Status and Research Plan of the Shanghai EBIT

Y. Zou$^{1,2}$ and R. Hutton$^{1,2,3}$

$^1$The Key Lab. of Applied Ion Beam Physics, Ministry of Education, P.R. China
$^2$Shanghai EBIT Lab, Modern Physics Institute, Fudan University, Shanghai, P.R. China.
$^3$Atomic Astrophysics, Astronomy Institute, Lund University, Sweden

Abstract
A brief introduction to the history of the Shanghai Electron Beam Ion Trap (EBIT) is sketched, along with some details of the current status and the surrounding instrumentation. Three separate works, done in preparation for EBIT operation, are discussed. The planned physics programs at the EBIT are also mentioned.

*Supported by NSFC no 10434050

Introduction
Ever since forbidden transitions of highly charged ions were identified in the Solar Corona by Edlén in the 1940’s, [1], there has been an important need to understand the physics of highly charged ions. A review of Edlén’s work and other early studies of highly charged ions can be found in [2]. The development of Beam-Foil Spectroscopy (BFS) in the mid 1960’s [3,4] greatly facilitated the studies of highly charged ions. There were of course other methods to generate highly charged ions, for example a low inductance vacuum spark device, constructed by Feldman et al. in 1976 [5] was later used by Brier and Kunze to study He-like Mo (Z=42) [6]. Using laser produced plasma techniques Seely (for example) in 1986 was able to produce ions with charge states up to around 50 [7]. Edlén’s early work relied on vacuum sparks to generate highly charged ions up to around 23 times ionized.

BFS represented a major step forward in the study of highly charged ions, as any ion in any charge state could be produced, depending on the accelerator of course. A second major advantage is due to the fact that the instantaneous ionization/excitation is, for all practical purposes, instantaneous on an atomic scale. Hence for the first time level lifetimes for highly charged ions could be routinely measured [8]. The method of BFS has only one minor drawback, it relies on large accelerator facilities for the production of very highly charged ions, however as such facilities existed it was natural to use them for HCI physics investigations. This drawback is due to the method of ionization/excitation through electron impact where the energy in the collision is provided by the fast moving ions. However if the role of electrons and ions is reversed, a much more compact device for the production of highly charged ions can be constructed.

An Electron Beam Ion Trap (EBIT) [9] is a device optimized for the production and trapping of highly charged ions. The ions are produced by collisions with electrons in an electron beam of the required energy. To produce a usable density of ions, the electron beam is compressed in a relatively high strength magnetic field. The space charge of the electron beam has a trapping effect on the ions in the radial direction. A series, (typically three), of isolated metal cylinders, called the drift tubes, define the interaction region. These tubes allow for final
tuning of the electron beam energy and also allow a potential trap to be generated to trap the ions in the longitudinal direction. The trapped ions then form a thin column, on the order of a few centimeters long and around 100 microns in diameter, almost perfect for spectroscopic studies of highly charged ions.

The Shanghai Electron Beam Ion Trap (EBIT) is under development at the Modern Physics Institute of Fudan University. It is a so-called Super EBIT [10]. There are a number of other working EBITs, and also a few more under development or construction, around the world. Links to these can be found at the National Institute of Science and Technology, NIST, (USA) EBIT home page [11]. EBITs are in general considered to be modifications of the more general EBIS (Electron Beam Ion Source), which was first developed by Donets [12]. However the EBIT/S idea had been around since the 1950’s [13].

A condensed history of the Shanghai EBIT is as follows. The project was launched in January of 2002 and the conceptual design was completed in July of the same year. In April of 2003 the engineering designs of the cryogenic cooling system, superconducting magnets, drift-tube assembly, electron collector assembly and transport system and relevant adjusting structures were finalized. July of 2003 saw the engineering design of the high voltage system and ion injection and extraction system completed. By November 2003 the engineering design of the power supply and control system was finished. Construction of the laboratory area was completed by March 2004 and installation of the EBIT began in April (2004). The installation was completed by October of 2004 and the first electron beam obtained in December of the same year. Some details of the Shanghai EBIT design can be found in [14]. The current status is that the electron beam energy can be run between around 2 and 100 keV with currents up to 100 milliamps at the higher beam energies. The control system has been designed/developed in such a way that changing electron beam energies over the above quoted range can be achieved in a short time. At the time of writing this report a metal vapor vacuum arc (MEVVA) ion source and metal rod injection are being installed and will shortly be tested for the injection of metal ions into the EBIT. The gas injection system has already been installed and tested. A further ion source based on a high intensity laser beam will be added in the future.

The EBIT and auxiliary instrumentation.

