THE INITIATION OF EBIS/T-BASED HCI RESEARCH IN JAPAN

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1. ON THE NICE PROJECT

In the course of controlled thermonuclear fusion research with magnetically confined plasmas, the impurity problem began to be discussed in mid-1970s, as both the temperature and the confinement time increased. The impurity atoms such as iron ejected from the wall of the vacuum vessel move inward becoming highly charged ions (HCIs) which emit high energy photons through the interaction with other plasma particles. It was then considered that the highly charged impurities played an important role in the overall energy balance of high-temperature plasmas. Therefore, appreciable amount of data and understandings of relevant atomic physics were required in order to predict what would happen for each impurity species.

In 1976, the research group in the late Institute of Plasma Physics, Nagoya, with inter-university collaborations was organized under Professors Y. Kaneko and T. Iwai to understand atomic processes of highly charged ions in plasmas. The group included N. Kobayashi and K. Okuno as young core researchers. This HCI-business was named the “NICE (Naked Ion Collision Experiments)” project.

The group constructed two EBISes to make atomic collision experiments with extracted HCIs, one with warm magnetic coils and another with a super-conducting solenoid. The latter designed by Kobayashi and Ohtani had been operated intensively for several years with the maximum parameters of (4keV,10mA!) for the electron beam.

A series of experimental studies for electron capture processes of HCIs was made including naked C, N, O, F and Ne and various kinds of other HCIs such as S\textsuperscript{q+}, Kr\textsuperscript{q+} and I\textsuperscript{q+} (up to q=41). In addition to the measurements of total and partial cross sections for electron capture, the NICE group made systematic observations for the levels into which an electron is transferred by using the translational energy spectroscopy.

The NICE project really performed the first systematic study for state-resolved electron capture processes of HCIs in the world [1].
2. INTRODUCTION

From the mid-1970s, a great deal of informations on electron capture processes in slow collisions between HCIs and atoms had been accumulated. A rapid growth in this field was promoted with the development of “novel” ion sources for slow ions such as ECRISes and EBISes. Among several activities in the world, the NICE group led a new research trend in the physics of HCI-collisions using the EBIS, especially through systematic investigation for final-state-selective electron capture processes.

3. TOTAL CROSS SECTIONS FOR ONE-ELECTRON CAPTURE

The NICE group measured total one-electron capture cross sections for HCIs from He atoms at collision energies below 1.5keV/amu. In Fig.1, one-electron capture cross sections at 0.8keV/amu are shown for highly stripped, simple (low Z) ions having no more than a few electrons together with fully stripped (F.S.) ions[2]. The lines are drawn to connect data for ions with the same iso-electronic sequences. The cross sections oscillate strongly with ion charge q around a thin dotted line which shows an empirical q-dependence $q^{1.17}$ derived by Müller and Salzborn.

![FIGURE 1](image)

FIGURE 1. Measured cross sections at 0.8 keV/amu as a function of the ionic charge q of projectile ions. Dotted line is obtained from an empirical formula of Müller and Salzborn.

In general, the electron capture by slow HCIs is considered to take place effectively in reaction with moderate exothermicity, through a favored crossing in the diabatic potential curve constructed with two atomic particles in the collision, which is also interpreted in terms of the so-called “Classical over-Barrier Model”(CBM). According to the CBM[3], an electron is captured into a selected level with a principal quantum number n. Such a level drastically changes from n to n+1 at a particular value of q with increasing q. This level change causes an increase of the crossing distance in the diabatic potential curves, which results in a significant increase in the q-dependent cross sections. On the same value of n, an ion with larger q gives a smaller crossing
distance, causing gradual decrease of the cross section. After all, the q-dependent cross sections would show a saw-tooth-type oscillation.

4. ELECTRON CAPTURING LEVELS IN HCIs

In order to see whether an electron is captured selectively into a particular level \( n \) in the HCI and whether the oscillation is caused by the change of \( n \), the NICE group observed translational energy spectra for charge-changed projectile ions[4]. The capturing level in HCIs can be identified by the translational energy gain of the HCIs scattered in the forward direction after collisions.

In order to measure the translational energy gain precisely, the energy width of incident HCIs must be as small as possible. Fortunately the widths of the HCIs extracted from the Nagoya EBIS were about 0.5\( q \) eV which was sufficient to analyze the final state in electron capture collisions.

