MEASUREMENT OF CARBON ION PHOTOABSORPTION CROSS SECTIONS USING LASER PLASMAS

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ABSTRACT. Laser plasmas are well-suited to studies of ionic photoabsorption because they can provide highly ionized, low temperature plasmas of high column density, as well as bright, compact continuum X-ray sources which can illuminate the plasma under study. In our experiment, continuum X-rays from a gold laser plasma are partially absorbed as they traverse a carbon plasma and are then dispersed by a grazing incidence reflection grating. An X-ray imaging camera records both the absorbed and unabsorbed spectra simultaneously for later computer analysis to determine the photoabsorption cross sections for each carbon ion species.

1. INTRODUCTION

Absorption spectra in the soft X-ray band are extremely important for studying cosmic accretion-powered sources as probes of the cool, circumsource, accreting material. In such photoionized nebulae (e.g. active galactic nuclei, cataclysmic variables, and X-ray binaries), a powerful, compact, X-ray emitting core photoionizes cooler surrounding gas, producing a series of ionization fronts. Electronic level populations in the ions are largely determined by the complex mechanisms of recombination cascades and photoexcitation, instead of collisional effects and spontaneous radiative decay as found in hot, optically thin, thermally emitting sources such as stellar coronae and supernovae remnants.

Future soft X-ray missions such as AXAF and XMM will provide abundant high resolution spectral data, but our ability to interpret these data may be severely limited by uncertainties in atomic physics and radiation transfer. This is especially true for photoionized nebulae where the complex processes described above are at work. Accurate photoabsorption cross sections would make calculation of ion column densities straightforward, thus constraining densities, temperatures, and source geometry, but experimental determination of these cross sections is very difficult because of the problems in producing and maintaining large column densities of highly ionized material. There are a few measurements for multiply-charged low Z ions, notably Jannitti *et al.* (1986), but available values come almost exclusively from theoretical efforts (using Hartree-Slater central field approximations, etc.) such as Reilman and Manson (1979). These calculations are generally accurate to within 10% or 20%, but can be off by factors of more than two near delayed

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maxima and Cooper minima. Furthermore, such calculations do not include autoionization and other subtle but important effects.

2. LASER PLASMAS

Laser plasmas are a very efficient means of producing large column densities of highly ionized atoms; of order 10% of the input laser energy is used in ionizing and exciting the plasma ions (Eidmann and Kishimoto 1986). In addition, one ionization state can often be selected to dominate the others (particularly for low Z materials) by varying the parameters of the laser pulse.

Laser plasmas also have relatively low kinetic temperatures, much like the photoionized gas surrounding an accretion source. This is because the recombination time scale for most ion species is usually much longer than the laser plasma cooling time (typically a few nanoseconds for a 1 ns pulse). During this cooling phase, the ions cascade down to their ground states. After the plasma has cooled, but before the ions have begun to recombine (usually a few tens of nanoseconds), the plasma is highly overionized relative to its kinetic temperature, and there is no recombination line emission.

As an example, one-dimensional computer simulations predict that a 10 Joule, 1 ns, 1064 nm (infrared) laser pulse focussed on a 10 mm × 100 μm × 1000 Å carbon foil will produce: a kinetic temperature peak of 70 eV, cooling to 10 eV after 10 ns; a 500 μm diameter cylinder of carbon plasma with 82% He-like and 17% Li-like carbon ions; and a He-like column density of 10^{19} ions/cm^2, or an optical depth of 2 at 20 Å.

Because of their excellent conversion efficiency and nearly continuum emission, high Z (e.g. Au and Ta) laser plasmas can be used as intense, compact X-ray sources. Nearly 50% of the laser pulse energy may be converted into X-ray emission during the plasma cooling phase (Eidmann and Kishimoto 1986). Such a bright source can shine through a cool, non-recombining, highly ionized laser plasma (just as in an accretion-powered photoionized nebula) and provide absorption spectra.

3. EXPERIMENTAL PROCEDURE

The basic approach of this experiment is much like that of Janniti *et al.* (1988), but with certain improvements which eliminate the largest sources of uncertainty in their data, namely plasma nonuniformity and shot-to-shot repeatability. Our first experiment is with carbon because it is easy to work with, being a solid.

A 1 nanosecond laser pulse of several Joules (the exact energy depending on the ionization state desired) is focussed on a 100 μm × 10 mm line on the carbon foil producing a cylinder of plasma with minimal density and temperature gradients in the center (Figure 1). After a few ns, when the plasma has cooled and thermal emission has died off (the exact timing to be determined with use of the X-ray streak camera described later), another 100 ps pulse of a few Joules is focussed on the end of a 50 μm diameter gold fiber, producing an intense continuum X-ray

backlighter. These X-rays pass through the carbon plasma where they are partially absorbed, and are then dispersed by a concave grazing incidence reflection grating (Figure 2). Depending on the angle towards the backlighter, the X-rays striking the grating may have passed through the carbon plasma (absorption) or only alongside the plasma cylinder (no absorption). In this way, an X-ray camera can record both the absorbed and unabsorbed spectra at the same time, avoiding the problem of shot-to-shot variation in the backlighter spectrum.

4. EXPERIMENTAL EQUIPMENT

This experiment is conducted at the JANUS laser facility of the Lawrence Livermore National Laboratory. One beam of the Nd-YAG (1064 nm) laser generates the gold backlighter plasma, while the other creates the cylinder of carbon plasma. Apart from the lasers themselves, all experimental equipment is operated within a large vacuum chamber with window ports to admit the laser beams. The laser beam focussing lenses, target rod, and diffraction grating are all mounted on remotely controllable translation and rotation stages.

