Progress of highly charged atomic physics at IMP

X. Ma¹, X. L. Zhu¹,², H. P. Liu¹, B. Li¹,², B. R. Wei¹,², S. Sha¹, S. P. Cao¹,², L. F. Chen¹,², S. F. Zhang¹,², W. T. Feng¹,², D. C. Zhang¹,², and D. B. Qian¹,²

¹Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, 730000, China
²Graduate School of the Chinese Academy of Sciences, Beijing 100039, China

Abstract: The progress of atomic physics researches at the Institute of Modern Physics (IMP) is reviewed, covering the studies on ion-atom/molecule collisions, ion-cluster interaction, negative ion formation, state-selective electron capture studied by COLTRIMS, as well as the progress of a new experimental area dedicated for atomic researches at moderate energies, and the advances of the cooler storage rings at the Heavy Ion Research Facility in Lanzhou (HIRFL). New opportunities to study collision dynamics from femto-second to atto-second regime are opened based on the present facilities and the on-going projects.

1. Introduction

Ion – atom collisions have been an important tool to investigate the many-body collision dynamics. With the quick development of ion source and accelerator techniques, highly charged ions up to bare uranium can be provided in laboratory nowadays; this opens new fields in ion-atom/molecule collisions and ion surface interactions [1,2,3]. The collision dynamics are quite different for low and high projectile energies. When a highly charged ion approaches an atom/molecular target, at very low velocities (v_p<1 au), the potential of the ion will dominate the collisions process, the electron cloud of the target will be polarized due to the strong attractive force of the projectile, electron capture process will be the dominant channel, and the velocities of the active electrons will be larger than the projectile velocity; Here the Born-Oppenheimer approximation holds. At intermediate velocities where v_p~1 au, capture and ionization processes have same strength, they are competing with each other. At higher velocities (v_p>1 au), the fast moving electromagnetic field can be considered equivalent to a virtual photon field, here ionization processes will dominate, and the Born approximation should be applicable. But recent complete experiment shows that the traditional Born approximation is not sufficient to describe the momentum transfer in the collisions. During the last years, advances are made based on the present accelerator facility in our institute.

In this paper, we report on processes of highly charged ion – atom/molecule/C_60 collisions at low energies, the construction of the dedicated experimental area at moderate ion energies for atomic physics and surface studies, the status of the heavy ion cooler storage rings (CSR) at the Heavy Ion Research Facility in Lanzhou (HIRFL), and the possibilities to perform there relativistic ion-atom collision experiments.

2. Ion – molecule collisions

Highly charged ions such as Xe^{q+} (q=15-24) are extracted from the ECR ion source, collimated, cleaned, and then collide with molecule N_2 and H_2, respectively [4]. A time-of-flight spectrometer is used to identify the recoil ions according to their mass to charge ratios, and the scattered ions are analyzed by a parallel-plate electrostatic deflector and then recorded by a position sensitive detector which gives the information on the number of electrons stabilized on the projectile. The primary beam is deflected into the Faraday Cup. By using coincidence technique and position sensitive detectors, all the charge transfer processes are obtained in one run of the experiment. Figure 1 shows a typical two-dimensional plot for 357 keV Xe^{21+} on N_2. The charge transfer reaction channels can be identified in the plot. For a
molecular target, the molecular ions will decay via dissociation (one neutral and one charged fragment, \( N_2 \rightarrow N^+ + N^0 \)) or Coulomb explosion (two charged fragments, \( N_2^{2+} \rightarrow N^+ + N^+ \)). The initial kinetic energy of ionic fragments clearly leads to a double peak structure. The kinetic energy release (KER) of the fragments is determined from the time difference of the double peaks in the TOF spectrum \([5,6,7]\). In Table 1, the average kinetic energies release for fragments \( N^+ \) and \( N_2^{2+} \) are deduced for \( \text{Xe}^{17+,18+,19+,20+,21+} \) on \( N_2 \), and compared to the KER calculated from Coulomb explosion model (CE). The results show that the KER for the symmetric fragmentation of \( N_2^{2+} \) agrees roughly with CE model calculation, while the KER for the asymmetric fragmentation of \( N_2^{3+} \) is evidently larger than CE model. The KER of asymmetric fragmentation of \( N_2^{3+} \) varies with the projectile charge state and collision energy.

