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The role of EBIT in X-ray laser research

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52.38.-r Laser-plasma interactions

52.25.Os Emission, absorption, and scattering of electromagnetic radiation

52.70.-m Plasma diagnostic techniques and instrumentation

42.55.Vc X- and gamma-ray lasers

07.60.Ly Interferometers

29.30.Kv X- and gamma-ray spectroscopy

31.15.-p Calculations and mathematical techniques in atomic physics

Abstract. Back in the early 1980's the X-ray laser program required a new level of understanding and measurements of the atomic physics of highly charged ions. The electron-beam ion trap (EBIT) was developed and built at Lawrence Livermore National Laboratory (LLNL) as part of the effort to understand and measure the cross sections and wavelengths of highly charged ions. In this paper we will discuss some of the early history of EBIT and how it was used to help in the development of X-ray lasers. EBIT's capability was unique and we will show some of the experimental results obtained over the years that were done related to X-ray lasers. As X-ray lasers have now become a table-top tool we will show some new areas of research that involve understanding the index of refraction in partially ionized plasmas and suggest new areas where EBIT may be able to contribute.

Introduction

In the early 1980's the X-ray laser became the topic of news articles because of a new application that would eventually be the primary motivation for X-ray laser research in the United States. Clarence Robinson wrote a 1981 Aviation Week article [1] that said that scientists from Lawrence Livermore National Laboratory (LLNL) had made a breakthrough in laser technology by demonstrating a compact laser device pumped by X-rays from a small nuclear detonation.

At LLNL the early 1980's was an exciting time for the X-ray laser program. LLNL was developing a large X-ray laser program to address the challenge presented by President Reagan to develop a missile defense system, know as "Star Wars" or SDI. As part of this program [2-4] LLNL succeeded in demonstrating the first X-ray laser in the early 1980's using a nuclear explosion to drive the X-ray laser. Later in the decade the first laboratory X-ray laser using Ne-like Se driven by the large Novette ICF laser was demonstrated at LLNL [5].

The Soviet Union also took a strong interest in X-ray lasers. In 1987 they successful produced X-ray lasers driven by nuclear explosions that produced lasers with about 20 kJ of output at 39 Å and 100 kJ of output at a wavelength of 28 Å. This is described in a 1997 article

[6] written by E. N. Avrorin and colleagues at Chelyabinsk-70 that tells how the Soviet Union initiated a program to understand X-ray laser physics and evaluate the feasibility of making an X-ray laser with the characteristics reported in the Aviation Week article. This was a time of intense competition between the United States and the Soviet Union. To facilitate the understanding and development of X-ray lasers at LLNL required a new level of understanding and measurements of the atomic physics of highly charged ions. The electron-beam ion trap (EBIT) was developed and built at LLNL as part of the effort to understand and measure the cross sections and wavelengths of highly-charged ions [7]. As an example of this need, the first laboratory X-ray laser using Ne-like Se did not lase on the 3p – 3s line at 182 Å, as expected, but instead lased on two other weaker lines at 206 and 209 Å [5].

Experiments before EBIT

Prior to the creation of the first EBIT facility in Livermore, LLNL researchers traveled to large facilities such as the UNILAC at GSI Darmstadt to measure high-Z line positions as part of the effort to understand multi-electron QED effects in atomic physics in support of the X-ray laser effort. Dan Dietrich from LLNL spent a year from July 1985 in Europe based in Oxford and Paris. During that year he did experiments at GSI and various people from LLNL visited GSI to participate in those experiments. In the experiments at GSI [8,9] the n = 3 and 4 to n=2 resonance lines of Ne-like Au (Z=79) and Bi (Z=83) were measured with high precision and compared with our theoretical codes. One of the difficulties with the measurements was that the large Doppler shift associated with the multi-GeV UNILAC beam used to create the Ne-like ions resulted in experimental uncertainties that were comparable to the difference between theory and experiment. For example, looking at the position of the Ne-like Au $(2p_{3/2})\ 4d_{5/2}$ (J=1) –> ground state transition, it was measured to be at 13802.8 eV with an uncertainty of 8.9 eV. This line was calculated to be at 13809.7 eV. The calculation was 6.9 eV higher energy than the measured value but the uncertainty of 8.9 eV was larger than the difference between theory and experiment [8]. The notation $(2p_{3/2})$ means a 2p hole in the closed 2p subshell.

