q.

1. As seen from Figs. 1 - 3, the energy distributions of the H^+ and D^+ ions have each one ("principal") maximum whose position is practically independent of the value of q. The energy of the "principal" maximum is (100 ± 10) eV. At the same time, additional maxima are observed on the distributions of Li^+ and Zi^+ (for example, in Fig. 2 the energy of the additional maximum of Li^+ corresponds to the energy of the maximum of Li^{2+}). In addition, a comparison of the forms of the energy distributions of the H^+ and D^+ ions with those of Li^+ and Zi^+ allows us to state that the complex structure of the distributions of the latter is not connected with the spatial inhomogeneity of q over the focal spot.

2. We measured E_{max} as a function of f(q) for hydrogen, deuterium, lithium, and zirconium ions. The functions were described by the expression $E_{max} \sim q^{\gamma}$, with $\gamma = 0.25 \pm 0.03$ for H and D and $\gamma = 0.52 \pm 0.05$ for Li and Zr. The stronger dependence of E_{max} on q for Li and Zi is connected with the increase of z_{max} with increasing q. By integrating the total energy spectra we obtained the dependence of the number Σ of the registered ions on q, namely $\Sigma \sim q^{\alpha}$, with $\alpha = 0.08 \pm 0.1$ for D and $\alpha = 1.1 \pm 0.1$ for Li. It is interesting to note that the zirconium hydride sample had a stoichiometry $ZiH_{1.9}$, but the complete integrals over the number of registered particles have a ratio $\Sigma_{Zr}/\Sigma_{H} \approx 70$ (Fig. 3). A similar picture was observed also for the LiD mixture. This indicates that the number of registered particles depends strongly on z_{max}, confirming the influence of the electric field in the plasma on the spreading of the registered part of the ions.

3. From the experimental results we can determine the ratio of the maximum velocities of the ions contained in the investigated targets. It turns out that $v^{D}_{max}/v^{Li}_{max} \approx 1.7$ and $v^{H}_{max}/v^{Zr}_{max} = 5.5$ at $q \sim 10^9$ W/cm^2. We see therefore

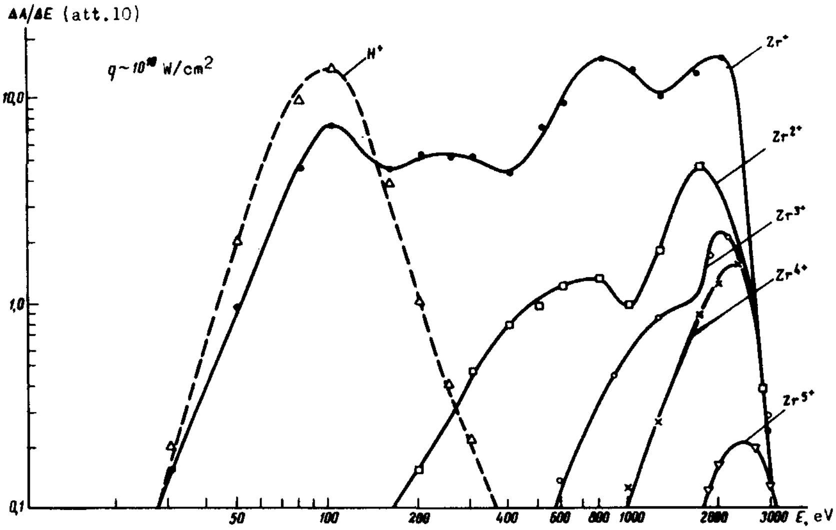

Fig. 3. ZrH target, $q \sim 10^{10}$ W/cm^2: Δ - H$^+$, ● - Zr$^+$, □ - Zr^{2+}, o - Zr^{3+}, × - Zr^{4+}, ∇ - Zr^{5+}.

that the H$^+$ and D$^+$ ions overtake the ions of the heavier elements having the same charge since all the elements form only singly-charged ions at this density [2]. With increasing q, the ratio of the maximum velocities decreases, since the value of u_{max} is influenced by z_{max}. For example at $q \sim 10^{11}$ W/cm^2 we have $v^H_{max}/v^{Zr}_{max} \approx 3.1$ [$z_{max}(Zr) = 6$] and $v^D_{max}/v^{Li}_{max} \approx 1$ [$Z_{max}(Li) = 3$].

