EBIT

Fritz Kretzschmar
Johann Wolfgang Goethe Universitaet Frankfurt a.M.

Abstract: The following report is about the usage of Electron Beam Ion Traps and the charge transfer approximation of residual–gas to Ion collisions in these.

1 Introduction

As a start I want to give a short abridgement, what my work at the GSI Summer Students Programm 2007 was all about.
My official main project was to extend a code, simulating the time evolution of ion charge states in a EBIT in respect of the charge transfer between gas Atoms (and rare gas molecules) and highly charged Ions.
Parallel to this, more theoretical work, I participated in an experiment my host working group was performing at the internal gas jet target in the Experimental Storage Ring .

2 The functionality of a EBIT

EBIT is the abbreviation for Electron Beam Ion Trap.
In atomic physics one of the major tasks is to prepare highly charged ions to make experiments with. This can be done on two ways primarily: Firstly with an accelerator, stripping the ions at high velocity by strafing them on a stripper foil and secondly with a EBIT. First of all it will be explained how a EBIT works in general.

As you see in [Fig.**??**]the principle of the EBIT is to strip ions by strafing them with a high density energetic electron beam. It is possible to tear bound electrons out of the atom by hitting it with free electrons. This process is called **Electron Impact Ionization**. If it is assumed only to tear one electron out of a shell the cross section for this ionization process can be calculated due to the Lotz formula [**?**]:

$$\sigma = \sum_{i=1}^{N} a_i q_i \frac{ln \frac{E}{P_i}}{E P_i} \left(1 - b_i \cdot e^{c_i(\frac{E}{P_i}-1)}\right) \qquad (1)$$

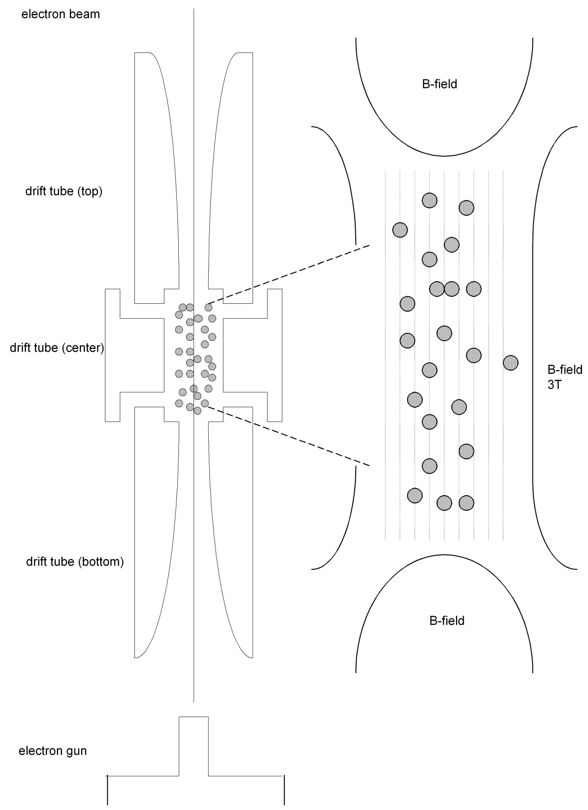

Fig. 1: *Scheme of a EBIT*

In this formula E is the energy of the electron Beam, P_i the ionization potential of the i–th shell and q_i the number of electrons in the i–th shell. Straightforward one can predict that there is a threshold for ionization when the kinetic energy of the free electron equals to the ionization potential of the bound electron. It is also possible to tear out two bound electrons with only one incident electron keeping in mind that in this process more kinetic energy in the incident electron is needed than the sum of the potential energies of the bound electrons that are to be teared out. For this process the cross section can be calculated with the Shevelko formula [?]:

$$\sigma_{i\rightarrow i+2} = \frac{14RyN^{1.08}}{I_n} \frac{ln(u+1)}{(u+1)} \left(\frac{u}{u+1}\right)^c \cdot 10^{-18} cm^2 \quad (2)$$

The ionizations of more than two electrons by only one incident electron usually do not take place because the energy of the electrons in the beam is much to low which means in terms of cross sections that the cross section for these processes are almost zero. If only these two productive processes would be working in the EBIT there would be no problem at all, to create bare ions of all sorts of atoms after some time.
But additionally to this productive effects there are also some counterproductive effects, that decrease the charge states of the ions. In fact there are two major processes that are causing this. First it is possible that a incident electron recombines with a charged ion again. This process we call **Radiative Recombination**. The second process, that my work is about, is the **Charge Transfer** between a neutral gas atom and a highly charged ion in which bound electrons of the neutral gas are transferred to the ion. By insertion of neutral gases the Ions are detained to thermal heating .
This means that the residual gas Atoms are absorbing the momentum of the ions. In fact the description of dynamics in the EBIT is very difficult. The whole System can be described as a chaotic plasma having different charge states which are depending on the energy of our electron Beam, the kind of our Ions and by the time passed by. Up to increasing time the higher charged states take higher and higher densities till finally a equilibrium is at hand. A plasma simulation is not applied here, because it is at one hand much to complicated and on the other hand not suitable for the energies which are too low. One has to distinguish between two things. First of all that a interaction happens and secondly what interaction happens. With a rate coefficient one can figure out how many collisions take place. Then the different processes that take place are weighted by their cross sections. In a very easy simulation of the EBIT the factors between the major processes in the EBIT are calculated: The Electron Impact Ionization and the Radiative Recombination. Using the Lotz [??] formula and a semi empirical RR formula.

