Progress of the spectroscopy research platform at the Shanghai electron beam ion trap

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Abstract. In this report we will focus on spectrometer development, spectroscopic studies and a few other recent developments at the Shanghai Electron Beam Ion Trap, EBIT laboratory. Currently the Shanghai EBIT has three spectrometers covering totally the wavelength region of 1 to 10000 Å. Two of these instruments are home made. A flat crystal spectrometer covers the wavelength range of around 1 – 20 Å while a flat field instrument covers the range of around 20 – 400 Å. The 3rd instrument is a commercial McPherson 225 normal incidence spectrometer. All spectrometers employ CCD cameras for photon detection. The Shanghai EBIT is also equipped with high purity Germanium detectors for, amongst other things, dielectronic recombination studies and time evolution studies of ion distributions. To back up these experimental studies computer codes have been developed for calculation of charge state balances etc. Parallel to the experimental program we have also developed experience at running a number of atomic structure codes (MCHF, MCDF, FAC) for various systems, e.g. the M3 decay of the 3d⁴s²⁵D₃ for Ni-like ions.

1. Introduction

The Shanghai Electron Beam Ion Trap, EBIT, project was initiated in the year 2002 and there are a number of papers describing the history and progress of this instrument, see [1] and references therein. Basically the Shanghai EBIT belongs to the class of so-called Super EBITs, i.e. the maximum design electron beam energy is 200 keV. At the time of writing this paper, an energy of 135 keV has been achieved with an electron beam current of 150 milliams. In this paper we will describe the suite of available and under-development spectrometers for spectroscopic studies of highly charged ions. Our design aim is to cover the wavelength region from around 1 – 10000 Å using three instruments: a flat crystal spectrometer for the region of 1 – 24 Å, a flat field aberration corrected instrument for the 20 – 400 Å region and finally a 1 meter normal incidence spectrometer for the 400 – 10000 Å wavelength region. Each of these separate wavelength regions will be described in the following sections.
2. The 1 – 24 Å wavelength region.
For the wavelength region below around 10Å there are no real choices other than crystal elements if wavelength dispersive instruments are to be used. There are other options for this wavelength region but these are better classified as energy dispersive, such as micro-calorimeters. Micro-calorimeters are already employed at the Livermore and NIST EBIT laboratories, see [2] and [3] respectively. There are various ways the crystal can be mounted to form an X-ray crystal spectrometer. We have chosen the flat crystal geometry. Flat crystal spectrometers are also in operation at the Tokyo [4] and Heidelberg [5] EBITs. There are a number of reasons why this geometry was chosen, one being the fact that the alignment is not so critical, which can be important in an EBIT when the exact location of the electron beam is difficult to define. The spectrometer and its connection to the EBIT are shown schematically in figure 1.

Figure 1: Schematic side-view diagram of the flat crystal spectrometer at the Shanghai EBIT. The diffraction plane is oriented perpendicular to the vertical electron beam. The crystals and the CCD are mounted inside the vacuum chamber and a fully automatic control system is used to rotate the crystals and the CCD.

The design of the flat crystal spectrometer allows for 3 crystals to be positioned in the vacuum chamber at any one time. The photon detector, which is an Andor DX436 CCD is positioned inside the vacuum chamber and in this way Bragg angles from 15 to 75 degrees are possible. The CCD chip has 2048x2048 13.5 micron pixels. All movements, i.e. changing the crystal and turning either the crystal or CCD can be done remotely via computer control. The spectrometer has been tested off-line using a home made X-ray generator and good resolution was observed. Recently it has been used to study M-shell X-ray spectra of highly charged Au ions, see section and [6]. In the Au work a resolution, \( \lambda/d\lambda \), of around 3000 using crystals of LiF(200) (2d=0.4027nm) and SiO\(_2\)(1010) (2d=0.8512nm) was obtained.

2.1. The 20 – 400 Å wavelength region.
This spectral region is traditionally studied using a grazing incidence spectrometer. The problem in using such instruments is that not only is the incidence angle high, the diffracted angle is also high. If the instrument is to use a multi-channel detector, such as a CCD, it must be positioned tangential to the Rowland circle and the incoming photons will have an angle high with respect to the CCD chip normal, hence the chip will act as a mirror and reflect a percentage of the photons. This percentage will depend strongly on the incidence angle, i.e. on the photon wavelength. One solution to this reflectivity problem is to use the detector oriented so that its center is perpendicular to the incoming photons, see [7] where a CCD was adapted for Beam-Foil spectroscopy. Unfortunately only the center of the detector will be at the focus of the spectrometer. A more elegant solution to this problem is afforded by using so-called flat-field gratings. The properties of such gratings were first elucidated in
the early 1980’s by Harada and Kita et al., [8, 9]. It was found that if the line spacing was allowed to vary across the surface of the grating a solution to the imaging equations could be found where the image plane was, to a very good approximation, flat. This is of course idea for a multi-channel detector such as a CCD. Many spectrometers have been designed using such gratings but we will limit our discussion to those used at EBITs. So far flat-field spectrometers are used at the EBITs in Livermore [10] NIST [11] and good results have been obtained. The current flat-field spectrometer at the Shanghai EBIT relies on standard Hitachi gratings. Due to the fixed focal length of these gratings and the geometry of the Shanghai EBIT a technique of refocusing the spectrometer for a distant object will be required [12].

