Fiz. 45, 1243 (1963) [Sov. Phys. JETP 18, 855 (1964)].

[5]H. Motz and C. J. H. Watson, in *Advances in Electronics and Electron Physics*, edited by L. Marton (Academic, New York, 1967), Vol. 23, p. 225, Eq. (7).

[6]The power reflected from and the power transmitted through the plasma are measured for a certain incident power at different values of $B$. Both signals are small near the electron-cyclotron resonance at $B = B_c = 3345$ G. Thus, the microwaves are absorbed in the plasma at the resonance. The propagation of whistler waves with little attenuation is observed when $B > B_c$. Enhanced fluctuations are observed in the ion saturation currents of the probe especially near the resonance.

[7]S. Takeda and M. Roux, J. Phys. Soc. Jpn. 16, 95 (1961).

[8]Here, the plasma is replaced by a movable metal short plunger, whose position simulates the density of the plasma to obtain the phase angle $\theta$.

[9]I. R. Gekker, E. Ja. Holz, B. P. Kononov, K. A. Sarksian, V. A. Silin, and L. E. Tsopp, in *Proceedings of the Seventh International Conference on Phenomena in Ionized Gases, Belgrade, 1965,* edited by B. Perovic and D. Tosić (Gradjevinska Knjiga Publishing House, Belgrade, Yujoslavia, 1966), Vol. II, p. 445.

[10]V. Ts. Gurovich and V. I. Karpman, Zh. Eksp. Teor. Fiz. 56, 1952 (1969) [Sov. Phys. JETP 29, 1048 (1969)].

# X-Ray Emission from Laser-Produced Plasmas*

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We measured several characteristics of the x-ray emission from plasmas produced at the focus of a high-power (~10 GW) laser. X-ray spectra in the 1–2-keV region show that the plasmas contain highly stripped atoms (10–12 electrons missing from Al, 20–22 from Zn, and 36–38 from Gd). The laser-plasma x-ray source can emit about 0.1 J of x rays above 1 keV in 1 nsec from a volume about 100 $\mu$m in diameter. This corresponds to more than $10^{13}$ W/cm$^3$.

Laser-generated plasmas sufficiently hot to emit kilovolt x rays have been produced recently by the use of focused laser power densities exceeding $10^{12}$ W/cm$^2$ on solid targets. $K$ radiation from elements up to Al was measured and interpreted by Peacock, Hobby, and Galanti.[1] Mallozzi *et al.*[2] and Aglitskiy *et al.*[3] resolved many $L$ lines of Fe but the latter authors have not interpreted the spectra. Mead *et al.*[4] measured unresolved clusters of $M$ lines from Au. But to date, there has been no systematic study of x-ray emission from plasmas produced by any single high-power laser. In this Letter, we report the results of a survey of x-ray spectra from elements across the periodic system. The work has two motivations: plasma diagnostics including tests of laser-plasma models,[5,6] and characterization of the laser plasma as a fast, intense source of soft x rays with several applications.

The Nd laser system used in this work consisted of a mode-locked oscillator and five amplifier stages.[7] Pulses of the 1.06-$\mu$m light [<1 Å full width at half-maximum (FWHM)] containing up to 5 J in 250 or 900 psec were focused on flat targets to spots about 50 $\mu$m in diameter. Hence, power densities exceeding $10^{14}$ W/cm$^2$ were available. Spectra were measured in single shots with simple, slitless spectrographs using flat potassium acid phthalate crystals ($2d = 26.6$ Å) and Kodak No-Screen film behind 25-$\mu$m Be foils (1% transmissive at 800 eV). Resolution was not optimized since it was desired to survey a wide photon-energy range. Energy calibration of new spectra was accomplished by coating the targets with powdered compounds of Na, Mg, or Al, the energies of whose lines are accurately known. Other x-ray characteristics (angular distribution, emission time, and source size) were also measured, as will be described later.

$K$ spectra resulting from transitions to the 1$s$ level have been obtained from Na (in NaF), Mg, Al, Si, and S. Spectra from all these elements are similar. Figure 1 shows the Al spectrum. Classification of lines in spectra such as this presented no problem because of many laboratory[8] and solar[9] measurements of similar emission lines from elements in this range. As indicated in Fig. 1, lines from three ion species appear. An intense Rydberg series and free-to-bound continuum from He-like (two-electron) Al are evident, as is the Lyman series of H-like (one-electron) Al. Poorly resolved satellites