While the GSI experimental uncertainties were reduced to about 2 eV in the Bi experiments published in Ref. 9 these experiments motivated the creation of a local facility at LLNL that

could measure more materials, more quickly, and with higher accuracy. A lot was learned in the GSI experiments and these experiments set the important precedent for publishing all the experimental results of the high-Z spectroscopy measurements.

The X-ray laser program was also helping to support spectroscopy measurements of the n = 3 to n = 2 lines of Ne-like Ag ions done at the Princeton Large Torus (PLT) Tokamak [10,11]. This work was part of the Ph. D. thesis of Peter Beiersdorfer who subsequently came to LLNL to work on EBIT for the next two decades.

At the same time as the GSI experiments the research of Donets [12] in the Soviet Union had captured the attention of many spectroscopists. He had taken the electron beam ion source (EBIS) concept and extended it to higher voltage and current so that it could produce almost fully stripped Xe (Z=54) ions. The original EBIS devices had been used to create fully stripped ion sources for Z < 10. The EBIS offered the potential to have a small laboratory-size alternative to using large accelerators for studying highly charged ions. Many researchers studied this work. There was a working EBIS device at Lawrence Berkeley Laboratory (LBL) that served as a training ground for many of the Livermore and Berkeley scientists. To meet the needs of the X-ray laser program at LLNL two competing designs were put forth. An effort at Sandia-Livermore led by Bob Schmeider worked to create a Super-EBIS device [13]. This was designed to produce Ne-like U ions and had a 1-m long super-conducting solenoid with an electron gun rated up to 80 kV. At the same time, the group at LLNL led by Ross Marrs in collaboration with Mort Levine from LBL worked to create the first electron beam ion trap (EBIT) [7]. The original EBIT trapped the ions in a 2-cm long drift tube and operated up to 30 kV and produced Ne-like Au ions. The big advantage of EBIT was that it was more compact than EBIS and the ions could be viewed directly in the trap. The EBIS concept produced more ions but they needed to be extracted from the source. In the end the EBIT technology proved to be more successful and was used by the X-ray laser program to do atomic physics measurements. EBIT has been a very valuable tool over the last 20 years. It enabled rapid response to important questions. The LLNL experimentalists no longer had to travel far distances and schedule beam time on other facilities. By controlling the voltage one could select a particular ionization stage to study with EBIT. With the low electron and ion temperatures in the trap very high-resolution spectroscopy could be

done with EBIT. When the Ne-like Ir ($2p_{3/2}$) $4d_{5/2}$ (J=1) –> ground state transition was measured [14] with EBIT the experimental uncertainty for Ir (Z=77) was 0.33 eV as compared with the 8.9 eV uncertainty measured for the same transition in Ne-like Au (Z=79) at GSI.

EBIT Experiments for X-ray laser research

As part of the X-ray laser program at LLNL many laser-driven X-ray laser experiments were done at the NOVA 2-beam laser facility [15-17]. The Nova 2-beam facility was funded by the Defense Sciences Department to help understand X-ray laser physics and more than a decade of research was conducted. Over the half-decade from 1992 to the decommissioning of the Nova 2-beam facility on November 14, 1997, EBIT was used to do many experiments [18 – 28] to support X-ray laser research. In this section we will describe some of the research that was pursued in support of the laboratory X-ray laser effort.

