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OBSERVATION OF TWO-PHOTON CONTINUUM EMISSION FROM NEON IX

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A prominent peak observed in the soft x-ray continuum emission of a deuterium-neon plasma is associated with radiation from the two-photon decay of the 2^1S "metastable" state of heliumlike Ne IX.

The predicted decay rate of the $2S$ states of hydrogen and hydrogenic ions due to two-photon emission[1,2] is[3,4] $8.226Z^6$ sec^{-1}. The excitation energy is split between the two photons such that a broad continuum results with a maximum intensity slightly above half this energy.[3] There is reason[2] to believe that the 2^1S_0 state of heliumlike ions will also decay by a two-quantum process,[5] whose rate is well estimated by $A \approx 8(Z-1)^6$ sec^{-1}.

Normally, the two-photon continuum is not observable, because in laboratory hydrogen plasmas, Stark effects caused by electric fields of ions and electrons lead to a mixing of the $2S$ and $2P$ levels and thus to a quenching of any overpopulation of $2S$ as compared with $2P$. However, with increasing Z the two-photon rate becomes much larger and, moreover, the Stark quenching rate is reduced considerably. For these reasons, it proved possible to detect simultaneous two-photon emission in an ionized helium beam,[6] using coincidence photon-counting techniques. There are, however, no previous direct observations of the frequency distribution of the two-photon emission, although such emission from ions should be a prominent feature in x-ray spectra of the low-density solar corona and nebulae, as has been predicted for the neutral-hydrogen case.[3]

In observing directly the dispersed radiation from high-Z ions in laboratory plasmas, electron densities of the order of 10^{16} cm^{-3} are required, at which level collisional depopulation of the $2S$ state becomes a competing and often dominating process compared with two-photon decay. Such competition tends to diminish with higher-Z species, because of the associated increased level separations and kinetic temperatures. For the hydrogenic ions, the $2S \rightarrow 2P$ collisional rate continues to exceed the two-photon rate by several orders of magnitude at $Z = 10$ (Ne X), ruling out any detection of this effect. However, for the heliumlike sequence, collisional transitions from the 2^1S to 2^1P level are less frequent because of a much greater separation.

For heliumlike impurity ions in a hot plasma, whose behavior is approximately described by a (time-dependent) corona model, the near-threshold excitation rates by electron impacts from the ground state are comparable for 2^1S and for 2^1P, apart perhaps from a statistical weight ratio of 1 to 3. Population of the $2S$ state by radiative recombination (both direct and through cascading) is not important in pulsed laboratory plasmas, where steady-state corona conditions do not exist, i.e., where a given ionization stage is present at higher electron temperatures than would correspond to steady-state ionization. Under the most favorable circumstances (no competing depopulation processes of the 2^1S level), the energy emitted by the two-photon process could thus well come within a factor of 3 of the energy emitted in the $2^1P \rightarrow 1^1S$ resonance transition.

Collisional excitation rates may be estimated, using rate coefficients $X = \langle \sigma v \rangle$ derived from a Bethe-Born–approximation cross section[7] averaged over a Maxwellian velocity distribution, from

$$n_e X = (2\pi/3mkT)^{1/2}(4\pi e^4 f \bar{g} n_e/\Delta E) \times \exp(-\Delta E/kT). \quad (1)$$

Here the effective mean Gaunt factor $\bar{g}$ is taken[7,8] to be 0.2 near threshold ($kT \lesssim \Delta E$) and 1.0 for the transition $2^1S \rightarrow 2^1P$. The quantities ΔE, f, n_e, T, and m represent the level separation, absorption oscillator strength, electron density, electron temperature, and electron mass, respectively. For the case of Ne IX, at a temperature of $kT \approx 350$ eV and an electron density n_e of $\sim 1 \times 10^{16}$ cm^{-3} (from measurements of the visible continuum emission), Eq. (1) results in 3×10^4 sec^{-1} and 6×10^7 sec^{-1} for $1^1S \rightarrow 2^1S$ and $2^1S \rightarrow 2^1P$ collisional transitions, respectively. With the two-photon transition probability[9] $A = \int A_\nu d\nu \approx 4.3 \times 10^6$ sec^{-1}, the modified corona formula for the two-photon continuum emission coefficient ϵ_ν becomes

$$\epsilon_\nu = n_{2S} A_\nu h\nu \approx n_{1S} n_e X(1^1S \rightarrow 2^1S) h\nu \left[\frac{A_\nu}{A + n_e X(2^1S \rightarrow 2^1P)} \right], \quad (2)$$

where n_{1S} and n_{2S} are the respective ion state densities. If the competing continuum intensity is assumed to be due to bremsstrahlung and recombination radiation[10] (mostly on neon ions), then the ratio of two-photon to background continuum emission has an estimated value, at the peak of the two-photon emission, near unity for the above conditions.