2.2. The 400 – 10000 Å wavelength region.
It is customary to cover the wavelength region over about 2000 Å with some sort of normal incidence spectrometer, normal incidence implying that the incidence and diffraction angles are kept close to the grating normal. This lower wavelength cut off comes from the fact that the spectrometer chamber can be de-coupled from any light source vacuum chamber by quartz a lens/window, hence it is a property of the coupling optics and not of the spectrometer geometry. Again there are a number of geometries that can be chosen, based on either plane or curved diffraction gratings. It is quite possible to use the normal incidence geometry down to wavelengths of around 185 Å [13] but to do this efficiently, the fewer reflections the better as the reflectivity of all materials drops as a function of wavelength. Hence a concave grating working in the Rowland circle geometry would appear as the best choice as only one reflection is needed. The more usual geometry for spectroscopy in the VUV is that of grazing incidence as the reflectivity of most materials becomes good at high angles to the optic normal as discussed in the previous section. The reason why normal incidence optics can be considered, even in the wavelength region where materials have low reflectivities, is because larger f-numbers, i.e. light collection angles, can be used. Grazing incidence leads to high aberrations, in particular astigmatism, leading to a limitation on the size of the grating for decent imaging [14]. Hence we have chosen to use a classic 1 meter normal incidence spectrometer from the McPherson company, the model 225 Nova instrument. A similar, in Geometry, 1 meter normal incidence instrument (Acton) has been previously implemented at the Livermore EBIT [15]. In [15] it was possible to position the spectrometer close enough to the EBIT that the electron beam could act as the spectrometer entrance slit. Diameters of electron beams in EBITs are on the order of 50 – 100 µm and hence equivalent to typical slit widths. Due to the construction of the Shanghai EBIT this is not possible and hence we use a focusing mirror to image the electron beam onto the entrance slit of the spectrometer. Currently this imaging is done by a spherical mirror operating at an incidence angle of 67.5 degrees. This will of course lead to some aberrations of the image. The mirror was designed to give maximum light throughput at the entrance slit. However, due to the weak nature of EBIT light sources this mirror is in the process of being replaced by a toroid. The mirror chamber acts as a differential pumping stage, isolating the very good vacuum of the EBIT from the $10^{-7}$ Torr vacuum of the spectrometer. The arrangement of the spectrometer and mirror chamber is shown in figure 2.
2.3. Other Instruments
The Shanghai EBIT has two high purity Germanium, hpg, detectors; (i) a standard detector which is positioned outside the EBIT, i.e. around 60 cm from the electron beam and (ii) an Iglet detector which is installed inside one of the viewing arms of the EBIT, and hence can get closer to the electron beam. These hpg detectors can be used for (a) monitoring the charge states and elements inside the EBIT and (b) measuring di-electronic recombination, DR, cross sections. The DR cross-sections are measured by recording the arrival of X-rays as a function of the electron beam energy. Similar techniques are used at all EBIT laboratories and more details of the procedure used in Shanghai can be found in [16]. One extra feature concerning DR measurements at the Shanghai EBIT is the ability to measure the electron beam energy to quite high precision using a high voltage divider [17]. We have also developed a slit-imaging system which can be used for measuring the width of the electron beam. This device and its use is described in [18].

3. Some results.
As mentioned above the flat crystal spectrometer has been used to study M-shell transitions in highly ionized gold. These experiments were done using electron beam energies between 5-20 keV, with
electron beam currents of 20 to 80 mA. The gold atoms were introduced into the EBIT from a Metal Vapor Vacuum Arc (MEVVA) ion source. Argon was used as a partial calibration for this experiment and He and Li-like Ar lines are shown in figure 3. From these lines we can deduce that the spectrometer resolution is around 3000. The spectra are under analysis and a sample spectrum is shown in figure 4. More details of this experiment will be available shortly [6].