One of the original concepts proposed to create an X-ray laser involved resonant photo-pumping in which a strong emission line in one material would photo-pump a transition in a second material and create lasing. In many ways this is analogous to the flashlamp pumped Nd:YAG laser [29]. In the Nd:YAG laser a flashlamp with a broadband spectral output photo-pumps broad absorption bands in the Nd^{3+} . The Nd^{3+} is a classic four-level system where the excited electrons in the absorption band quickly decay to a $^4F_{3/2}$ metastable level that becomes the upper laser level. This lases by a 1.06 μm transition to the $^4I_{11/2}$ lower laser level which quickly decays back to the ground state. For the X-ray laser scheme one replaces the broadband flashlamp with a strong narrow emission line. The lasing material then has a strong narrow absorption line where the excited electrons decay rapidly to a metastable upper laser state. The advantage of the photo-pumped system is that the power from a strong isotropic emission line can be converted into a laser line. One big challenge is finding a good resonance where the resonance is good to a few parts in 10^4. Typically theoretical calculations are not adequate and EBIT was used to evaluate many of the proposed X-ray laser schemes before they were tried on NOVA.

An example of one resonant photo-pumped scheme [19] is to use the strong He-α line of Ar at 3.9491 Å to drive the ground state to ($2p_{1/2}$) $5d_{5/2}$ (J=1) transition in Ne-like Y and then lase on

the $(2p_{1/2})\ 3p_{1/2}$ (J=0) to $(2p_{1/2})\ 3s_{1/2}$ (J=1) transition at 155 Å, as shown in Fig. 1. The $(2p_{1/2})$ $5d_{5/2}$ (J=1) state rapidly decays to the $(2p_{1/2})\ 3p_{1/2}$ (J=0) upper laser state with a rate of 1667 $nsec^{-1}$. The radiative decay rates [R] are shown in Fig. 1 in units of $nsec^{-1}$. The $(2p_{1/2})\ 3p_{1/2}$ (J=0) upper laser state is metastable and is dipole forbidden for decay directly to the ground state. The $(2p_{1/2})\ 3s_{1/2}$ (J=1) lower laser state rapidly decays back to the Ne-like ground state with a rate of 5318 $nsec^{-1}$. Calculations [19] predicted gain of about 10 cm^{-1} for this laser line for an Y plasma with an ion density of 10^{19} cm^{-3} and a Ar He-α line with a pump strength of 0.001 photons per mode.

EBIT experiments were done to carefully measure the position of the Ar and Y lines. In this case the Ar He-α line (w in Fig. 2) at 3.94911 Å was used as the reference line and the 45.08 mÅ separation between lines w and z was used to establish the dispersion. Lines w, x, y, and z have the upper states 1s2p $^1P_1$, 1s2p $^3P_2$, 1s2p $^3P_1$, and 1s2s $^3S_1$, respectively. The EBIT experiment measured the Ne-like Y line at 3.94849 Å with an uncertainty of 0.11 mÅ. The Ar and Y lines are only separated by 0.6 mÅ which is less than the 1.5 mÅ Doppler width of the He-α pump line at a 1000 eV ion temperature. Therefore we expect a very good resonance. This scheme was not actually tried at NOVA because of the difficulty of making an Ar target.

Another scheme [20] that was tried on NOVA was to use the very strong $(3d_{3/2})\ 4f_{5/2}$ (J=1) to ground state transition (f_{osc}=6) in Ni-like Pt as the pump line to photo-pump the ground state to $(2p_{1/2})\ 4d_{3/2}$ (J=1) line in Ne-like Rb. This $(2p_{1/2})\ 4d_{3/2}$ (J=1) state decays to the $(2p_{1/2})\ 3p_{1/2}$ (J=0) upper laser state that then lases at 165 Å to the $(2p_{1/2})\ 3s_{1/2}$ (J=1) lower laser state. EBIT measured the Ni-like Pt line at 2511.9(5) eV and the Ne-like Rb line at 2512.3(5) eV with the uncertainty in the last digit shown in parenthesis. The -0.4 eV difference between these lines makes a good resonance while theory had predicted a difference of +2.5 eV between the lines, which was not an adequate resonance. The Pt pumped Rb scheme was tried in a series of experiments on NOVA but no lasing was observed. Even though there was a good resonance it turned out to be difficult to create a strong Ni-like Pt pump line and efficiently couple it to the Ne-like Rb lasing plasma. Also, it was not possible to make a pure Rb target so RbCl targets were used and this further reduced the potential Rb gain.