![Energy gain spectra of forward scattered product ions A\(^{3+}\) in A\(^{6+}\) + He collisions at 1 keV/q (A=C, N, O and F).](image.png)
In a series of systematic investigations using the translational energy spectroscopy, it was found that an electron is captured into a selective n level and that there is good similarity among energy spectra for HCIIs with the same q. As an example, energy spectra for (A$^{6+}$+He) collisions at 1keV/q are shown in Fig.2, where energy levels with (n,l) in the charge-changed projectiles A$^{5+}$ are also indicated. In each spectrum only a single peak is observed within the present energy resolution at the energy gain of around 30 eV, which corresponds to an electron transfer into n=3. This similarity is considered to be due to the similarity of the potential curves for the collision system. In Fig.3, the diabatic potential curves are shown for (A$^{6+}$+He) collisions. As is shown in the figure, for the final states with n$\geq$3 in A$^{5+}$(n), these curves are dependent little on the number of core electrons in the projectile ions A$^{6+}$ and consequently they are very similar, giving almost the same crossing distances for n$\geq$3. Such similarity should give similar energy spectra for an electron capture processes by various projectiles with the same charge q=6. For other q-systems, similarities in the energy spectra for different projectiles with the same q were also seen.

Finally the measured spectra were summarizes according to charge state q rather than the iso-electronic sequences for projectile HCIIs. Figure 4 shows the summarized data for capturing levels n observed and corresponding crossing distances Rc($\AA$) in the potential curves as a function of the projectile q. As is shown, with increasing q, the value of n increases stepwise, while Rc shows non-monotonic increase. A dashed line is drawn to visualize the strong oscillation with q. According to the prediction from the classical model (CBM) described before, the oscillation of electron-capture cross sections might be caused by the capturing-level change and consequent movement of the crossing distance Rc. This prediction is seemed to be confirmed here qualitatively by observing Rc-oscillation with q[5].
5. ELECTRON CAPTURE FROM H ATOMS

Electron capture collisions of HCl ions in collisions with atomic hydrogen are important atomic processes in hot plasmas, which are directly relevant to schemes of the additional heating by neutral beam injection and to the detailed understandings of energy and particle balance in plasmas. Knowledge of state-selective electron-capture processes is useful and requisite for plasma diagnostics. Fully stripped impurity ions such as C$^{6+}$ and O$^{8+}$ can not be observed directly with spectroscopic methods. However, useful information about spatial, temporal and temperature distribution of the impurities would be obtained from measurements of the intensity enhancement of a particular line emitted from one-electron-capture-fully-stripped ions, that is, H-like product ions, during the neutral beam injection period. Based on these applied aspects, the NICE group systematically investigated state-selective electron-capture processes of HCl ions in collisions with H and H$_2$[6]

As an example, in Fig.5 are shown the energy gain spectra for collisions of fully stripped (naked) ions of C, N and O with H atoms (the system contains just electron) at 1.5$q$ keV (about 0.7 keV/amu). As clearly seen, an electron is captured predominantly into a single level $n$; $n=4$ for C$^{6+}$-collisions, and $n=5$ for N$^{7+}$-and O$^{8+}$-collisions.

**FIGURE 5 (LEFT).** Energy gain spectra of forward scattered C$^{5+}$, N$^{6+}$ and O$^{7+}$ ions in (a) C$^{6+}$ - H, (b) N$^{7+}$ - H and (c) O$^{8+}$ - H collisions at 1.5 x q keV.

**FIGURE 6 (RIGHT).** Energy gain spectra for I$^{q+}$ + He collisions (q=13, 19, 27 and 34). Strong peaks correspond to the one-electron capture process whereas weak peaks on the right probably to the transfer ionization process.
These dominantly populated n-levels were found to be higher by unity than those for collisions of C^{6+}, N^{7+} and O^{8+} with He. This increment in n is understood to be due to the smaller ionization energy of H than that of He, and also explained well in terms of the classical model (CBM). Similar observations were performed for various projectiles including H-and He-like ions[7].

6. HIGHER-q HCI-COLLISIONS

Further experimental studies were made with higher-q HCIs such as S^{q+}, Kr^{q+} and I^{q+}(1 \leq q \leq 41) in order to observe what would happen in these collisions[8,9]. The measured energy-gain spectra are shown in Fig.6 for some cases in the (I^{q+}+He) systems at the collision energy of 1.25q keV. The strong peaks in the spectra, which are narrow but slightly broader than those of the projectile ions, are due to one electron-capture processes of the incident I^{q+} ions. The observed energy gain divided by (q-1) becomes smaller with increasing q, that is, the derived crossing distance Rc where an electron is transferred in the potential curves becomes consequently larger with q. In these spectra there are small peaks or shoulders in the high energy-gain region, which are considered to be due to indirect processes such as the transfer ionization (see discussion letter on).

