Investigation of generation of fast ions in a laser plasma on the basis of x-ray line emission

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An analysis of the profile of the $1s^2$–$1s2p$ resonance emission line of phosphorus ions P XIV in a laser plasma was used to construct the energy spectrum and the indicatrix of the flight of fast ions. The results obtained were interpreted using a model of acceleration of ions by ponderomotive forces under conditions of relativistic self-focusing of laser radiation in a plasma corona.

The mechanisms of generation of fast ions in a laser plasma are being investigated as part of research on laser thermonuclear fusion,[1,2] because of the need to study the hydrodynamic efficiency of target compression. Fast ions accelerated as a result of nonlinear effects of the interaction of laser radiation with the target material can carry away a significant fraction of the absorbed laser energy and thus reduce the compression efficiency.[2] For this reason it is necessary to determine the energy carried away by fast ions in experiments on compression and heating of laser thermonuclear targets and to carry out model experiments in order to investigate ion acceleration mechanisms in a plasma.

The methods for the determination of the energy of fast particles in laser plasma experiments are discussed in many papers (for a bibliography see Secs. 5 and 14 in Ref. 2). These methods involve determination of the current in an ion collector, of the deflection of ions by an external electromagnetic field,[3] and of the interaction of ions with a medium.[4] Several theoretical explanations of the generation of fast ions in a laser plasma have been put forward and are based on acceleration in an expanding plasma,[5] acceleration under the action of resonance mechanisms of laser energy absorption,[6] and acceleration of ions by spontaneous magnetic fields.[7] These models agree qualitatively more or less with experimental results, but a detailed understanding of the processes of interaction of laser radiation with thermonuclear targets requires precise quantitative data for each of the ion components in a wide range of energies allowing for asymmetry of the flight of fast ions.

In analyzing the method of mass-spectrometric investigations of plasma we must remember also fundamental difficulties encountered in the interpretation of the results of determination of the energy of ions which fly in various directions. The first difficulty is that detection of charged particles can provide information on the final velocities of ions during the later stages of plasma expansion and on acceleration processes only in the low-density collisionless part of the corona. This ignores the mechanisms of acceleration of ions in a plasma with a density $N_e > 10^{20}$ cm^{-3} because of the possible further deceleration. Other fundamental difficulties encountered in the use of mass spectrometry are the requirements of multichannel analysis of the directionality of the flight of ions and the need for a high vacuum in the target chamber. This results in complications and sometimes makes it necessary to exclude mass spectrometry from combinations with other methods used in plasma investigations, such as, for example, determination of the absorbed laser energy from the velocity of shock waves expanding in the atmosphere of the residual gas.[8]

These complications have made it necessary to look for other ways of investigating characteristics of fast ions in a laser plasma. The technique of recording the emission spectra of multiply charged ions, developed in Refs. 9 and 10, makes it possible to tackle this task successfully. Determination of the Doppler shift of line radiation of fast ions will be shown below to give an opportunity for constructing the energy spectrum and the indicatrix of the flight of ions.

1. OBSERVATION OF RADIATION EMITTED BY FAST P XIV IONS IN A LASER PLASMA

We observed radiation of fast ions in a laser plasma by employing the heating radiation from the outputs of preamplification stages of the Del'fin-1 facility[11] with the following parameters: the energy carried by the beam was 20–30 J, the duration of the pulses was ~ 2.5 nsec, corresponding to a laser radiation power $P_l \approx 0.01$ TW, the divergence was $\approx 2.3 \times 10^{-4}$ rad, and the power density of the radiation reaching the target surface was $\approx (5\text{–}7) \times 10^{14}$ W/cm^2. The range of values of the electron temperature of the plasma was 0.5–0.8 keV and the state of its ionization by such laser radiation were the reasons why phosphorus was used as the target to ensure the maximum intensity in the K emission spectrum.[12] The optimal crystal for the analysis of x-ray radiation into a spectrum was in this case calcium fluoride CaF_2 with the [111] orientation, characterized by high ($R_c = 2 \times 10^{-4}$ rad) integral reflection coefficient[3)] in the investigated region and a sufficiently high resolution (the halfwidth of the reflection curve was $W = 10'$, the ratio $\lambda/\Delta\lambda$ was 3.4×10^4, and the lattice parameter was $2d = 6.28$ Å). The spectrograph configuration (Fig. 1) made it possible to record x rays at angles of 7°–22° relative to the target surface.