In the attempt to reach shorter wavelength several X-ray laser schemes were proposed that involved lasing on inner shell transitions. One such scheme [24] whose resonance was verified by EBIT involved using the Ly-α_1 line of H-like Na at 10.0232 Å to photo-pump the ground state to $(2s_{1/2})\ 4p_{3/2}$ (J=1) transition in Ne-like Co. The $(2s_{1/2})\ 4p_{3/2}$ (J=1) level rapidly decays to the $(2s_{1/2})\ 3s_{1/2}$ (J=0) upper laser state that then lases at 83 Å via a 2p3/2 to 2s1/2 transtion to the $(2p_{3/2})\ 3s_{1/2}$ (J=1) lower laser state. The lower laser state quickly decays back to the Ne-like ground state. Using EBIT the Ne-like Co $(2s_{1/2})\ 4p_{3/2}$ (J=1) to ground state transition was measured at 10.0222(11) Å, making an excellent resonance with the Ly-α line. This scheme was particularly interesting because the SATURN machine at Sandia National Laboratory (SNL) could produce very strong Ly-α radiation [30]. We have never had the opportunity to try this scheme.

EBIT was used to verify when we did not have a good resonance so that we would not waste valuable resources at the NOVA facility doing experiments that had little chance of success. One example [26] of this was the idea that we could used the strong Ly-α_2 line (1727.7 eV) of H-like Al to photo-pump the ground state to $(3d_{3/2})\ 4f_{5/2}$ (J=1) transition of Ni-like Er (Z=68) and enhance the gain of five Ni-like 4d – 4p transitions (between 54 and 89 Å) that had already been observed to lase from collisional excitation and also create a new laser line at 64.8 Å. Existing data in the literature made this resonance look promising but EBIT measured the Er line at 1725.9(3) eV which made the Al-Er resonance differ by 1.8 eV which is too large for a good resonance. The result was that this idea was never tried at NOVA or SATURN.

X-ray lasers today

Today X-ray lasers are created at table-top laser facilities such as the COMET laser facility at LLNL [31]. A typical X-ray laser is the Ni-like Pd laser that lases at 14.7 nm and is driven by a combination of a 2-J, 600-ps pre-pulse [17] and 5-J, 6-psec main pulse from an optical laser at 1.05 μm that is focused into a 1.6-cm long by 140-μm line onto a 1.2-cm long Pd slab target. An important application of X-ray lasers is to do X-ray laser interferometry of other plasmas to measure the two dimensional (2D) electron density distribution of these other plasmas [32].

In the course of doing interferometry measurements of many different types of plasmas we have observed some anomalous effects in our interferograms [33 - 38]. We should point out that the basic assumption of X-ray laser interferomtry is that the index of refraction of the plasma is due only to the free electrons and is therefore less than one. The index of refraction n can be written as $n = 1 - [(f_1 N_{ion}) / (2 N_{crit})]$ where f_1 is the optical constant of the plasma, N_{ion} is the ion density and N_{crit} is the critical density of the plasma at that wavelength. At wavelength λ, $N_{crit} = \pi / (r_0 \lambda^2)$ where r_0 is the classical electron radius, 2.818×10^{-13} cm [39]. If only the free electrons contribute to the index of refraction than f_1 is equal to Z*, the number of free electrons per ion.