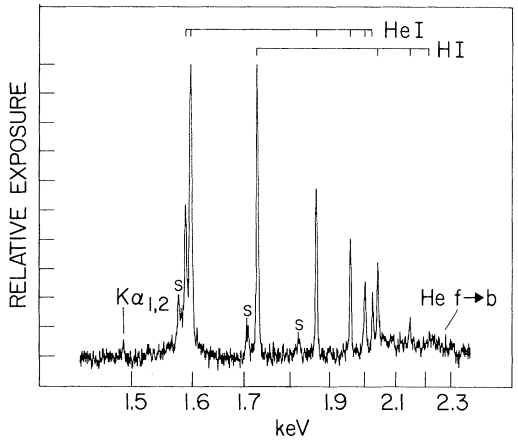


FIG. 1. Al $K$ x-ray spectrum from a plasma produced by a 1.8-J, 0.25-nsec laser pulse. Rydberg series from Al ions isoelectronic with H and He atoms, and the He-like free-to-bound continuum and satellite lines $S$ constitute the plasma spectrum. The $K\alpha_{1,2}$ lines are from target fluorescence.

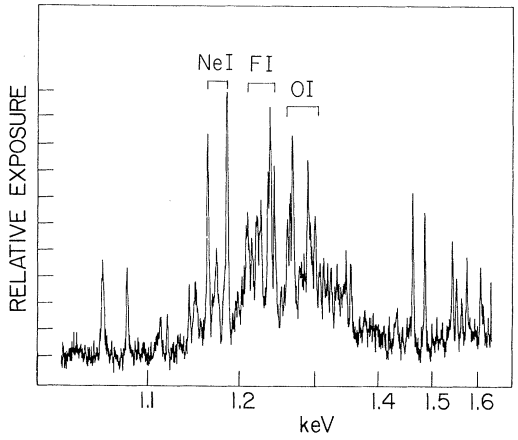


FIG. 2. Zn $L$ x-ray spectrum from a plasma generated by a 2.0-J, 0.9-nsec laser pulse. Groups of lines from $2p$-$3d$ transitions in Zn ions isoelectronic with O, F, and Ne atoms are indicated.

from transitions in Li-like (three-electron) ions appear near the He-like $1s$-$2p$ resonance line, while satellites from He-like ions accompany the H-like $1s$-$2p$ (Lyman $\alpha$) line. Similar satellites have been observed with better resolution in F spectra.[1,10]

$L$ spectra from transitions to the $2s$ and $2p$ levels were measured from Cr, Fe, Co, Ni, Zn, and Br (in KBr). The spectrum of Zn given in Fig. 2 is typical of these spectra. It is more complex than the $K$ spectrum in Fig. 1 because of the larger number of possible ionization states and the strong multiplet structure present for most transitions. Interpretation of the Zn spectrum is not complete, but it is possible to identify the major ionization stages. Again, laboratory[11] and solar[9] spectra from lighter elements were used to interpret our results. Transition-energy calculations using self-consistent-field Dirac-Slater wave functions[12] were made to confirm identifications of the major lines in the Zn spectrum. As indicated in Fig. 2, $2p$-$3d$ transitions in Ne-like (ten-electron), F-like (nine-electron), and O-like (eight-electron) Zn ions dominate the spectrum. Two pairs of lines from Ne-like ions are also strong, $2p$-$3s$ below 1.1 keV and $2p$-$4d$ near 1.47 keV.

$M$ spectra due to transitions to the $3p$ and $3d$ levels from Ba (in $BaCO_3$), Sm, Gd, Dy, and Er were also measured. Figure 3 shows the spectrum of Gd which is representative of the $M$ spectra. Just as the $K$ and $L$ spectra are quite distinctive in appearance, the $M$ spectra also have a characteristic pattern. But much less was known about this $M$ radiation compared to the $K$ and $L$ spectra in the other figures. Spectral measurements (in the uv) for transitions to the $3p, d$ levels had been made only up to Mo,[13] fourteen atomic numbers below Ba. Hence we had to rely on the self-consistent-field calculations to identify the ionization stages and transitions which produced the spectrum in Fig. 3. As shown in the figure, $3d$-$4f$ transitions occurred in Ni-like (28-electron), Co-like (27-electron) and Fe-like (26-electron) Gd ions. Four other transitions are important. The three strongest lines below

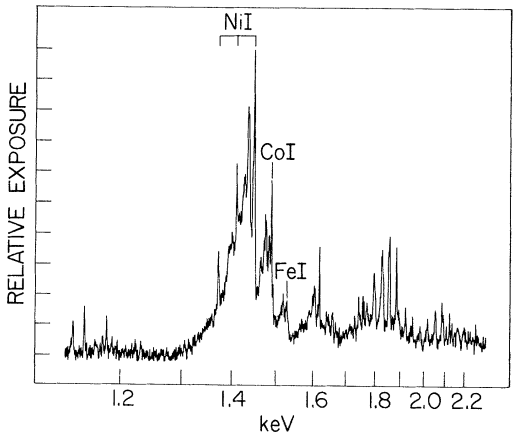


FIG. 3. Gd $M$ x-ray spectrum from a plasma produced by a 3.5-J, 0.9-nsec laser pulse. Lines from $3d$-$4f$ transitions in Gd ions isoelectronic with Fe, Co, and Ni are labeled.