![Fig. 1. A typical two-dimensional plot of ion-molecule collisions recorded for \( \text{Xe}^{21+} \) on \( N_2 \), the horizontal axis represents the charge states of the scattered ions, and the vertical axis the time-of-flight of the recoil ions which is proportional to the mass to charge ratio of the recoils. The identified recoil ions and the fragments are labeled in the plot.](image)

| Collision system | Product ion pair observed | Measured average KER (eV) | Calculated KER (eV) |
|------------------|---------------------------|----------------------------|---------------------|
| 340keV           | \( N^+ + N^+ \)           | 11.7 ± 1.2                 | 13.1                |
| \( \text{Xe}^{17+} + N_2 \) | \( N^+ + N_2^{2+} \)     | 29.4 ± 3.9                 | 26.2                |
| 360keV           | \( N^+ + N^+ \)           | 11.5 ± 1.2                 | 13.1                |
| \( \text{Xe}^{18+} + N_2 \) | \( N^+ + N_2^{2+} \)     | 28.5 ± 3.9                 | 26.2                |
| 400keV           | \( N^+ + N^+ \)           | 12.7 ± 1.3                 | 13.1                |
| \( \text{Xe}^{20+} + N_2 \) | \( N^+ + N_2^{2+} \)     | 30.2 ± 4.0                 | 26.2                |
| 420keV           | \( N^+ + N^+ \)           | 12.8 ± 1.3                 | 13.1                |
| \( \text{Xe}^{21+} + N_2 \) | \( N^+ + N_2^{2+} \)     | 32.1 ± 4.1                 | 26.18               |
In the calculation, the initial distance of the two fragments is assumed to be the balance distance between the two nuclei of the atom. The measured kinetic energies are larger than the calculated ones, and the discrepancies increase with the projectile charge states, which might be due to post-collision effects.

3. HCI - C\textsubscript{60} collisions

The production of multiply charged C\textsubscript{60} ions and the mass spectra resulting from fragmentation process of these ions are of particular interest in obtaining a better understanding of the structure and stability of C\textsubscript{60} as well as its electronic properties. During the last ten years, highly charged ions (HCI) have been used to excite C\textsubscript{60} and to observe its response. Systematic investigations as a function of ion mass, charge, and impact velocity have provided significant new information about excitation, ionization, and charge transfer [8].

Here we report some results for very high charge states of projectiles colliding with C\textsubscript{60}. The projectiles are Xe\textsuperscript{(17-22)+}, and Ar\textsuperscript{(8-13)+}. Figure 2 shows a typical TOF spectrum for Xe\textsuperscript{21+} on C\textsubscript{60}. The spectrum was not corrected for detection efficiencies. From the figure we find that up to 8+ ions (C\textsubscript{60}\textsuperscript{8+}) are observed and the fragments are much less compared to light, low charged ion impact. This may be understood due to the very high charges, the electron capture dominantly occurs at very large impact parameters, the electrons are removed from large distances and the left electrons are not strongly disturbed; then the energy deposition in the C\textsubscript{60} are small and not enough to overcome the fission barrier [9,10].

In the case of 20q keV Ar\textsuperscript{q+} (q=8~13) impact on C\textsubscript{60}, the multiply charged C\textsubscript{60}\textsuperscript{r+} ions with r up to 7 were observed. Correspondingly, there are one or more electrons stabilized to the projectiles finally. After the collision, the final charge state of the C\textsubscript{60} can be much higher than the number of stabilized electrons on the projectiles. That indicates a lot of Auger electrons are ejected after the capture process. With increasing the initial charge of the projectiles, the multiple charged ions C\textsubscript{60}\textsuperscript{r+} increase and the relative cross section for the production of C\textsubscript{60}\textsuperscript{r+} (r\geq 4) increases also.

![Fig. 2. A time-of-flight spectrum for Xe\textsuperscript{21+} on C\textsubscript{60}, the horizontal axis represents the time-of-flight of the recoil ions. The identified recoil ions are labeled in the spectrum.](image)

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4. Negative ion formation in HCl-C₆₀ collisions

In ion-surface collisions, negative ions were observed from the emerged beam. C₆₀ has a large spherical surface and large number of electrons are distributed on the surface; it is interesting to question: are there negative ions formed in ion-C₆₀ collisions? In cooperation with LASIM group of Lyon University 1, we performed a testing experiment at the Institute of Modern Physics, studying the collision systems of F₄₊ C₆₀ (q=2-4) and S₃₊ C₆₀. The experimental setup was designed to record the negative projectile as well as the neutralized projectile in the same experiment with a position sensitive micro-channel plate detector. Figure 3 shows the charge state of the scattered ions in the F₄₊ C₆₀ and S₃₊ C₆₀ collision systems. For S₃₊ and F₂₊ ions, obviously the negative ions F⁻ and S⁻ were recorded, respectively. In order to form S⁻ and F⁻ ions, at least 4- and 3-electrons must be transferred to the projectiles, which will lead to the charge state of C₆₀ up to 4+ and 3+, whose potential energies are much larger than the electron affinity of the neutral S and F atoms. It is surprising that the weakly bound electron states of the negative ions can survive in the vicinity of the fullerene ion potential well. From the point of view of the classical over barrier model, the possibilities approach zero.

