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ABSTRACT

We report preliminary results from the analysis of streaked soft x-ray neon spectra obtained from the interaction of a picosecond Nd:glass laser with a gas jet target. In these experiments streaked spectra show prompt harmonic emission followed by longer time duration soft x-ray line emission. The majority of the line emission observed was found to originate from Li- and Be-like Ne and the major transitions in the observed spectra have been identified. Li-like emission lines were observed to decay faster in time than Be-like transitions, suggesting that recombination is taking place. Line ratios of n=4-2 and n=3-2 transitions supported the view that these lines were optically thin and thick, respectively. The time history of Li-like Ne 2p-4d and 2p-3d lines is in good agreement with a simple adiabatic expansion model coupled to a time dependent collisional-radiative code. Further x-ray spectroscopic analysis is underway which is aimed at diagnosing plasma conditions and assessing the potential of this recombining neon plasma as a quasi-steady-state recombination x-ray laser medium.

I. INTRODUCTION

The advent of short-pulse ($\tau <$ 1-10 ps) very high peak power lasers has spurred many investigations into their potential applications.[1] The strong scaling of required x-ray laser pump power with wavelength[2] makes short-pulse, high-brightness lasers a natural choice for a potential pump source for an x-ray laser. To date two major schemes for short-pulse laser pumped x-ray lasers have been discussed. The first of these involves using an ultrashort x-ray pulse produced by a short-pulse laser target interaction as a pump for an inner-shell photoionization x-ray laser.[3-4] The second major scheme, to be considered in this paper, is the use of short-pulse drivers as a pump for a recombination x-ray laser.[5-10]

The basic ideas behind recombination lasers pumped by short-pulse drivers have been discussed elsewhere.[5-10] Essentially, there are two time scales over which inversion may take place. The first is the decay time of the upper lasing level. In this "transient" recombination x-ray laser, population inversions occurs immediately after the pump laser is turned off during the initial recombination cascade. In this scheme inversions between excited and ground states are possible as the strong nonlinear behavior of optical field induced ionization can in principle completely ionize the target plasma. Inversions of this type are self-terminating and are very short lived; the gain duration in this case is of order the decay time of the upper lasing level (usually of order 1-10 ps). Population inversions of this type have been considered previously.[11] The advent of high peak power short-pulse lasers has increased interest in these schemes, and several experiments have been proposed.[8-10,12] Transient schemes pumped by short-pulse lasers are very attractive in that very short wavelengths may be accessed by relatively modest sized lasers.

The second time scale of interest over which inversion may occur is the recombination time of the lasant ion. In this case the ground state is appreciably filled and inversion takes place between excited states. Inversions of this type can be pumped by longer pulse drivers with pulselengths ranging from several picoseconds to nanoseconds; the gain duration is correspondingly longer. The relatively long heating pulse makes transient inversion impossible. The bulk of the "classical" recombination laser literature[13] is based on recombination schemes of this type. This reflects the fact that ultra-short-pulse drivers have become available only recently. A number of researchers have reported success in measuring gain in the soft x-ray region with this "quasi-steady" lasing scheme.[13] In addition, calculations have shown that short-pulse laser plasmas are also good candidates for quasi-steady-state recombination laser schemes.[7] Indeed, a very high gain length quasi-steady-state x-ray laser has not been reported previously and short pulse lasers provide the possibility of producing such a system on a tabletop.

In this paper we report preliminary spectroscopic analysis of soft x-ray spectra obtained from short-pulse-laser/neon gas target interaction experiments. The purpose of this study is to use x-ray spectroscopy to diagnose plasma conditions and assess the suitability of a recombining Ne plasma as a gain medium for a quasi-steady-state recombination x-ray laser. In addition to this primary goal, there are several additional reasons for considering this problem. First, the degree of electron heating in short-pulse laser-produced plasmas is critical to examining their feasibility as an x-ray laser source.[8,14] Spectroscopic measurements of T_e at late time may shed light on the early time dynamics of electron heating important for transiently pumped lasers. Secondly, little analysis of soft x-ray spectra from short-pulse laser produced plasmas has been done to date; the results may have important implications for our overall understanding of short-pulse laser-produced plasmas.