**Figure 4:** This shows He and Li-like Argon lines and indicates a spectrometer resolution of around 3000.

**Figure 5:** part of the M X-ray spectrum of Au taken using the crystal spectrometer. The electron beam energy was 18 keV, 68 milliamps, and the crystal (Si(111)) operated at a Brag angle of 39.5 degrees for the left most spectrum. The brighter line on the left hand side of the CDD centre in the top left spectrum is the Z line of He-like Ar at 3104 eV. Livermore EBIT [19] sees lines at 3012 and 3132 eV and predicts other lines at 3100 and 3136 eV using the HULLAC codes for charge states Ni-Kr like, so we may assume our charge state balance is different as we see an Au line at 3064 eV. Further analysis is ongoing.

4. Future Developments.
As mentioned above the spherical focusing mirror for the normal incidence spectrometer is due to be replaced by a toroidal mirror. This will increase the light collection properties by a factor of about 10. A flat field spectrometer based on customized gratings has been designed and is currently under
construction. This instrument has some interesting properties and uses 3 gratings to cover the wavelength region of 20 – 400 Å. It also has one grating to give a survey spectrum.

5. Other activities.

In anticipation of future experiments we have initiated an active program of investigating the effects of the hyperfine interaction on the lifetimes of atomic energy levels. This program originated in a statement made in a paper from 1991, “The hyperfine interaction has been proposed to quench metastable beam fractions from an ECR” [20] and updated now with a study of the decay channels available to the 3d’4s 3D3 level in Ni-like ions. In particular Ni-like Xe was studied as there was a substantial discrepancy between theory and experimental results of Träbert et al [21]. This discrepancy was explained by hyperfine effects in [22,23] and confirmed by more refined experiments in [24]. The 3D3 level was previously considered to decay only through an M3 decay. However, for nuclei with a non-zero spin the hyperfine interaction will mix levels of different j quantum numbers, i.e. j is no longer a good quantum number and the f quantum number becomes the important quantity. F is the vector sum of the nuclear spin and the atomic angular momentum, i.e. F = I + J. Hence the 3D3 will no longer decay by purely an M3 decay. The 1D2 level will mix with the 3,1D2 levels where the mixing with the 3D dominated due to the closeness in energy. As the 1D2 has a much faster E2 decay the effect of this albeit small mixing will be very noticeable on the lifetime of the 3D3 level. In fact each f sub-level of the 1D2 will have a different lifetime. Lifetimes now become f-dependent and as an example the two f –sub levels of the 1D2 for the 129 isotope of Ni-like Xe have lifetimes differing by a factor of 7 [22,23]. Since then other Ni-like ions have been studied [25] and other iso-electronic sequences are under investigation. Results for Ne-like ions are presented in these proceedings [26]. Many cases of reduced lifetimes for forbidden transitions were found. In other cases one can expect redistribution of spectral intensity, as found for Ga II in [27]. Cleary by introducing changes in level lifetimes we can also expect a change in branching fractions, which means a redistribution of line intensities. In the case of Ga II it was not possible to simulate astrophysical spectra where Ga II was observed until the hyperfine interaction was included in the calculations of the atomic properties. Similar effects can be expected in other systems when ever there is a change in an atomic level lifetime. In more recent experiments, the effects of the hyperfine interaction have been studied using heavy ion storage ring techniques [28]. It remains to be seen what impact f-dependent lifetimes will have on the field of, for example, astrophysical plasma diagnostics, its “predecessor” j-dependent lifetimes certainly has a well documented significance to both atomic physics and plasma diagnostics. An interesting effect along similar lines was shown by Beiersdorfer et al when they observed magnetic sensitive lines [29]. In that paper they reported on the single photon decay of the 2p3s 3P0 level in Ne-like Ar induced by the magnetic field in their light source, namely the Livermore EBIT. The intensity off this line, with respect to lines from the decay of the other 2p3s levels, increased as a function of the magnetic field. These effects are showing that a very small mixing, induced by say the hyperfine interaction or the Zeeman effect, may have very little effect on the energy of an atomic level, but depending on the detailed atomic structure, can have a very big influence on the lifetimes of forbidden transitions. For example the magnetic sensitive line mentioned above had a zero single photon decay rate in the absence of the magnetic field (2p6 1S0 – 2p3s 3P0). The field induced decay rates are similar in size to the M2 decay of the 2p5s3 3P2 level. More studies along these lines are anticipated. At first though one may imagine these small effects leading to shorter lifetimes as only affecting a very specific area of a spectrum, however deeper thought reveals that changing lifetimes of metastable levels can have consequences throughout a spectrum. Quenching of metastable levels means that population mechanisms can be drastically changes and hence these effects need fuller study.
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