The electron temperature of the plasma, determined from the ratio of the intensity of the resonance [He]-like line of phosphorus P XIV to the intensity of dielectronic k, j satellites, was $T_e \approx 0.6$ keV and the ratio of the intensities of the resonance and intercombination lines gave the value of the electron density $N_e \approx 2 \times 10^{20}$ cm^{-3} (Ref. 10).

Figure 2 shows a part of the spectrum near the strongest resonance line $1s^2\,{}^1S_0$–$1s2p\,{}^1P_1$ at $\lambda_0 = 5.760 \pm 5 \times 10^{-3}$ Å. The asymmetric broadening of the line profile toward

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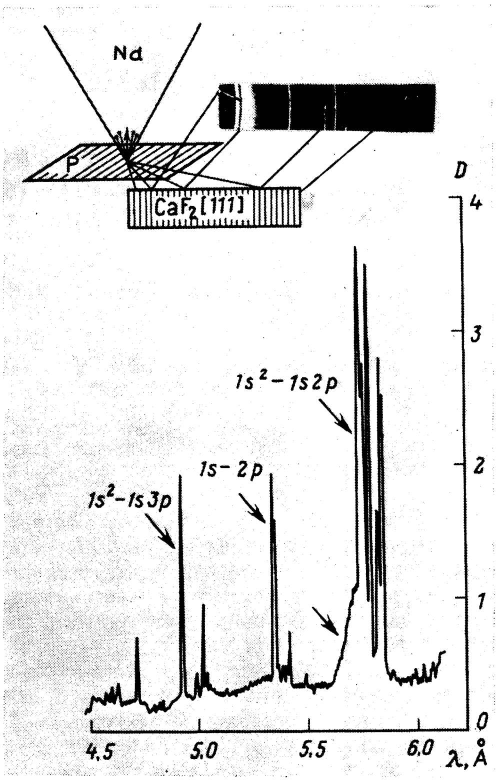

FIG. 1. Geometry used in the experimental recording of radiation emitted by phosphorus ions. The lower part of the figure is a densitogram of the K x-ray emission spectrum with arrows identifying the characteristic lines, showing asymmetric broadening of the profile because of the Doppler shift of the radiation emitted by fast ions.

shorter wavelengths in the spectrum was interpreted as the Doppler shift of the radiation due to fast P XIV ions accelerated in the laser plasma[4)] (Ref. 9). The size of the plasma deducd from the image obtained using a pinhole camera behind a beryllium filter of $50\,\mu$ thickness (radiation cutoff 1.7 keV) was $\sim 300\,\mu$, so that the real resolution of the velocity of fast ions under experimental conditions, when the size of

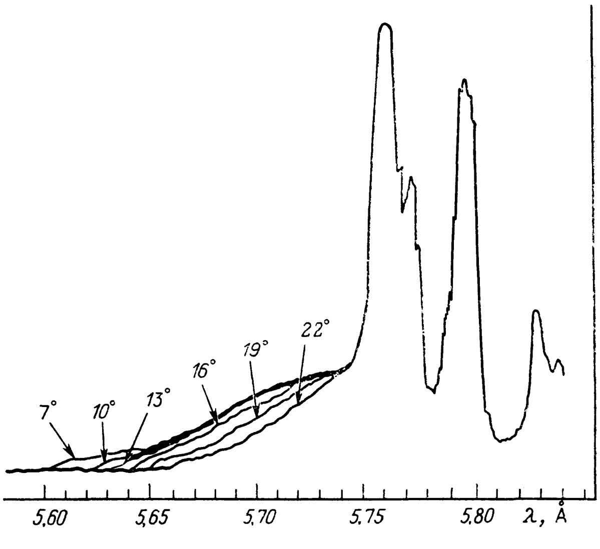

FIG. 2. Detailed densitogram of the spectrum near the resonance line of the [He]-like ion of phosphorus obtained for different directions of observation of the emitted radiation in the range 7°–22° relative to the target surface.

the source governed the spectral resolution, amounted to $\delta v_i = \pm 2.5\times 10^7$ cm/sec.