In the next section we present the experimental setup and the results of our preliminary analysis. We conclude in Sec. III.

II. EXPERIMENTAL RESULTS AND ANALYSIS

Figure 1 shows the experimental setup used in this work. These experiments used a short pulse Nd:glass laser[15] which produces 500 fs pulses of 0.53-μm light. Best focus of the laser was set directly below the gas jet output orifice shown in Fig. 1. The diameter of the focal spot at best focus was 30 μm which yielded a peak focused intensity of approximately 10^{18} W/cm^2. A variable line spaced grating[16] spectrometer (labeled "Hettrick spectrometer" in Fig. 1) was used to monitor the emergent soft x-rays. The x-ray spectrometer was aligned so as to view both soft x-ray line emission and narrow divergence harmonic radiation. Time resolution was obtained by coupling the x-ray spectrometer to a Kentech streak camera; the time resolution for this series of experiments was 30 ps. While the wavelength coverage of the x-ray spectrometer can be varied, we focus on results obtained in the 40-110 Å spectral region, as this is the region where the Ne x-ray spectral lines of interest are present. The spectral resolution of the x-ray spectrometer in these experiments was approximately 1 Å. Typical streak camera data for experiments of this type have been presented elsewhere.[17] For our purposes we note that the spectra to be discussed are time resolved and spatially integrated.

Figure 2 shows a Grotrian diagram for Li-like Ne. The 4f-3d, 5f-3d, and 4f-3d transitions in Li-like Ne are potential quasi-steady-state lasing transitions. A useful technique for determining if inversion is present on these lines is to look at the 2s-np and 2p-nd spectral sequences. The relative intensity of lines in this sequence (assuming they are optically thin) may be used to infer the presence of population inversions between levels in the n=3,4, and 5 manifold. In addition, looking at the ratio of lines terminating on high principal quantum number levels (such as 2p-6d/2p-5d) and assuming their upper states are in LTE yields a value for T_e. The results reported in this paper are based on analysis of 2s-np and 2p-nd line emission. These lines fall in the range 60-110 Å, which is the region covered by the streaked x-ray spectrometer. Some spectra were also taken in the range of the potential 4f-3d lasing transition near 300 Å. These spectra are more complex and it is planned to analyze them in the near future.

We now consider analysis of the streak camera data. Figure 3 shows the observed Ne soft x-ray spectra a few hundred ps after the end of the pump laser pulse; this is near the time of peak emission. The 2s-np and 2p-nd sequences in Li-like Ne (NeVIII) are readily observable. Several other Be-like Ne (NeVII) transitions are also identified in Fig 3. The Li- and Be-like Ne lines were also observed to have different time histories, as shown in Figure 4. In this figure the intensity of the NeVII and NeVIII 2p-3d transitions at 98.2 Å and 110.6 Å, respectively, is shown as a function of time. The sharper fall-off in NeVIII emission as opposed to NeVII suggests that the plasma is recombining. It should also be pointed out that analysis showed that lines from the same ionization stage had the same time histories. This removes any possible ambiguity in line identification. It is also an important physics point. The timescales for ionization and excitation processes imply that excited state populations should equilibrate among themselves nearly instantaneously compared to the nanosecond time scales considered here. For singly excited levels of the type considered here this implies that lines from the same ionization stage should have very similar time histories.

As mentioned earlier our goal is to analyze the line ratios in the spectra of Fig. 2 for purposes of diagnosing plasma conditions and the presence of inversions. To this end, the effects of opacity on the plasma must be assessed. In order to estimate whether opacity is of significance we considered line ratios of transitions originating from common or near common upper states. In principle, if the plasma is optically thin the intensity ratio of these lines should reflect the relative gA value of each transition, where g is the statistical weight of the upper state and A is the radiative decay probability for that line.