1.2 keV are due to $3d$-$4p$ transitions in Ni-like ions. Isoelectronic extrapolation of the lighter-atom uv data confirmed the $3d$-$4p,f$ identifications for Ni-like Gd. The group of lines around 1.6 keV is due to $3p$-$4d$ electron jumps. Another group (1.7–1.9 keV) is from $4d$-$5p,f$ transitions. And, finally, the radiation above 2.0 keV is due to $4d$-$6p,f$ electron jumps.

$N$ spectra from very high–atomic-number elements might also be expected. But laser irradiation of U did not result in any resolved lines >800 eV. Study of U emission with a grating spectrometer would be worthwhile.

Film-efficiency corrections[14] were made prior to plotting the figures so that the spectra are given interms of relative exposure rather than photographic density. Corrections for crystal efficiency[15] and Be-window absorption were also made prior to integration of the spectra above background over the energy regions shown in each figure. Angular-distribution measurements made with film indicate that the x-ray intensity is approximately independent of emission direction. The ratios of integrated x-ray line energy (emitted into $4\pi$ sr) to the incident laser energy are 0.5% for Al, 9.0% for Zn, and 1.5% for Gd (±20% relative). These values assume no reciprocity loss in the film.[16] Future integrated-intensity measurements will be made with electronic detectors. An upper limit on the x-ray emission time was obtained with a fast pyroelectronic infrared detector which was found to be x-ray sensitive. The measured x-ray pulse width was 1.6 nsec FWHM. Unfolding the measuring-system response time gave ~1 nsec FWHM, which is nearly equal to the 0.9-nsec laser pulse width. Pinhole-camera images (and spectral linewidths) show that the x-ray source size can be as small as 50 $\mu$m.[17] Taken together, these data show that the laser plasma emits x rays at a rate exceeding $10^{13}$ W per cubic centimeter of the plasma.

Results just presented will be considered from two viewpoints in the remainder of this Letter. First, the use of x-ray measurements for determining the temperature and density of laser plasmas will be discussed. Then, present and potential uses of laser plasmas as x-ray sources will be enumerated. Both these x-ray interests are extensions of work done in the uv and extreme ultraviolet regions using lower-power lasers and often low–atomic-number targets.[18,19]

The appearance of intense spectra in the 1–2 keV range immediately indicates that the plasma electron temperatures are ~0.5 keV. Acutally, the temperature is a rapidly varying function of both time and spatial coordinates, but the concept of a single, effective temperature is useful albeit approximate. With the coronal equilibrium model (plus three-body recombination),[20] the ratio of the intensity of two resonance lines (the $1s$-$2p$ transitions in H- and He-like Al ions) yielded temperatures which increase from 0.5 to 0.8 keV (±30%) as the laser power is increased. A separate analysis of He-like $1s$-$2p$ intercombination and Li-like satellite line intensities gave similar results (within 20%). Transient ionization and resonant reabsorption may influence, but are not expected to invalidate, these effective-temperature determinations.

The present spectra are not of sufficient resolution to determine plasma-density values as was recently done by using longer-wavelength data taken with a grating spectrometer.[10] However, high-resolution x-ray measurements are possible and, because of current interest in producing controlled fusion reactions initiated by lasers, they may also be important. Attainment of high densities (~$10^3$ g/cm$^3$) in the laser target pellet is necessary to generate significant thermonuclear energy. Reaction-product (neutron, $\alpha$ particle) measurements will indicate the compression obtained, once significant density increases are achieved. But techniques are needed to determine pellet densities for intermediate compression values. We suggest that the measurement of line profiles in uv or x-ray spectra may yield the desired density information. Implosion of thin spherical shells of C or Al and spectral measurements could provide valuable tests of the compression codes which are generally untested by experimental data at present.