It is worth noting the different values of the Doppler shift of the radiation emitted by fast ions for different angles of recording of the spectral line relative to the target plane (Fig. 2). The greatest shift was observed at low angles. This asymmetry was due to acceleration of ions as a result of self-focusing of the laser beam in the plasma.

2. CALCULATION OF THE ENERGY AND ANGULAR CHARACTERISTICS OF THE FLIGHT OF FAST IONS

The energy distribution of ions can be deduced if the spectral line profile is represented by a superposition of radiation due to ions "at rest" and lines due to fast ions flying away from the target at various velocities. The Doppler shift gives then the velocity, and the line intensity provides information on the number of ions traveling at a given velocity. The experimentally determined dependence of the radiation emitted by fast ions on the angle of observation, found over a range of such angles, is extrapolated to the region outside the recorded range. An analysis of the profile of a resonance line carried out in this way gives the distribution of the ion velocities and the indicatrix of the flight of ions.

The number of photons emitted by ions at rest can be found from[13]

$$N_\Sigma^{h\nu} = \frac{4\pi L^2}{R_c}\,\frac{\operatorname{tg}\theta_0}{\lambda_0}\int I(\lambda)\,d\lambda, \qquad (1)$$

where L is the source-crystal-photographic films distance; $I(\lambda)$ is the radiation flux of the recording plane (in keV/keV units). Consequently, we find that $N_\Sigma^{h\nu} = 8.2\times 10^{13}$. Similarly, we can use Eq. (1) to calculate the number of photons in the line wing. In this case the number of photons emitted by ions flying at velocities of $v_i > 5\times 10^7$ cm/sec ($E_i > 0.04$ MeV) is $N_{fi}^{h\nu} = 1.6\times 10^{13}$. The error in the determination of the number of photons amounting to $\pm 10\%$ is governed by the precision of determination of the reflection curve of a crystal and of the density curve of the photographic material.

The number of photons emitted by ions can be determined correctly only when the plasma is transparent, so that in the case of the resonance [He]-like line of phosphorus we have to obtain estimates of the optical thickness of the plasma. Photoabsorption cross section can be calculated from[15]

$$\sigma_{\rm ph} = {}^3/_4\lambda^2 A/\Delta\omega, \qquad (2)$$

where A is the probability of radiative decay and $\Delta\omega$ is the width of the spectral line. Hence, in the case of ions flying at velocities $v_i < 5\times 10^7$ cm/sec we have the photoabsorption cross section $\sigma_{ph} = 2.56\times 10^{-17}$ cm^2 and the optical thickness of a plasma with the parameters found in our experiments is

$$\tau = r_0 N_e \sigma_{\rm ph} \bar{z}^{-1} \leqslant 10, \qquad (3)$$

where r_0 is the plasma size and $\bar{z}$ is the average charge. Consequently, the requirement that τ_2 be small so that the radiation trapping effects are absent and the optical thickness of the plasma does not affect the intensity of the spectral line,[16]

$$A/(\tau+1) > N_e\langle v_i\sigma_{\rm ph}\rangle, \qquad (4)$$

is clearly satisfied. In the case of radiation of P XIV ions

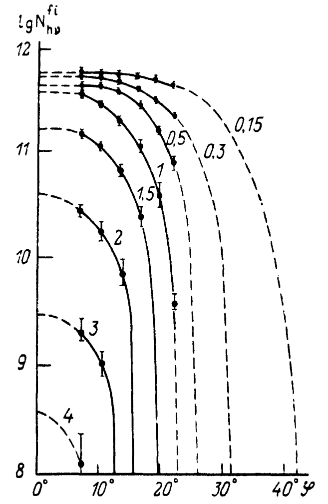

FIG. 3. Distribution of the number of photons emitted in the form of the $1s^2$–$1s2p$ line plotted as a function of the angle at which light was recorded.