An example of an analysis of this type is shown in Fig. 5a) and b). Figure 5a) shows the intensity ratio versus time of the Li-like Ne 2p-4d and 2s-4p transitions at 73.5 Å and 67.4 Å, respectively. A simple analysis shows that the $1s^24d$ and $1s^24p$ states should be statistically populated. Assuming this and that the 2p-4d and 2s-4p lines are optically thin, one would expect the intensity ratio of these lines to be equal to the ratio of gA for these two transitions. The gA ratio is also shown in Fig. 5a). It is apparent that for much of the plasma duration, the relative intensities of the 2p-4d and 2s-4p transitions are close to the optically thin value. This is not the case for the 2p-3d and 2s-3p transitions, as shown in Fig. 5b). This simple analysis thus suggests that opacity may be affecting the 2-3 transitions more than the 2-4 lines, which is in accord with the fact that the 2–3 lines have roughly a factor of 4 greater oscillator strength.

As a final point, analysis of the 2s-np and 2p-nd spectra for population inversion and temperature information is underway. Results to this point indicate that T_e is typically several tens of eV a few hundred picoseconds after the pump laser pulse. This is in qualitative agreement with earlier recombination continua measurements. A quantitative and more complete discussion of these issues will be given elsewhere when the analysis is complete.

We have also compared measured time histories to those computed using simple models. Figure 6 compares the measured NeVIII 2p-4d time history with that predicted by supplying the electron temperature and density time history from a simple adiabatic expansion model as input to a time dependent collisional radiative model based on the RATION[18] code. No opacity effects were considered. The initial T_e and N_e chosen for the adiabatic expansion were 80 eV and 8×10^{19} cm^{-3}, respectively. The neon was assumed to be ionized to the He-like stage, which is consistent with the available laser intensity.[8,19] The initial T_e was chosen based on simulations of electron heating arising from Raman scattering.[8] The agreement between experiment and this simple model at this point is very good. Similar agreement is seen for the 2p-3d transition. An improved calculation including optical depth effects in the time-dependent kinetics is underway; comparisons of the full calculated and observed spectra will also be made. As a final point, the simulation curve in Fig. 6 represents essentially only the line emissivity vs. time and is appropriate for the case where the line in question is optically thin in the direction of observation. Simple estimates indicate opacity along the spectrometer line of sight is significant, and so this effect must also be included.

III. CONCLUSION

We have presented preliminary results from the analysis of soft x-ray Ne spectra produced during the interaction of a high intensity short pulse laser focused onto a gas jet target. The observed spectra indicate that NeVIII (Li-like) and NeVII (Be-like) are the dominant ion species present. Lines from the same ionization stage were observed to have very similar time histories. NeVIII emission was observed to have a shorter decay time than NeVII, suggesting that the plasma is recombining. Line ratio analysis shows that 3-2 line emission to be affected by opacity more than 4-2 transitions. The measured time histories of NeVIII lines are in good agreement with those predicted by a simple adiabatic expansion model coupled to a time dependent collisional radiative code. Further analysis is underway to determine the plasma conditions with an eye towards assessing the potential of the recombining Ne plasma as a quasi-steady-state recombination x-ray laser medium. The results to date show that much interesting information relative to the evolution of short pulse laser heated gas target plasmas can be extracted from soft x-ray spectra.

Acknowledgments

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Figure Captions

Figure 1: Experimental setup for short-pulse high intensity laser/gas target interaction experiments.

Figure 2: Grotrian diagram for Li-like Ne, showing transitions of interest.

Figure 3: Ne soft x-ray spectra at time of peak emission as obtained by the streaked soft x-ray spectrometer. Lines from Be-like Ne (NeVII) and Li-like Ne (NeVIII) are present.

Figure 4: Time history of the intensity of the Be-like Ne and Li-like Ne 2p-3d transitions at 109.8 Å and 98.2 Å, respectively.