The unique characteristics of laser-generated plasmas as x-ray sources, regardless of microscopic details of the plasmas, make possible several applications. The laser plasma is the most versatile x-ray source now used for spectroscopy to assist interpretation of data from laboratory plasmas and the sun. All elements can be excited by this method (since elements which are liquid or gaseous at room temperature can be used as compounds, frozen, or implanted in solids). Also, the temperature can be controlled (up to about 1 keV) by variation of the focusing conditions. The high speed and soft spectrum of laser-plasma x-ray emission make it attractive for radiography of another plasma.[21] It should also be possible to do transient-radia-

tion-effect studies, e.g., color-center decay,[22] using x rays from laser plasmas. And finally, there has been considerable discussion of schemes for attaining laser action in the soft-x-ray region lately.[23] Several suggestions involve the use of laser-generated plasmas, either as a lasing medium or to generate x rays to pump another medium.

We are investigating variations of the x-ray emission and plasma conditions with laser-pulse, focusing, and target parameters. Detailed studies of $K$,[24] $L$,[25] and $M$[26] spectra are being made as a basis for more extensive plasma diagnostic work.

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[1]N. J. Peacock, M. G. Hobby, and M. Galanti, J. Phys. B: Proc. Phys. Soc., London 6, L298 (1973).

[2]P. J. Mallozzi *et al.*, in *Fundamental and Applied Laser Physics*, edited by M. S. Feld, J. Javan, and N. A. Kurnit (Wiley, New York, 1973), p. 165. P. J. Mallozzi *et al.*, J. Appl. Phys. 45, 1891 (1974).

[3]Ye. V. Aglitskiy *et al.*, Kratk. Soobshch. Fiz. 12, 36 (1971) [available as U. S. Naval Research Laboratory Translation No. 1238 (unpublished)].

[4]S. N. Mead *et al.*, Appl. Opt. 11, 345 (1972).

[5]N. K. Winsor and D. A. Tidman, Phys. Rev. Lett. 31, 1044 (1973).

[6]K. Whitney and J. Davis, to be published.

[7]J. M. McMahon and J. L. Emmett, in *Record of Eleventh Symposium on Electron, Ion and Laser Beam Technology*, edited by R. F. M. Thornley (San Francisco Press, San Francisco, Calif., 1971), p. 269.

[8]N. J. Peacock, R. J. Speer, and M. G. Hobby, J. Phys. B: Proc. Phys. Soc., London 2, 798 (1969).

[9]G. A. Doschek, Space Sci. Rev. 13, 765 (1972).

[10]U. Feldman *et al.*, Astrophys. J. 187, 417 (1974).

[11]M. Swartz *et al.*, J. Phys. B: Proc. Phys. Soc., London 4, 1747 (1971).

[12]D. Liberman, J. T. Waber, and D. T. Cromer, Phys. Rev. 137, A27 (1965).

[13]E. Alexander *et al.*, J. Opt. Soc. Amer. 61, 508 (1971).

[14]C. M. Dozier, J. V. Gilfrich, and L. S. Birks, Appl. Opt. 6, 2136 (1967), and unpublished data.

[15]D. B. Brown, M. Fatemi, and L. S. Birks, in *Advances in X-Ray Analysis*, edited by C. L. Grant *et al.* (Plenum, New York, 1974), Vol. 17.

[16]L. S. Birks *et al.*, J. Opt. Soc. Amer. 60, 649 (1970).

[17]J. F. Holzrichter, C. M. Dozier, and J. M. McMahon, Appl. Phys. Lett. 23, 687 (1973).

[18]T. P. Donaldson, R. J. Hutcheon, and M. H. Key, J. Phys. B: Proc. Phys. Soc., London 6, 1525 (1973).

[19]T. U. Arifov, G. A. Askar'yan, and N. M. Tarasova, Zh. Eksp. Teor. Fiz. 56, 516 (1969) [Sov. Phys. JETP 29, 282 (1969)].

[20]R. C. Elton, in *Plasma Physics*, edited by H. A. Griem and R. H. Lovberg (Academic, New York, 1970), Vol. 9, pt. A, p. 115.

[21]S. K. Handel and B. Sternerhag, in *High Speed Photography*, edited by N. R. Nilsson and L. Hogberg (Wiley, New York, 1968), p. 253.

[22]R. G. Fuller, R. T. Williams, and M. N. Kabler, Phys. Rev. Lett. 25, 446 (1970).

[23]D. J. Nagel, Phys. Fenn., 9 (S1), 381 (1974).

[24]U. Feldman *et al.*, to be published.

[25]P. G. Burkhalter, D. J. Nagel, and R. D. Cowan, unpublished.

[26]P. G. Burkhalter, D. J. Nagel, and R. R. Whitlock, Phys. Rev. A 9, 2331 (1974).