We have observed plasmas, such as Ag [38], with an index of refraction greater than one where the fringe lines in the interferometer bend the opposite direction than expected. We were able to explain this by considering the contribution of the bound electrons to the index of refraction. Figure 3 shows a calculation of the optical constant f_1 for a Ag plasma with an ion density of 10^{20} cm^{-3} at a temperature of 4 eV. For this case the average atom code [40] gives a Z*=2.02, indicating the average charge state of the ion is doubly ionized. If the index of refraction is due only to the free electrons than the optical constant f1 should equal Z* = 2.02 and be independent of the photon energy. However one can see that this is not the case. In fact, when f_1 goes negative the index of refraction becomes greater than one. The average atom code calculates the energy of the 4d – 4f absorption line at 29.3 eV while the more sophisticated multi-configuration Dirac-Fock (MCDF) code [41] has the strong 4d – 4f line at 25.5 eV. Using data from experiments done in doubly ionized Sn plasmas we had to shift the MCDF calculations by +3 eV to agree with the experimental data [38]. This entire regime of a few times ionized plasmas at mid to high-Z is an area where there is very little experimental data yet the accurate calculation and explanation of X-ray optical constants depends on knowing the line positions accurately. This is a regime where even knowing the line positions to 1% would be a tremendous improvement. Maybe EBIT can be used to measure these warm partially ionized plasmas.

Conclusion

Back in the early 1980's the X-ray laser program required a new level of understanding and measurements of the atomic physics of highly charged ions. The electron-beam ion trap (EBIT)

was developed and built at LLNL as part of the effort to understand and measure the cross sections and wavelengths of highly charged ions. In this paper we discussed some of the early history of EBIT and how it was used to help in the development of X-ray lasers. EBIT's capability was unique and we showed some of the experimental results obtained over the years that were done related to X-ray lasers. As X-ray lasers have now become a table-top tool we showed some new areas of research that involve understanding the index of refraction in partially ionized plasmas and suggested new experiments that EBIT may be able to do.

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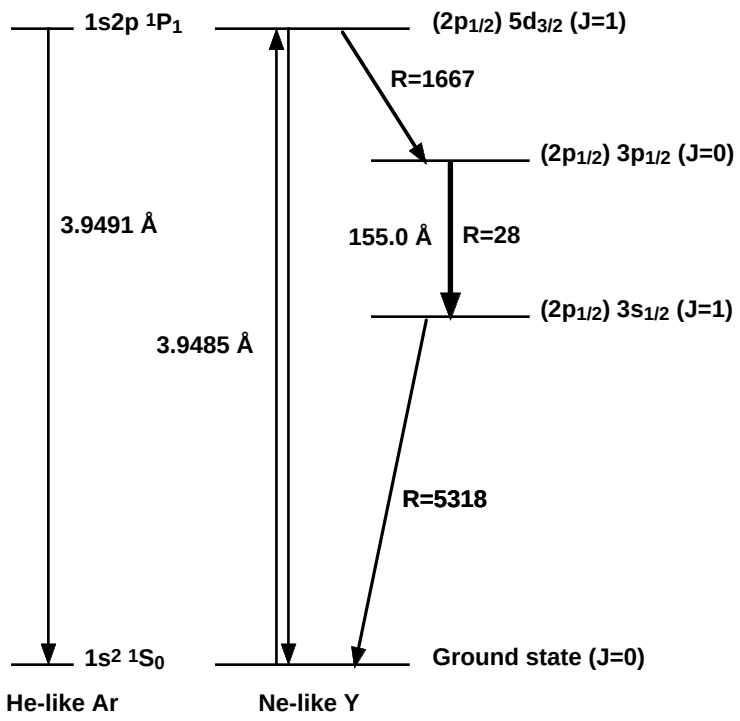
Figures

Fig. 1. Energy level diagram (not to scale) showing the He-α line of Ar resonantly photo-pumping Ne-like Y and creating gain on the 155 Å laser line. Some select radiative decay rates, in $nsec^{-1}$, are denoted by R.