Figure 5a): Measured ratio of the Li-like Ne 2p-4d (73.5 Å) and 2s-4p transitions (67.4 Å) versus time. Fig. 5b): Measured ratio of the Li-like Ne 2p-3d (98.2 Å) and 2s-3p (88.1 Å) versus time. For both Fig. 5a) and Fig. 5b) the gA ratio for the two lines under consideration is also shown.

Figure 6: Measured and calculated time history of the Li-like Ne 2p-4d transition at 73.5 Å. Calculations are based on a adiabatic expansion model coupled to a time dependent version of the RATION code.

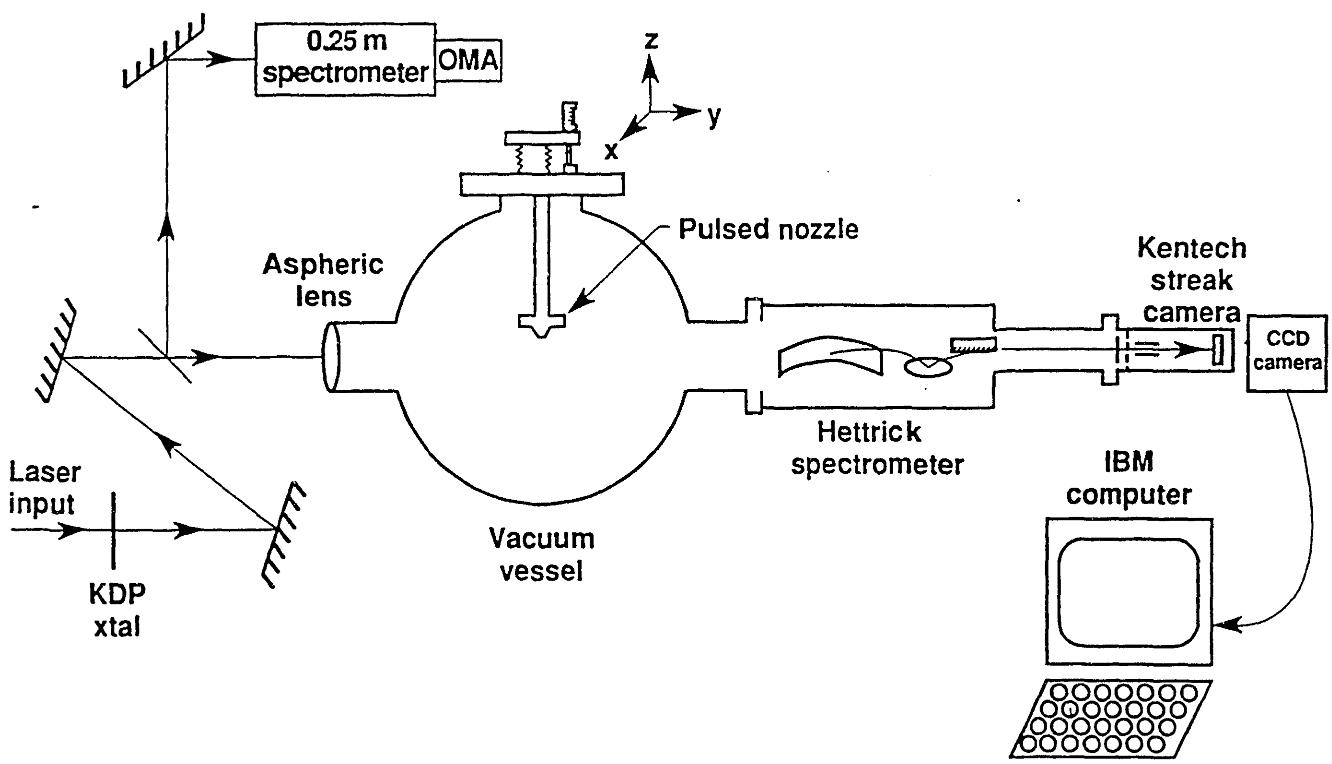