As mentioned already, the Shanghai EBIT belongs to the class of EBITs known as Super EBITs, i.e. designed for operation with a high-energy electron beam. Some of the design parameters of the Shanghai EBIT can be seen in table 1 where they are compared to other Super EBIT parameters. The layout of the Shanghai EBIT in the laboratory is shown schematically in figure 1. The main power supplies for the EBIT are on the ground floor of the laboratory whereas the EBIT itself is on the 1st floor. The second floor will be home to an ion extraction system in the near future. One important parameter for good EBIT operation is a high quality magnetic field. The uniformity of the magnet used here was discussed in [15]. The working length of the drift tubes, where the ions are formed, is 20 mm and the magnetic field is found to be as uniform as $10^{-5}$ over this length. The EBIT is designed to operate with two separate electron guns and the properties of these are also discussed in [15].
Table 1. Operating parameters of the Shanghai EBIT compared to other Super EBITs

|                | E-energy KeV | Density A/cm² | E-beam current mA | E-Beam radius mm | Magnetic field T | LHe L/hr |
|----------------|-------------|---------------|-------------------|------------------|-----------------|----------|
| Shanghai EBIT  | 200         | 5000          | 200-250           | 30-50            | 5               | 0.2-0.5  |
| SuperEBIT Livermore | 220     | 6000          | 200               | 35               | 3               | 6        |
| FreEBIT Heidelberg | 350   | 10000         | 750               | 30               | 8               | 0.2      |
| YEBIS Tokyo    | 340         | 10000         | 350               | 30               | 4.5             | 4.5      |

The EBIT produces highly charged ions in excited states and hence one line of research will be to study the spectra of these ions. For this purpose the Shanghai EBIT is equipped with a number of spectrometers. One of these is a 1-meter normal incidence spectrometer from McPherson, the model 225 instrument. This instrument is coupled to the EBIT via a focusing spherical mirror, where the mirror chamber also acts as a differential pumping stage so that the spectrometer can be coupled directly to the EBIT without any window. In this case the normal incidence spectrometer can be used from around 400 Å up to 10000 Å by a correct choice of one of the four available gratings. Two gratings can be accommodated in the...
spectrometer at any time, 300/600 lines/mm for wavelengths greater than 2000 Å and 1200/2400 lines/mm for below 2000 Å. Photon detection can be done either in the multi-channel mode using an Andor DO436 CCD (2000x2000 13.7 micron pixels) detector or in single channel mode, for timing experiments, using a Hammamatsu R331 photomultiplier via a second exit port on the spectrometer. The DO436 is an open-ended CCD and there is cold finger protection in case of a spectrometer vacuum accident. A flat crystal spectrometer has been constructed for the X-ray region of 1 – 10 Å (1 – 10 keV), this instrument accommodates 3 crystals in the vacuum chamber. The dispersed X-rays will be detected using an Andor DX436 CCD (similar chip to the DO436), and again has cold finger protection in case of vacuum problems. Other spectrometers will follow in the near future. We intend to cover the wavelength region from hard X-ray to infrared with a minimum number of spectrometers. The EBIT is also equipped with a high purity Germanium detector with associated electronics for event-mode data acquisition, see figure 2 which shows di-electronic recombination for charge states round to Be-like Xe.

![Figure 2: Di-electronic recombination for ions of charge states around Be-like Xe, the axis between 19.5 and 21.5 is the electron beam energy, in keV, which was slowly scanned. The axis covering 5 to 35 is the x ray energy, also keV, and the vertical axis shows the number of photons at a given x ray energy in resonance with a certain electron beam energy, i.e. the DR resonance photons.](image)

**Preparation Studies**

Earlier, in anticipation of EBIT operation a number of theoretical and simulation studies of EBIT related physics were done in this Lab. Examples of these studies are simulations of EBIT charge state distributions, where up to 4 electron exchange ion-atom collisions were included. As a result of this, charge state distributions could be obtained which showed a better agreement with experimental data compared to simulations where only single electron capture collisions were considered, this is demonstrated for high charge states of Thorium ions, see [16]. The simulation work also allowed calculation of the ion temperature and the effects of the addition of cooler gas on charge state evolution and storage times. Other studies focused on radiative recombinations [17]. The main result of this work was a systematic study of the photon angular distribution and polarization following radiative recombination to bare and He-like ions along the iso-electronic sequences. This work was based on a distorted-
wave treatment. The results are in good agreement with a previous fully relativistic calculation for He-like Ni [18]. Based on the extensive set of calculations presented in this work, two scaling rules were found for quick and relatively accurate estimation of polarization. Large scale Multi-Configuration Dirac-Fock (MCDF) calculations of atomic structure, concentrating on the $4s^2 \ ^1S_0 - 4s4p \ ^3P_1$ intercombination line and hyperfine quenching of the $4s4p \ ^3P_0$ level, for highly charged ions of the Zn I sequence were also performed [19]. As well as indicating possible areas of experimental study for the EBIT in the future, these calculations resolved some existing conflicts in both previous theoretical work and experimental results for the wavelength of the Zn-like $4s^2 \ ^1S_0 - 4s4p \ ^3P_1$ intercombination transition.