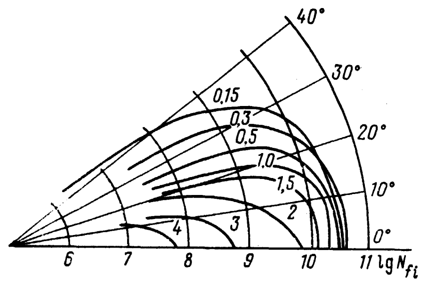

FIG. 4. Indicatrix of directions of flight of phosphorus ions of energies in the range 0.15–4 MeV.

flying at velocities $v_i > 5\times10^7$ cm/sec the optical thickness of the plasma is much less[21] because these ions emit frequencies which are shifted relative to ω_0 in accordance with the Doppler effect.

These estimates of the optical thickness show that the $1s^2$–$1s2p$ spectral line should have also a red wing as a result of emission by fast ions flying in the direction away from the observer. Such a wing clearly exists, but on the long-wavelength side there is a strong intercombination line and a series of dielectronic satellites which mask the wing (Fig. 2).

Figure 3 shows the dependences of the number of photons $N_{h\nu}^m$ obtained by measuring the intensity of the radiation emitted by ions traveling at different velocities in the range of angles of observation 7°–22° relative to the target and the numbers alongside the curves represent the kinetic energy (in megaelectron volts) of the emitting phosphorus P XIV ions. We can construct the complete angular distribution of the radiation by extrapolating the functional dependences $N_{h\nu}^m$ obtained for different ion energies E_i^m to the range of angles φ outside that investigated experimentally. We can then approximate the number of photons $N_{h\nu}^m$ by the function

$$N_{h\nu}{}^m(\varphi_k) = \sum_{\varphi=0}^{90°} c_k \xi_k(\varphi), \qquad (5)$$

where $\xi_k(\varphi)$ are the orthonormalized Chebyshev polynomials. The degree of a polynomial $N_{h\nu}^m(\varphi)$ is selected on the basis of the statistical criterion of proximity of the approximating function to the distribution curve on the assumption that it is monotonic[17] and symmetric relative to the laser radiation axis; the coefficients c_k are then found by least squares.

We shall now convert the number of photons to the number of emitting ions and estimate the frequency, under the selected experimental conditions, of electron–ion collisions ν_{ei} which create photons corresponding to the resonance transition. We can do this using an expression describing the rate of excitation of the $1s^{2\,1}S_0$–$1s2p\,^1P_1$ transition in the [He]-like phosphorus ion[15]:

$$\langle v\sigma_{0-1}\rangle = 10^{-8}\left(\frac{\mathrm{Ry}}{\Delta E}\right)^{3/2}\left(\frac{E_1}{E_0}\right)^{1/2}\cdot\frac{2}{3}\,e^{-\beta}\,\frac{10.7(\beta+1)\beta^{1/2}}{\beta+0.048}. \qquad (6)$$

Here, $\mathrm{Ry} = 13.6$ eV; E_0 and E_1 are the energies of the ground and excited states measured from the ionization limit; ΔE is the difference between the ionization energy and the energy of the resonance transition; $\beta = \Delta E/kT_e$. Multiplying the right- and left-hand sides of Eq. (6) by the electron density of the plasma, we find that $\nu_{ei} = 9.6\times10^{10}$ sec^{-1}. Consequently, the distance traveled by an ion between the photon-creating collisions under our experimental conditions amounts to $\sim 5\,\mu$ for $v_i = 5\times10^7$ cm/sec and $50\,\mu$ for $v_i = 5\times10^8$ cm/sec.

An analysis of the line profiles of the resonance transition carried out on the above basis gives the angular distributions of the ions of different energies (Fig. 4) and integration of the indicatrix of the flight of ions gives the distribution of the energies of fast ions (Fig. 5).