Figure 1

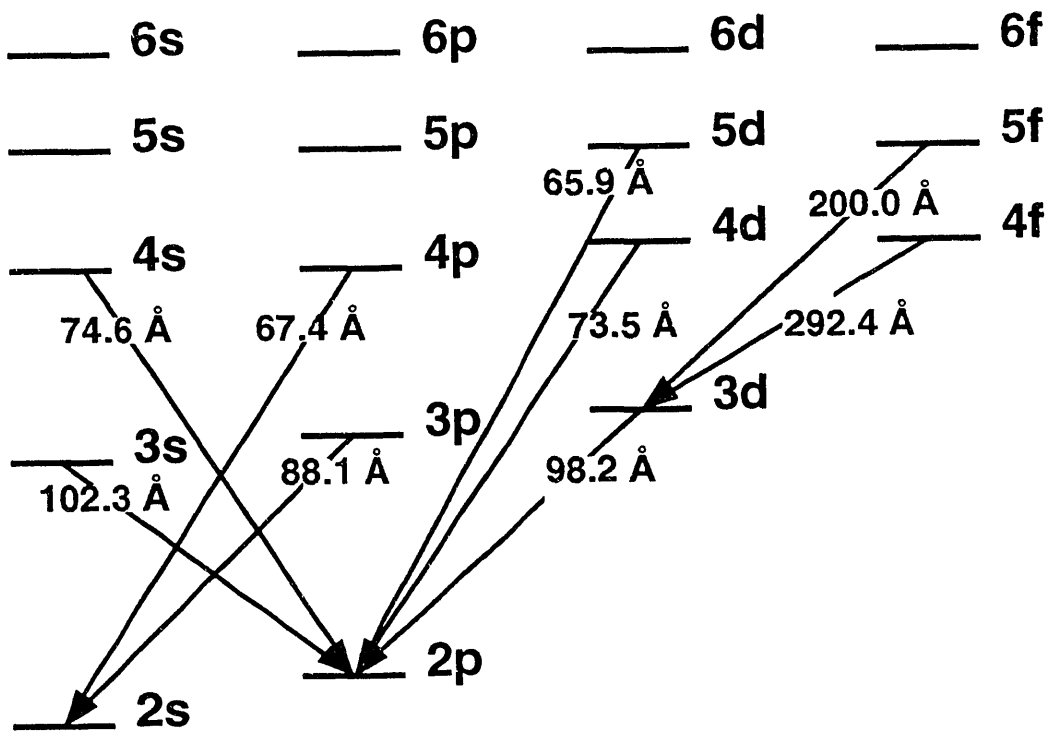


Figure 2

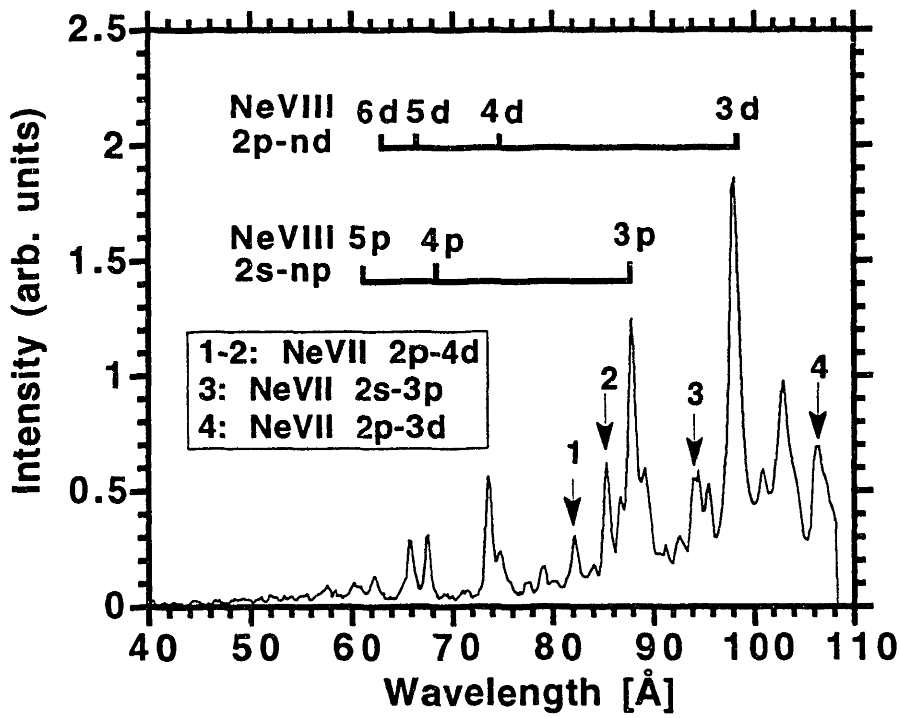


Figure 3

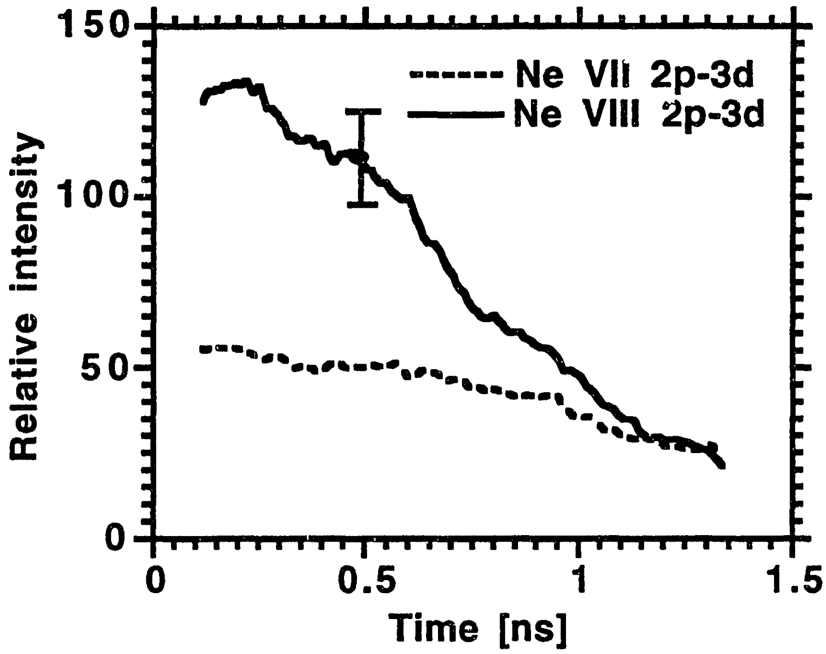
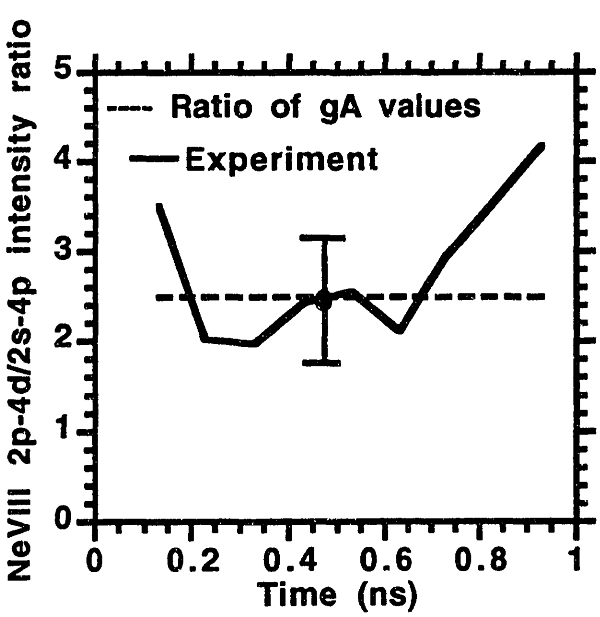
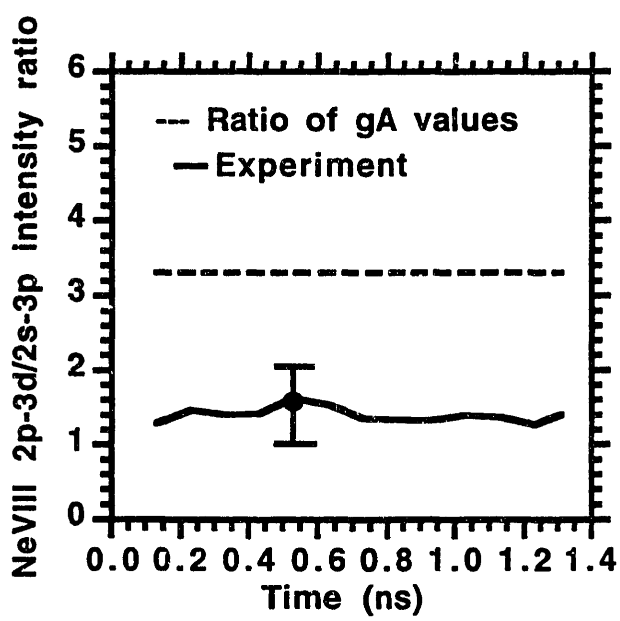


