Spectroscopic observation of MeV-range multiply charged ions in a laser plasma

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The broadening of the resonance line of the helium-like ion of phosphorus emitted by a laser plasma is discussed. The broadening is interpreted as a Doppler frequency shift of the emission of high-energy P^{+13} ions. The energy spectrum of these fast ions is determined. The temperature of the electrons responsible for the ion acceleration is estimated.

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The methods of x-ray spectroscopy[1] are widely used in research on laser plasmas, particularly in experiments on the heating and compression of targets in laser fusion devices (see Ref. 2, for example). An important part of such experiments is to study the mechanisms for the production of electrons and ions in the plasma; these mechanisms significantly affect both the energy balance in the targets and the compression of the targets. In the present experiments we detected the emission of fast ions from a laser plasma, constructed their energy spectrum, and estimated the temperature of the fast electrons responsible for the ion acceleration.

The laser plasma is produced by the linear stages of the preamplifier of the Del'fin device.[3] The beam from a neodymium laser with an energy ~20 J and a divergence 2.3×10^{-4} rad is focused by an aspherical objective onto a massive plane phosphorus target. The diameter of the focal spot is $\sim 40\,\mu$m, and the corresponding irradiance on the target surface is $\sim 2 \times 10^{14}$ W/cm^2.

The emission spectrum from the laser plasma (Fig. 1) is measured over the wavelength interval 4.4–6 Å with an x-ray spectrograph with a plane CaF_2 crystal on UF-VR x-ray film, whose blackening curve has been published.[4] The calcium fluoride crystal used in these experiments ([111], $2d = 6.28$ Å) has a reflection coefficient[4)] which is quite high in comparison with those of the crystals ordinarily used in the x-ray spectroscopy of laser plasmas.[1] The use of the CaF_2 crystal significantly improves the sensitivity of the spectrograph and makes it possible to detect some spectral features which have not been observed previously, including faint lines in the spectral intervals 4.78–4.81 Å, 4.92–5.06 Å, and 5.39–5.45 Å.

Analysis of the experimental geometry leads to the conclusion that the dimensions of the plasma burst have no significant effect on the broadening of the line of interest.

Shown at the bottom of Fig. 1 is a part of the spectrum near the most intense resonance line of the helium-like phosphorus ion, P XIV. The electron density N_e and

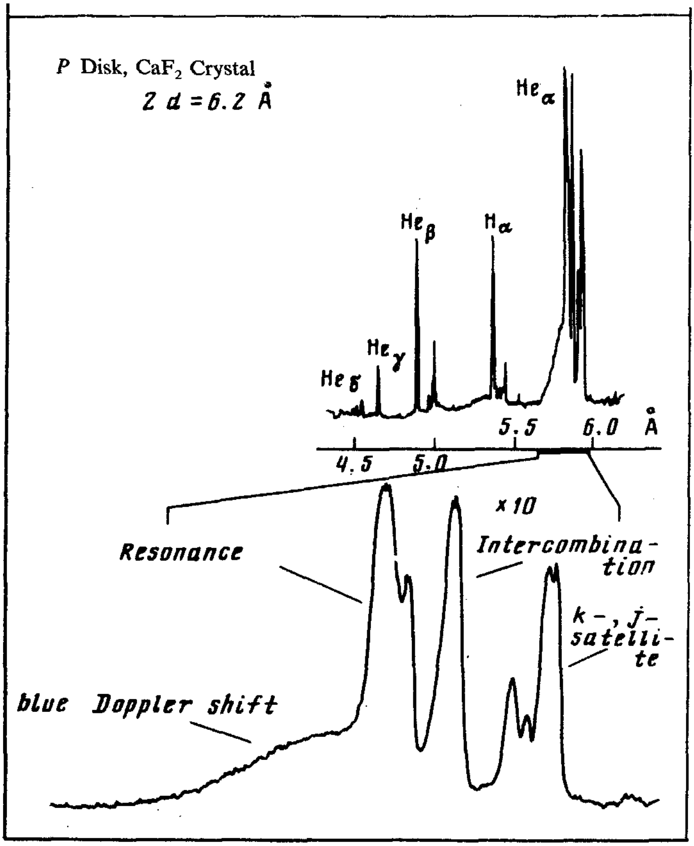

FIG. 1. X-ray emission spectrum of a laser plasma in the range 4.5–6 Å.