**FIGURE 7 (LEFT).** Potential energy diagrams compared with energy gain spectra in (I^{13+} + He and I^{34+} + He) collisions at 1.25 q keV.
**FIGURE 8 (RIGHT).** Observed and calculated total one-electron capture cross sections as a function of charge q in I^{q+} and Kr^{q+} + He collisions. ○, in I^{q} + He at the energy of 1.25q keV; +, the MCLZ calculation; ---, scaling low.
There is no accurate information on the energy levels in HCl's of Iodine with high q and n. However, in such highly stripped heavy ions their energy-level structures could be assumed to be hydrogenic, and thus the energy of their highly excited states is given by $13.6q^2/n^{*2}$ (eV), $n^*$ being the effective principal quantum number.

Examples of correspondences between energy levels and energy gain spectra are shown in Fig. 7 for $(I^{13+}+\text{He})$ and $(I^{34+}+\text{He})$ collision systems. As clearly seen, the electron is captured mainly into $n^*=6$ for $q=13$, whereas that $q=35$ is captured predominantly into $n^*=14$. For high q-collisions, as shown in Fig. 7, an electron is transferred at a large Rc region and into a limited number of high $n^*$, around which a number of levels including sublevels are densely located. Therefore the number of crossings increases with Rc and $q$. Under this situation there must be a fair chance to fit into the favored Rc region with a broad width. The multi-channel Landau-Zener consideration shows that when several crossings exist at larger Rc, all of them may contribute to the total electron-capture cross sections. Then, even if the diabatic transition probability is small at an individual crossing, the total cross sections should become larger with the number of crossings. As a result, it is expected that the one electron-capture cross sections obey the scaling law for high q collisions containing the densely located high n-levels.

Finally in Fig. 8, we show the measured total cross sections for Kr$^{2+}$ and I$^{2+}$ in collisions with He together with those by Multi-Channel Landau-Zener (MCLZ) calculations as a function of $q$. They agree well with the scaling low shown by a broken line. Figure 9 shows the summarize data for measured n-values of capturing levels in HCI-collisions of C, N, O, F, Ne, Kr and I with H and He. It was confirmed here that the capturing levels show the same n-values for respective collisions of different ion species with the same q. A solid-and a broken-line is a fitted $q$-dependence with $q^{0.71}$ which is similar to that with $q^{0.75}$, an asymptotic form obtained from the classical model.

**FIGURE 9.** Electron capturing level n as a function of q. A solid- and broken lines are fitted scaling with $q^{0.71}$. 
7. STATE SELECTIVE TRANSFER IONIZATION PROCESSES

In Fig. 10, the translational energy spectra are shown for \( A^{7+} \) (A=N, O, F and Ne)-collisions with He. It is also shown here that there is good similarity in the spectral patterns for the same charge state (q=7) of projectiles, irrespectively of ion species. The dominant peaks at energy gain of around 20 eV observed are corresponding to one-electron transfer into \( n=4 \). This similarity is reasonably caused by the similarity of the diabatic potential curves for respective \( (A^{7+} + \text{He}) \) collision systems. In addition to the dominant peaks, there are weak peaks at around 70 eV in all of the energy spectra. These peaks were assigned as being due to the transfer ionization processes. The transfer ionization is explained as follows, that is, two electrons from He are captured into doubly excited states in the projectile ions, for example, into \( \text{N}^{5+} \) (3\( l \)3\( l \)'), \( \text{O}^{5+} \) (1\( s \)3\( l \)3\( l \)') for \( \text{N}^{7+}, \text{O}^{7+} \)-collisions, respectively. These hallow atomic states immediately decay emitting one electron via autoionization. Therefore these processes can be detected state-selectively in the energy gain spectra for the product ions with q=6[10].

**FIGURE 10.** Energy gain spectra of forward scattered product ions \( A^{6+} \) in \( A^{7+} + \text{He} \) collisions at 1 keV/q (A=N, O, F, Ne). Weak and broad peaks at around 70 eV of energy gain are thought to be due to transfer ionization processes.
Thus the NICE experiment showed for the first time that the translational energy spectroscopy would give us useful information about the intermediate multiple-excited states in the transfer ionization processes, and therefore it would be a powerful method for spectroscopy of the so-called hollow atoms.

8. SUMMARY

Although the NICE group did not make much effort in the machine study for EBIS-developments, it did contribute to open up a new field in the HCI-physics with the EBIS during several years from late 1970s.

The group consisted of Y. Kaneko, N. Kobayashi, K. Okuno (TMU); T. Iwai, M. Kimura, S. Tsurubuchi (Osaka); H. Tawara (Kyushu), T. Watanabe (Riken), S. Ohtani (IPP, Nagoya), and several graduate students.

Subsequently to the NICE project, a lot of HCI-research activities have been developed in Japan using e.g. mini-EBISes and the Tokyo EBIT.

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