Fig. 2. Spectra of the n = 2 –> 1 lines in Ar and the Ne-like Y ($2p_{1/2}$) $5d_{5/2}$ (J=1) to ground state line. Ar lines w, x, y, and z have the upper states 1s2p $^1P_1$, 1s2p $^3P_2$, 1s2p $^3P_1$, and 1s2s $^3S_1$, respectively.

Fig. 3. Optical constant f_1 versus photon energy calculated by the average atom code for a Ag plasma with an ion density of 10^{20} cm^{-3}, a temperature of 4 eV, and Z* = 2.08.



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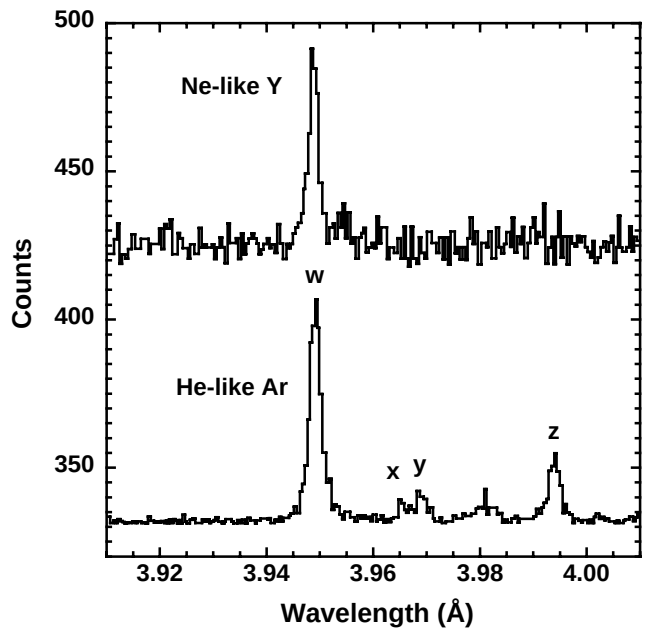

Fig. 2. Spectra of the n = 2 –> 1 lines in Ar and the Ne-like Y ($2p_{1/2}$) $5d_{5/2}$ (J=1) to ground state line. Ar lines w, x, y, and z have the upper states 1s2p $^1P_1$, 1s2p $^3P_2$, 1s2p $^3P_1$, and 1s2s $^3S_1$, respectively.

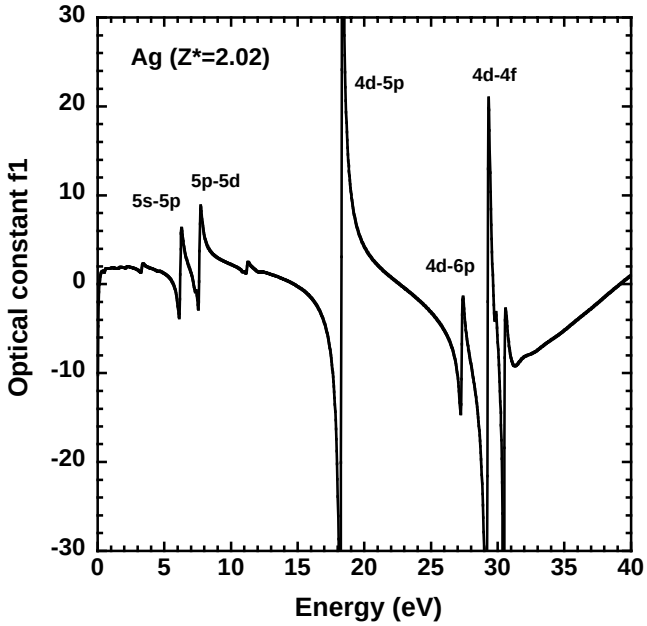

Fig. 3. Optical constant f_1 versus photon energy calculated by the average atom code for a Ag plasma with an ion density of 10^{20} cm^{-3}, a temperature of 4 eV, and Z* = 2.08.