Rates for depopulation of the 2^1S level by electron collisions leading to ionization and into the $n = 2$ triplet levels through electron spin exchange are of negligible magnitude[11,12] compared with the $2^1S \rightarrow 2^1P$ excitation rate. Also, depopulation of the 2^1S level through $2^1S \rightarrow n^1P \rightarrow 1^1S$ collisional-radiative transitions (for $n > 2$) is more than compensated by $1^1S \rightarrow n^1P \rightarrow 2^1S$ cascading transitions. Finally, corresponding rates for ion collisions are also expected to be negligible.

In searching for the two-photon continuum in a high-temperature plasma, the Ne IX ion was chosen because of the arguments advanced above favoring high-Z heliumlike species and also because neon is a chemically inert gas easy to introduce into the plasma. The two-photon continuum emission from Ne IX also occurs in a spectral region relatively free from impurity line radiation (see Fig. 1) and convenient for use with thin foils which absorb radiation of longer wavelengths.

The two-photon emission was observed in a deuterium plasma of length ~50 cm and diameter ~3 cm, with a total initial pressure of 15 mTorr including 12% neon (initial concentration). The plasma was generated in a 50-kJ theta-pinch device generating a peak magnetic field of 30 kG in a coil of length 80 cm and inside diameter 10 cm. An initial field of 3 kG antiparallel to the main compression field was used for additional heating. The plasma was viewed axially with a 2.2-m grazing-incidence grating spectrometer using a gold-coated grating with a blaze angle of 1° 30′. Using Kodak SWR plates, 80 discharges were required for an adequate exposure through a 0.025-mm-wide entrance slit and a ~4000-Å-thick filter of VYNS-3 (10% vinyl acetate, 90% vinyl chloride copolymer).

The results are summarized in Fig. 1, where densitometer tracings of the photographic plate density versus wavelength are reproduced, both with 12% neon and with 6% (molecular) oxygen included in the deuterium filling gas. Strong lines[13] of hydrogenic and heliumlike ions of low-Z impurity elements are indicated for several orders. Because of the VYNS-3 filter used, no first-order continuum emission is recorded between 30 and 62 Å. The distinct peak at 36 Å, which arises only with neon added and is of intensity comparable with the background continuum level (as predicted above), is identified with the second order of the two-photon continuum emission, shown below in Fig. 1 for comparison as calculated from Eq. (2) according to $\epsilon_x = D^{-1}(c/\lambda^2)\epsilon_\nu$, where D^{-1} is the instrumental plate factor (inverse dispersion). The small (~1 Å in first order) dif-

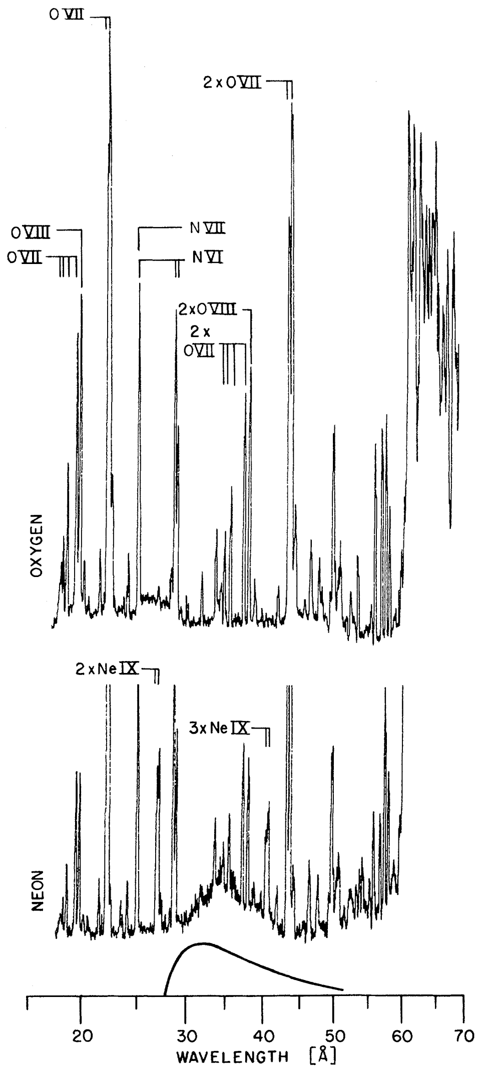

FIG. 1. Densitometer tracings of spectra obtained with 6% (molecular) oxygen and 12% neon included in the deuterium filling gas. The VYNS-3 filter (~4000 Å thick) used is essentially opaque from 30 Å to the chlorine K edge at 62 Å, in which region the observed continuum radiation is of second-order origin. The lower curve represents the corresponding theoretical Ne IX two-photon emission profile. No corrections have been made for variations in instrumental sensitivity with wavelength.

ference in the positions of the calculated and experimental continuum peaks may be attributed to a wavelength dependence of the instrumental sensitivity and particularly to the 60-Å blazed grating used. A calibration of the instrument to unfold this effect is presently underway.