4. It was shown in [2] that at a constant flux density, for elements with atomic number $A \leq 20$, E_{max} increases with increasing A. E_{max} is constant for elements with $A > 20$. We shall show that for elements with $A \leq 20$ an increase of z_{max} with increasing A occurs at q = const, and that for heavier elements the maximum charge multiplicity was the same. The ratio E_{max}/z^{α}_{max} (where $\alpha = 1 - 2$) turns out to be independent of A in the entire range of investigaged elements and radiation flux densities, i.e., E_{max} actually depends little on the ion mass and is a function of z_{max}, thus indicating an electrostatic mechanism of ion acceleration.

5. Taking into account the aperture of the analyzer section of the instrument and the gain of the recording section, we can estimate the absolute number of ions emitted by the plasma, $N_{emit} \approx 10^{11}$ particles at $q \sim 10^{11}$ W/cm^2. At this value of q, the number of evaporated atoms is $N \sim 10^{16}$ [4]. The ratio of the number of accelerated ions to the total number, assuming that the ions are accelerated by an electrostatic field due mainly to a peripheral distribution of the plasmoid charges, is estimated at

$$N_{acc}/N_{tot} \sim r_D/R_0 .$$

where r_D is the local Debye radius and R_0 the initial radius of the plasma. For characteristic values $r_D \sim 10^{-6} - 10^{-7}$ and $R_0 \approx 10^{-2}$ we obtain $N_{acc}/a_{tot} \sim 10^{-4} - 10^{-5}$, which is in satisfactory agreement with experiment. We can conclude from the foregoing data that during the later stage of the expansion of the laser plasma only accelerated ions are registered, and the bulk of the ions moves with thermal velocities and recombines.

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LUMINESCENCE RESONANT RAMAN SCATTERING IN $Zn_xCd_{1-x}Te$ CRYSTALS

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Resonant Raman scattering (RRS) in semiconductors has been the subject of a number of investigations [1 - 5]. The role of bound excitons in RRS and resolution of the emission spectrum into a hot-luminescence spectrum and Raman scattering (RS) spectrum has been investigated in [5, 8, 11]. Theoretical calculations [6, 7] show that equality of the frequency of the exciting light ω_L or of the scattered light ω_s to the frequency of the exciton transition ω_{exc} is accompanied by a sharp increase of the RRS intensity. The experimental results [2, 3] indeed show that enhancement of RRS is observed when the frequencies ω_L or ω_s are close to ω_{exc}. It has been impossible so far, however, to investigate in detail the behavior of the intensity of the scattered light when the frequency is continuously varied in the region of exciton absorption[1]. The present paper is devoted to this question.

We investigated RRS in mixed $Zn_xCd_{1-x}Te$ crystals, in which the width of the forbidden band (and consequently the frequency of the exciton transition) varies smoothly in a wide range (7800 - 5200 Å) [9] when the crystal composition is varied. An investigation of the RRS of a group of samples with different compositions has made it possible to vary in suitable fashion the frequency of the exciton line relative to the fixed frequency of the exciting light.

The experiments were performed with an He-Ne laser (E_L = 1.9586 eV) at T = 4.2°K and T = 77°K. The concentration x in the investigated samples ranged from 0.4 to 0.5, corresponding (at T = 4.2°K) to a change in the forbidden-band width from 1.905 to 1.965 eV.

The emission spectrum obtained by us for the mixed crystals $Zn_xCd_{1-x}Te$ at T = 4.2°K consists of a series of luminescence lines (line group 1, 2, 3, 4 in Fig. 1). Line 1 corresponds to the emission line n = 1A of the free exciton, as established by comparing the luminescence spectra with the exciton-reflection spectra. Line 2 is due to emission of bound excitons with binding energy ~3 meV, which apparently corresponds to the "exciton plus neutral donor"

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[1] Damen and Shah [8] investigated RRS with the aid of a continuously tunable laser. Extensive use of such lasers is presently difficult, however, in view of their imperfections.