**Research Plans at the Shanghai EBIT**

The research at our EBIT will be centered around two experimental platforms, one for high resolution spectroscopy studies of highly charged ions and the other will be an extraction beam line for collision between highly charged ions and atoms, electrons and photons. The first part is well underway as described above and we expect to study spectroscopy of importance to Quantum-Electro-Dynamics (QED), hyperfine interactions and parity non-conservation physics. For example, for Hydrogen like ions, the energy intervals between the main shells ($n=1,2$ etc) are proportional to the square of the atomic numbers $Z$, whereas the energy-intervals between sub-shells inside a main shell are linearly proportional to $Z$. The spin-orbit interaction, which arises from relativistic effects, is proportional to the fourth power of $Z$ and also the Lamb shift, which is a manifestation of QED effects, scales roughly with the fourth power of $Z$, but with an extra $1/\alpha$ compared to the spin-orbit interaction.

It is a little more difficult to discuss the $Z$ dependence of the Hyperfine interaction as for ions with no nuclear spin there will be no interaction, even for very highly charged ions. However rough scaling rules can be given, see for example reference [19] and works quoted therein. Typically there is a $Z^3$ scaling associated with the hyperfine interaction. Again there are a number of forms of parity non-conservation, in highly charged He-like ions for example, there is a $Z^3$ scaling rule, see for example [20]. So, there are many good reasons to push high-resolution spectroscopy to the limits for few electron highly charged ions. The hyperfine interaction has been mostly studied through its effect on spectral line splitting. For $Z>50$ H-like ions however, the ground state splitting is already large enough so that transitions among these levels fall into the range suitable for very high resolution spectroscopy studies i.e. the visible region. Precise studies of hyperfine splitting, can lead to important knowledge concerning nuclear electric and magnetic distributions. These properties are very important to not only nuclear physics, but also to a precise understanding of QED effects. The hyperfine interaction also produces changes in level lifetimes, often opening a previously highly forbidden decay branch. Levels decaying through the hyperfine interaction can have extremely useful properties in the diagnostics of very tenuous plasmas [21], but such diagnostics rely on the hyperfine induced decay rates, which are presently known mostly from theory. An interesting side effect of doing spectroscopy in an EBIT is the fact that the ions are in a region of a strong magnetic field, on the order of a few Tesla. This field will of course Zeeman split energy levels by removing space degeneracy, this is of course well known. However, this splitting, or small change in the energy of the levels involved can have an effect on level lifetimes [22] and this effect will also be investigated at the Shanghai EBIT. The results of [22] show Zeeman quenching to be relatively important concerning lifetimes of forbidden transitions, such as E2 and M1 decays.

As mentioned earlier the second floor of the building will accommodate the ion extraction system along with the necessary beam lines. For ion collision studies a recoil microscope is
under development for precise studies of collision dynamics. The area of study regarding this part of the program will be discussed in future papers.

References

[1] B. Edlén., Arkiv For Matematik, Astronomi och Fysik 28B, no 1 (942).
[2] B. Edlén Physica Scripta T3, 5 (1983).
[3] S. Bashkin. Nucl. Instrum. Methods 28 (1964) 88.
[4] L. Kay. Phys. Letts. 5 (1963) 36.
[5] U. Feldman, M. Swartz and L. Cohen, Rev. Sci. Instrum. 38, (1967) 1372.
[6] R.J. Beier and H.J. Kunze, Z. Physik A285 (1978), 347.
[7] J. F. Seely et al., Phys. Rev. Letts. 57 (1986) 2924.
[8] I. Martinson. Rep. Prog. Phys. 52 (1989) 157.
[9] M.A. Levine et al. Physica Scripta T22, (1988) 157.
[10] R.E. Marrs, M.A. Levine, D.A.Knapp, et al., Phys. Rev. Lett. 60, (1988) 1715.
[11] http://physics.nist.gov/MajResFac/EBIT/ebit.html
[12] E.D. Donets. The Physics and Technology of Ion Sources, ed. I.G. Brown Wiley, New York (1989) 245.
[13] R.H. Plumlee. Rev Sci. Instrum., 28 (1957) 830.
[14] X. Zhu et al. J Phys. Conference Series 2, (2004) 65.
[15] X. Zhu et al., Nucl. Instrum. Methods B235, (2005) 509.
[16] Y.F. Liu, K. Yao, R, Hutton and Y. Zou, J. Phys. B38, (2005) 3207.
[17] W.Y. Ou et al., Chin. Phys. Lett. 22, (2005) 2248.
[18] J.H. Scoffield, Phys. Rev A40, (1989) 3054.
[19] L.Yong et al., J.Phys.B. Accepted.
[20] V.G. Gorshkov and L.N. Labzowski, Pis’tma Zh. Eksp. Teor. Fiz. 19, (1974) 768.
[21] T. Brage, P. G. Judge and C.R. Proffit, Phys. Rev. Lett. 89, (2002) 281101.
[22] M. Andersson, T. Brage and P. Jonsson, Private communication.