The first order of the two-photon continuum, which should peak at 16-17 Å, is difficult to see since it is partially masked by the edge of a central-image trap which was designed to reduce scattered light on the plate. However, third- and fourth-order (as well as second-order) spectra of the two-photon peak, taken through an aluminum filter (opaque from 30 to 150 Å), further support the identification of the second-order peak shown in Fig. 1.

In replacing the neon with oxygen, an attempt was made to reproduce almost identical plasma conditions with the same background continuum level. With an oxygen (molecular) concentration of 6%, it is seen from Fig. 1 that the continuum is essentially smooth in the region of interest. There is also a suggestion of a slight peak at 26 Å which may be due to the first order of the two-photon continuum from O VII, somewhat attenuated by the filter. Further data at reduced temperature and subsequently reduced O VIII recombination radiation are needed in this case.

In summary, peaks in the continuum emission from a high-temperature deuterium plasma seeded with neon have been associated with the second, third, and fourth orders of the two-photon continuum emission from the 2^1S state of heliumlike Ne XI. The intensity relative to the underlying bremsstrahlung and recombination continuum is consistent with calculations of a modified corona model for collisional excitation of the ion levels. An unfolding of the instrumental sensitivity to obtain the intensity distribution in neon and other heliumlike ions is planned, as are absolute intensity measurements.

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PHASE MODULATION OF Q-SWITCHED LASER BEAMS IN SMALL-SCALE FILAMENTS*

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It has been observed[1-3] that the spectra of small-scale trapped filaments of laser light in carbon disulfide and other liquids contain discrete bands of frequencies extending to either side of the laser frequency. These bands may be several to several tens in number, with a total frequency spread of a few tens to a few hundreds of wave numbers, as shown in Fig. 1. The regularity of these patterns, and yet the lack of a fixed frequency between bands[3] as expected for various modulation processes, have been puzzling. It is found that the patterns observed correspond to the intensity envelope of an underlying structure of equally spaced sidebands. Their basic features are explained by a more or less periodic variation in intensity of the laser light and the resulting variation of the index of refraction in the filament. The simplest case, which can be best compared with experimental results, involves the admixture with the laser light of a very weak wave of slightly different frequency, giving a sinusoidal phase modulation.

Consider two plane waves of amplitudes E_0 and E_1 and differing in frequency by $\omega_S \ll \omega_0$ traveling through a nonlinear medium where the index of refraction is $n=n_0+\Delta n\approx n_0+n_2E^2$. The electric field is

$$E(z,t)=[E_0e^{i(\omega_0t-nk_0z)}+E_1e^{i(\omega_1t-nk_1z)}], \quad (1)$$

where

$$\omega_i/k_i=c \text{ and } \omega_1=\omega_0+\omega_S.$$

The beating between the two frequencies ω_0 and ω_1 will modulate the index of refraction at a frequency ω_S and introduce a time-varying optical path length, and hence a varying phase shift $\Delta\varphi(z,t)$. In the case of a nonzero relaxation time τ of the nonlinear index of refraction,

$$\Delta n(z,t)=\frac{n_2}{\tau}\int_{-\infty}^{t}\langle E^2(t')\rangle e^{-(t-t')/\tau}dt'=n_2\left(\frac{E_0^2+E_1^2}{2}\right)+\mathrm{Re}\left\{\frac{n_2E_0E_1}{[1+(\omega_S\tau)^2]^{1/2}}\exp[i\omega_St-i\arctan(\omega_S\tau)]\right\}.$$

Hence

$$\Delta\varphi(z,t)=\frac{2kzn_2E_0E_1}{[1+(\omega_S\tau)^2]^{1/2}}\mathrm{Re}\{\exp[i\omega_St-i\arctan(\omega_S\tau)]\}.$$

The Fourier spectrum, after the filament has traversed a distance L, is given by

$$S(L,\omega)=(cn/8\pi)|E(L,\omega)|^2. \quad (2)$$

The situation described is somewhat similar to a variety of cases of phase modulation. Lallemand[4] treated the case of two strong unperturbed waves separated by a small frequency and modulating a third much weaker wave. Smith[5] has considered a case closer to the self-modulation which will be discussed below, although he included modulation of a single wave only. It has also been shown[6,7]