the temperature T_e of the plasma, determined from the intensity ratios of the resonance and intercombinational lines and also of the resonance line and the dielectronic satellites, are 3×10^{20} cm^{-3} and 260 eV, respectively. It is interesting to note the asymmetric broadening of the resonance line of the helium-like phosphorus ion, P XIV ($1s^2\,{}^1S_0 - 1s\,2p\,{}^1P_1$, $\lambda_0 = 5.7591$ Å) in the short-wave part of the spectrum. We believe that this broadening is caused by a Doppler frequency shift of the emission of fast P^{+13} ions escaping from the laser plasma. Under this assumption, the broadening of the line with respect to λ_0 in the short-wave region is explained on the basis that the outward flight of the fast ions is not spherically symmetric. There is the possibility that the resonance line is broadened by radiation self-absorption, but for this mechanism to operate the plasma would have to have a large optical thickness ($\tau\gg1$), and there would be a significant shift of the peak of the spectral line with respect to the wavelength of the unreabsorbed transition. Since this shift is not found on the spectrogram, we conclude that this mechanism does not operate in the present experiments.

The formation of the high-energy ions responsible for the observed Doppler shift of the emission frequency can be explained, for example, by the model of ion accelera-

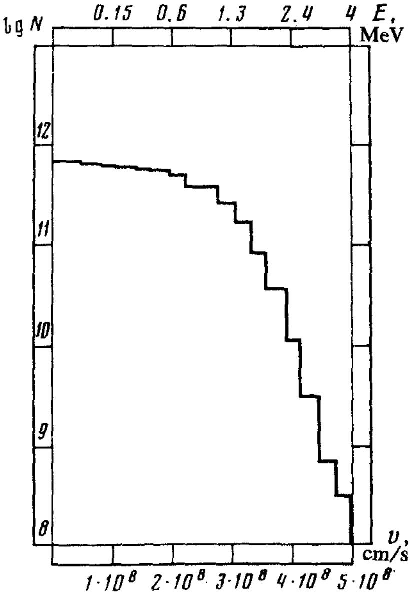

FIG. 2. Velocity distribution of the fast ions in the laser plasma.

tion by fast electrons during the expansion of a low-density plasma.[8] An estimate of the average temperature of the fast electrons according to this model yields $T_h \sim 8$–15 keV, which agrees well with the experimental results on T_h found from the spectrum of the hard component of the continuous x-ray emission. Another possible mechanism for the formation of the high-energy ions is a "cumulative" acceleration of plasma resulting from an inhomogeneous heating of the target surface. This acceleration has been observed in experiments with laser plasmas,[9,10] including experiments in the Del'fin.

From the Doppler frequency shift of the emission of the P XIV ions we constructed the velocity distribution of the fast ions (Fig. 2). In this figure we can distinguish two energy regions, in which the number of ions (N) behaves in very different ways as a function of the velocity. Beginning at $E \sim 1$ MeV ($v \simeq 2.6 \times 10^8$ cm/s) the number of fast ions drops off sharply and continues to do so up to the maximum energy, ~4 MeV ($v \simeq 5.2 \times 10^8$ cm/s), detected in this experiment.

The total intensity of the emission of ions with kinetic energies up to ~50 keV is $\sim 10^{13}$ photons; the intensity of the resonance line is $\sim 10^{14}$ photons. An estimate of the kinetic energy of the ions with velocities $> 5 \times 10^7$ cm/s yields values up to 5% of the energy absorbed from the laser beam.

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4) The reflection coefficient of the ideal CaF_2 crystal, calculated from the dynamic theory of x-ray interference,[5] is 8.7×10^{-5} rad for $\lambda = 5.76$ Å.

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