The carbon and gold targets are mounted on a stainless steel target rod with a 1.0 mm wide slot along the cylinder at the end of the rod (Figure 1). Carbon foils as thin as 400 Å are easily suspended across the slot by a flotation technique. Behind the foil is a brass mount for the gold fiber. The mount permits positioning of the fiber tip to an accuracy of better than 100 μm. One laser beam is focussed in a line on the carbon foil while the other beam (coming from the opposite direction) focusses on the end of the gold fiber through a hole in the target rod.

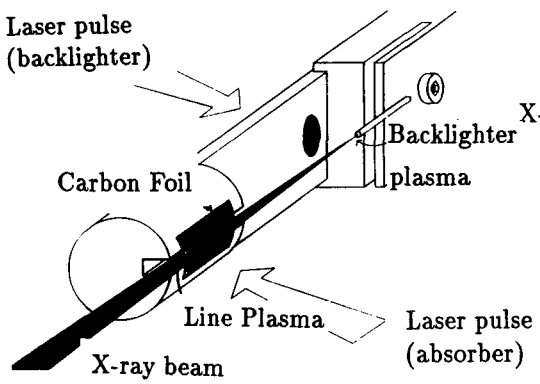

Figure 1. Target rod, 1.4× actual size. The laser pulse incident on the carbon foil creates a thin cylinder of absorbing plasma. A few nano-seconds later, the other beam shoots at the gold backlighter. X-rays from the backlighter pass through and to either side of the absorbing carbon plasma, and are dispersed by the reflection grating. The absorbed and unabsorbed spectra are then recorded simultaneously by the X-ray camera.

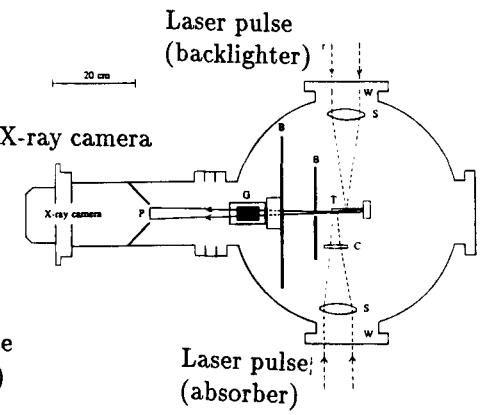

Figure 2. Top view of experimental setup. Solid arrowed lines are X-rays from backlighter. W window ports for incident laser beams; S spherical lenses for focussing beams; C cylindrical lens for line focussing; T target rod holding gold fiber and carbon foil; B baffles to stop charged particles and stray light; G grazing incidence reflection diffraction grating; P X-ray camera photocathode.

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X-rays from the gold backlighter are dispersed by a variable line spacing, flat focal plane, grazing incidence diffraction grating (Kita *et al.* 1983). A 2400 line/mm 1^{o} incidence grating provides coverage from 15 to 100 Å, and a 1200 line/mm 3^{o} grating covers 50 to 300 Å. The grating is mounted on vertical and horizontal stages for focussing the spectrum on the X-ray camera photocathode.

Two X-ray cameras are used, a streak camera for time-resolved studies of the laser plasmas, and a gated X-ray imager (GXI) for two-dimensional data recording. In both cameras, X-rays hit a thin photocathode (potassium bromide on 1000 Å of Lexan) at the front of the camera, releasing electrons. A positively biased, fine copper mesh immediately behind the photocathode attracts the electrons, preserving the "image" of the X-rays on the photocathode. An electron optics system focusses the electrons onto a phosphor where they are "converted" back into a visible image. The image is intensified by a microchannel plate and recorded on calibrated film.

In the streak camera, a narrow slit is placed in front of the photocathode. As part of the electron optics system, a ramped bias voltage can be triggered by the laser pulse (using a photodiode) to sweep the electron "image" of the slit across the phosphor. Time-resolved pictures of the spectrum are used to determine the relative timing between the pulses that create the carbon plasma and the X-ray backlighter--a delay long enough to let the backlighter dominate any emission from the carbon plasma, but not so long that the carbon ions begin to recombine.

A gated X-ray imaging camera (GXI) records the final data by taking a two-dimensional snapshot of the spectrum (wavelength versus angle toward the backlighter). A 100 picosecond exposure is triggered by the second laser pulse so that the backlighter is at its brightest. Such short exposures are made by briefly applying a large bias across a thin metal film on the front of the phosphor, allowing electrons to penetrate the thin coating, reach the phosphor, and be "converted" back to visible photons. The spatial resolution of the GXI approaches 100 μm and limits our spectral resolution to about $\lambda/\Delta\lambda = 200$.

5. DISCUSSION

We have devised a method for measuring photoabsorption cross sections of multiply-ionized atoms that is simple and reliable. The carbon experiment was being run at the time of submission of this paper, and will provide much needed data for the interpretation of high resolution cosmic X-ray spectra. Experiments for other astrophysically abundant elements will be conducted in the near future.

REFERENCES

Eidmann, K., and Kishimoto, T. 1986, *Appl. Phys. Lett.*, **49**, 377.
Jannitti, E., Nicolosi, P., and Tondello, G. 1986, *Physica Scripta*, **36**, 93.
———. 1988, *Proc. of IAU Colloq. No. 102 on UV and X-Ray Spectroscopy of Astrophysical and Laboratory Plasmas*, ed. F. Bely-Dubau and P. Faucher, *Journal de Physique*, **49** Coll. C1 Suppl. 3, C1-71.
Kita, T., Harada, T., Nakano, N., and Kuroda, H. 1983, *Appl. Opt.*, **22**, 512.
Reilman, R. F., and Manson, S. T. 1979, *Ap. J. Suppl.*, **40**, 815.