Phosphorus ions emitting as a result of other transitions and ions with different charges are accelerated in a similar manner. The intensity of the radiation emitted under these conditions is insufficient for reliable recording of the wings of the spectral lines. Calculations of the ionization state of a plasma at measured values of T_e and N_e can be used to estimate the total number of accelerated ions. The total number of phosphorus ions is found to be $\sim 1.1\times10^{12}$ and the total kinetic energy is $W_{fi} \sim 0.12$ J, or $\sim 1.5\%$ of the laser energy absorbed in the plasma. The number of ions accelerated to the maximum energy $E_{i\max} = 4$ MeV is $\sim 10^8$ ($W_{fi} = 7\times10^{-5}$ J). These data indicate that fast ions have a considerable influence on the hydrodynamic coefficient representing laser energy transfer under these experimental conditions. Fast ions carry $\sim$ 10–20% of the total energy of an expanding plasma.

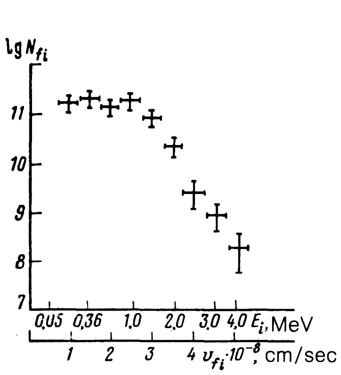

FIG. 5. Distribution of the velocities of fast ions.

3. DISCUSSION OF RESULTS

The experimentally observed angular distribution of fast ions, which acquires more and more pronounced orientation along the target surface on increase in the ion energy, can be explained on the basis of a model of acceleration by ponderomotive forces in the case of relativistic self-focusing of laser radiation in a plasma.[6,18]
Such self-focusing appears when the plasma oscillation energy approaches $m_e c^2$ and this results in a change in the optical constants of the plasma because of the relativistic change in the electron mass.

As a result of self-focusing of a laser beam the nonlinear forces form a "funnel" in a plasma and its characteristic size can be right down to the laser wavelength λ_l (Ref. 6). When the average density of the laser radiation flux reaching a target is $q_l \sim (10^{-3} - 10^{-1}) q_{\rm rel}$, the conditions for the relativistic self-focusing corresponding to $q_l \sim q_{\rm rel}$ are established at the center of such a funnel[19]:

$$q_l / q_{rel} = {}^3/_4 E_{i\,max} / z m_e c^2, \quad (7)$$

where $q_{\rm rel}$ [W/cm^2] $= 3\times 10^{18}/\lambda_l^2$ [μ]. The maximum value of the energy of the accelerated ions considered in the framework of the model of relativistic self-focusing is governed by the laser radiation power:[19,20]

$$Ei_{max}\,[M\partial B] = 30 z P_l\,[\mathrm{TW}]. \quad (8)$$

The measured value $E_{i\max} = 4$ MeV found in our experiments is in good agreement with the result deduced from Eq. (8): $E_{i\max}^{\rm theor} = 3.9$ MeV.

In the region of the minimum size of the funnel, where q_l reaches $\sim 10^{18}$ W/cm^2, the geometry of the laser beam in the plasma is clearly cylindrical with a very high transverse field gradient. A nonlinear force f_{nl}, maximal in the radial direction,[6,19] is then established and it accelerates ions:

$$f_{nl} = -\frac{\partial}{\partial r}\left(\frac{E^2+H^2}{8\pi}\right). \quad (9)$$

It is shown analytically in Ref. 20 that this nonlinear force is the likely reason for preferential flight of ions of $E_i > 0.1$ MeV energy in a plane perpendicular to the laser beam. The measured number of fast ions with the maximum energy is in order-of-magnitude agreement with the results of numerical calculations of ion acceleration[19] carried out using the model of relativistic self-focusing of laser radiation in a plasma.

[1]Friedrich Schiller University, Jena, East Germany.
[2]University of New South Wales, Kensington, Sidney, N. S. W., Australia.

[3]The integrated reflection coefficient of crystals[13] is $R_c = \int C(\theta) d\theta$, where $C(\theta)$ is the reflection curve and θ is the Bragg angle.
[4]A similar shift was observed in Ref. 14 for resonance [He]-like ions of Fe XXV and Ca XIX in studies of solar flares. The observed broadening of the line profile is explained as the Doppler shift of the radiation emitted by fast ions in solar protuberances.

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