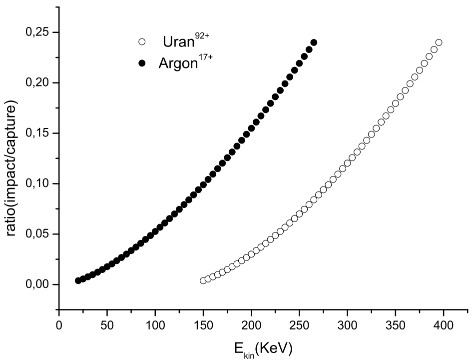

Fig. 2: *Cross–sections in the EBIT*

This all means that the EBIT can be used as a ion source, if it is possible to extract the ions after the stripping process.This device is then called EBIS which means Electron Beam Ion Source. In fact one should remember again, that there is not only one species of charge states in the EBIT but a time depended density distribution what makes the extraction difficult.

3 Charge Transfer

What my work was about at this place was to expand a part of the code calculating the cross sections for the electron capture of the ions.
The former code was using the following formula [?]:

$$\sigma_{z,z-k} = A_k \cdot z^{\alpha_k} \cdot P^{\beta_k} \quad (3)$$

This formula was developed by Mueller and Salzborn and is a semi empirical formula which fits experimental data with tree parameters as shown in Table[??]. This formula was originally developed for charge transfer between Ne,Ar,Kr and Xe ions with rare gas Molecules, such as H_2 f.e. It is not directly energy depended, but only useful in the low energy range between 1KeV and some hundred KeV (what matches with energy range we are operating with in the EBIT). This formula is using the following fit parameters:
Here k stands for k–th ionization. Usually this formula should be useful for collisions in which there is no big difference between the projectile and the targets masses.

Tab. 1: *salzborn fitting parameters*

k	A_k	α_k	β_k
1	$1,43$	$1,17$	$-2,76$
2	$1,08$	$0,71$	$-2,80$

At this point it should figured out what residual gases are used. The usual gases used for the stopping process are He,Ne,Ar,CO_2 and O_2. In the EBIT focussed in this code it is assumed to work with highly charged heavy Ions such as U^{64+} and higher. That means that the mass difference is very high in this purpose. For electron capture processes between Ions and Atoms with a high mass difference usually the classical–over–barrier model is used.

A Japanese group around M. Kimura found out that it is possible to use the classical over Barrier model proposed by A. Niehaus in 1985 with some small modifications for our purpose. The over barrier model is a "‘classical“ ,that means not quantum mecanical model, which pays respect to the binding energy of the electron and the distance between the two centers of the ion and the gas atom. If there is a highly charged ion and a atom at large distances it is not possible for the atomic electrons to transfer to the ion. If the distance in between now decreases the potential barrier of the atomic shells also decreases which means that at a certain point the electron is bound molecular to each ion and atom. At this point one could ponder that it is possible to tunnel trough this barrier before. But for the Tunnel Effect there is no use for because of the low energies which are used here. So all at all quantum effects are neglected because of their non existing cross sections. At the end the cross–sections are calculated as follows with the Kimura formula [?] :

$$\sigma_z^k = \pi \cdot R_k^2 - \pi \cdot R_{k+1}^2 \qquad (4)$$

where the interaction radius where the barrier can be crossed is given as:

$$R_k = \frac{z(\frac{1}{\alpha_k} - 1) + \frac{k}{(1-\alpha_k)}}{P_k} \qquad (5)$$

Here z is the charge of the incoming ion, k is the number of the electron and

$$\alpha = \frac{1}{1 + \sqrt{k/q}}$$

Thus it seems that this formula is better applicable for our usage. Now the calculated values are compared to the experimental data given by several experimental groups. Although the programm would be able to calculate processes were up to 4 electrons are captured, only the first 2 of them are taken into account. For the comparison of which is the better model for this purpose it is relayed on experimental data of cross section measurements done by N. Selberg [?]. Here charged Xe ions were shot onto He, Ar and Xe targets. In the following the calculated cross section data of our code together with the experimental data are plotted against the charge of the incoming Ions. For one electron capture with He as residual gas the following plot is obtained:

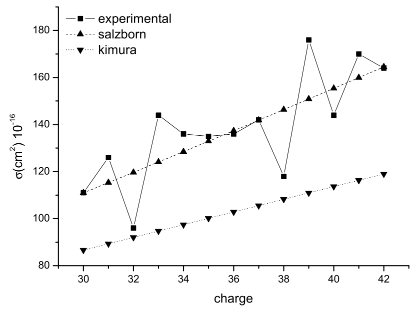

Fig. 3: *Helium 1 electron capture.*

In this plot it can be seen, that for the electron capture between He and a highly charged ion the Mueller–Salzborn formula [Form. ??] is more suitable. By going higher in energy to Argon we see following:

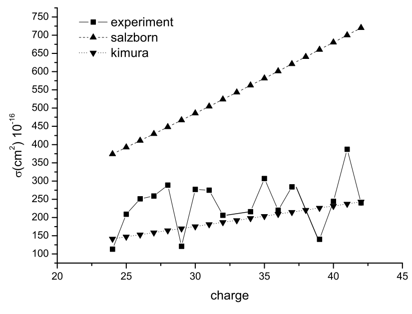

Fig. 4: *Argon 1 electron capture.*

Here the data calculated with the Kimura formula [Form. 4] are better suiting. For the 2 electron capture process the following is obtained:

Here it can be seen, that in lower Ion charge states the Mueller Salzborn formula [Form. ??]

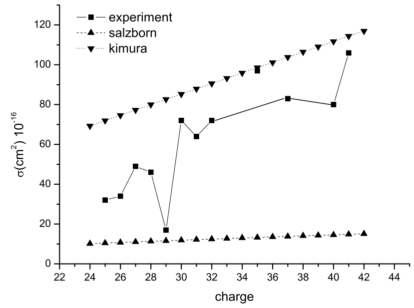

Fig. 5: *Argon 2 electron capture.*

is better suiting but up to charge states higher than 30 the Kimura formula[Form. 4] is giving the better results. At least the charge transfer for Xe as residual gas is plotted.

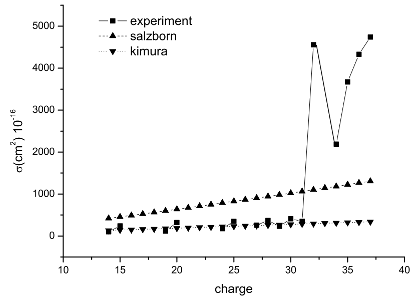

Fig. 6: *Xenon 1 electron capture.*

Here the Kimura formula is better suiting in the charge states up to 31. At higher charge states the experimental cross section is far away from both approximations. For the 2 electron capture it is obtained:

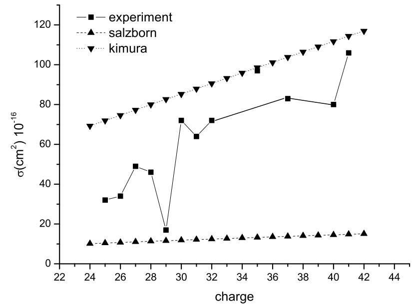

Fig. 7: *Xenon 2 electron capture.*

And here again the Kimura formula is the better approximative function.

One can see conclusively that for higher charge states the Kimura Formula provides a more suitable Approximation in respect to the experimental data. Also the effect is obtained, that the second ionization cross sections are much lower than the first.

4 Summary

In this report a introduction of a EBIT is given. Additionally the cross sections for electron capture between residual gases and ions are calculated and compared.

5 Acknowledgement

Best wishes go to the whole working group. Special thanks go to Sebastian Hess, Regina Reuschl, and especially Guenter Weber for having so much patience with me and helping me with my work.

References

[1] A Niehaus, (1986), A classical model for multi–electron capture in slow collisions of highly charged ions with atoms *J. Phys. At. Mol. Phys*, **19** 2925-2937 .

[2] M.Kimura, (1995), A scaling law of cross sections for multiple electron transfer in slow collisions between highly charged ions and atoms *I. Phys. At. Mol. Opt. Phys.* B **28**L643-L647.

[3] E. Salzborn and A. Mueller,Scaling of cross sections for multiple electron transfer of highly charged ions colliding with atoms and molecules, *Phys. Lett* A **62**, (1977).

[4] N. Sehlberg, Absolute charge-exchange cross–sections for the interaction between slow Xe^{q+} (15¡q¡43) projectiles and neutral He, Ar and Xe *Phys. Rev* A **56**, (1997).

[5] W. Lotz, An empirical formula for the electron–impact ionization cross–section *Zeitschrift fuer Physik A Hadrons and Nuclei* **62**, (1967).

[6] R. Becker, WSUK code , (2000).

[7] A. Simon, Summary of single and double electron capture cross sections for ion–atom collisions at low and intermediate energy *Gsi. SS Reports* **22**, (2003).