Figure 4

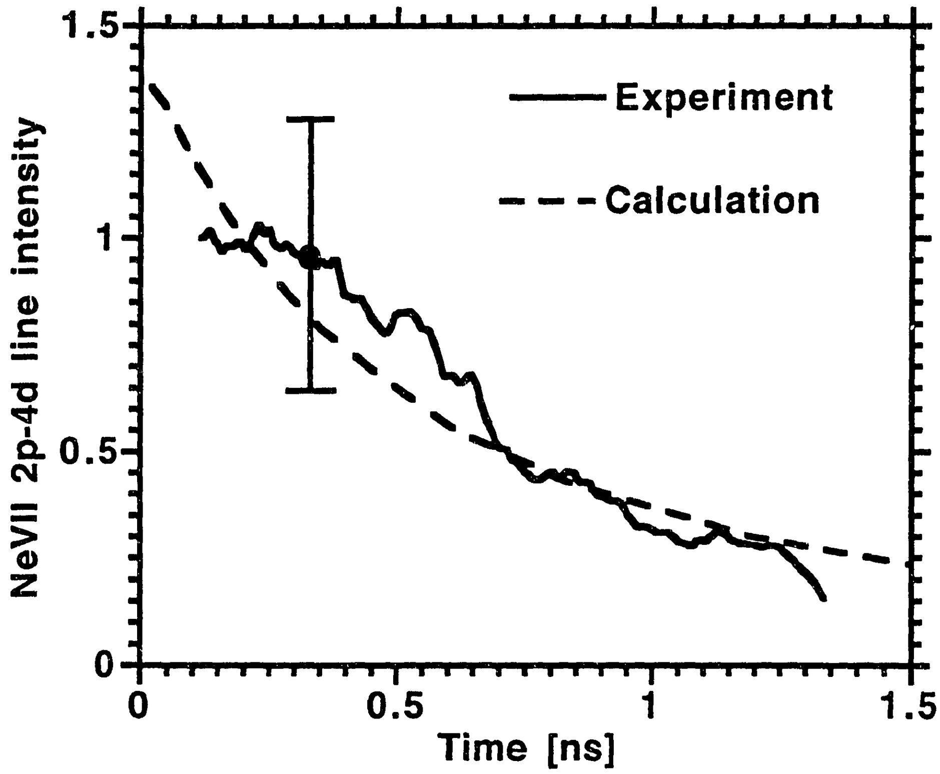


a)



b)

Figure 5



NeVII 2p-4d line intensity
Time [ns]
Experiment
Calculation
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0.5
1
1.5

Figure 6

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