5. State-selective electron capture in He₂⁺ on He collisions studied by COLTRIMS

During last forty years, a lot of experiment for low energy collisions between charged particles and atoms were performed, mainly total cross sections were deduced. For the last ten years, the quick development of recoil ion momentum spectroscopy with cold target gases (COLTRIMS) make it possible to measure differential cross sections and investigate the reaction dynamics in great details [2,11,12]. We have carried out kinematically complete experiments on single and double electron capture in He₂⁺ on He target for incident energy from 20keV to 50keV, fast collisions were studied in reference [13]. Our interest is to study the state-selective electron capture processes, and to understand how the state-selective capture processes depend on the impact parameters. The momentum transfer between projectile and target atom is small when compared with the impact momentum. For pure electron capture reactions, the longitudinal momentum $p_{l,R}$ contains the information on state-selective capture via Q-values according to the following equation:

$$p_{l,R} = -Q / v_p - m v_p / 2$$

where n is the number of captured electron and $v_p$ is the projectile velocity, all in atomic units. Figure 4 presents a two dimensional plot for the longitudinal momentum and vertical momentum component. Figure 5 shows the recoil ion longitudinal momentum for He₂⁺ + He(1s) → He⁺(n) + He⁺(n′) reaction. According to the above equation, electron capture into
different states of the projectile can be deduced, as indicated in the figure. Our analysis shows that the captured one electron dominantly populates the \( n=2 \) states, the capture into ground state \((n=1)\) and into the excited states \((n\geq 3)\) is less important. It is also found that the capture into higher states is strongly depending on impact parameter.

![Figure 4. Recoil ion momentum spectrum obtained in \( \text{He}^2+ \) on \( \text{He} \) at 30 keV. Horizontal axis is the longitudinal momentum and the vertical axis is the vertical momentum component.](image1)

![Figure 5. Longitudinal momentum of \( \text{He}^+ \) recoils produced in \( \text{He}^2+ \) on \( \text{He} \) at 30 keV.](image2)

**5a. Target ionization in low-energy \( \text{He}^2+ \rightarrow \text{Ar} \) collisions**

Target atom ionization induced by slow charged ions are of interest. There are large amount of total cross section data for charge transfer in low energy collisions \([14]\). The data on target ionization at relatively low energies are scarce. We have performed experiments for \( \text{He}^+ \) on \( \text{Ar} \) collisions for incident energy from 20keV to 42keV. In our experiment singly, doubly, triply, and quadruply charged \( \text{Ar} \) ions were observed. It should be noted that the \( \text{Ar}^{3+} \) and \( \text{Ar}^{4+} \) ions must be produced via Auger decay of multiply excited states of recoils. It is interesting then to know the energy transfer in such collisions. From the measured longitudinal momentum distribution of \( \text{Ar}^2+ \) and \( \text{Ar}^3+ \) recoil ions, apparently the momentum distributions for \( \text{Ar}^2+ \) and \( \text{Ar}^3+ \) recoil ions are different. Further analysis of the spectra using
structure data will manifest the multiply excited states formed in the collisions. Quite
different distribution of longitudinal momentum was observed when conditions were set to
\( \text{Ar}^{+} \) in the TOF spectrum. These data are being under analysis presently.

6. A high-voltage ECR platform dedicated for atomic physics and material sciences
The interactions between highly charged ions and materials (atoms, molecules, clusters,
surfaces, and bio-molecules, etc) have great importance not only for fundamental interests but
also for applied research [15]. For low-energy collisions, the highly charged projectiles are
usually provided by ECR ion sources or EBIT/S. The projectile energy is around 30q keV
(\( q \) is the projectile charge) and below, while for energies up to several 100q keV, there
are only a few facilities available. In order to extend the experimental possibilities to higher
impact energies, a project is presently realized at the Institute of Modern Physics (IMP) which
aims to accelerate the ions up to 320q keV. The dynamical range of the projectile velocity
will be from 0.3 to 2 atomic unit covering the reactions from electron capture dominant
channels to ionization dominant channels. The overall layout of the beamline is shown in
figure 6. The permanent magnet ECR ion source sits on the high voltage platform. The beam
lines are equipped with five experimental terminals [16] as following: (1) surface studies, (2)
atomic physics research (collision dynamics as well as spectroscopy with atomic or molecular
target beams), (3) atomic experimental terminal; (4) material science, and (5) biophysics
searches, respectively.
The construction phase just finished recently, and the vacuum of the beam-line is better than
5x10^{-9}mbar. The tuning of the permanent magnetic ECR ion source and the commissioning of
the beam-line have been initiated.

![Fig. 6. Schematic view of the dedicated experimental area for atomic and surface studies;
Five experimental terminals are provided. The permanent magnet ECR ion source sits on the
HV-platform (320kV).](image)

7. News from the cooler storage rings
The Heavy Ion Research Facility in Lanzhou with its cooler storage rings (HIRFL-CSR) have
been under construction presently at the Institute of Modern Physics (IMP) [17,18], the
facility will provide heavy and highly charged ions up to bare uranium with high quality.
HIRFL-CSR is a multipurpose Cooling Storage Ring system, which consists of a main ring
(CSRm) and an experimental ring (CSRe), as shown in figure 7. The two existing cyclotrons
SFC (\( K=69 \)) and SSC (\( K=450 \)) of the HIRFL will be used as its injector system. The heavy
ion beams with the energy range of 10–50 MeV/u from the HIRFL-SSC will be accumulated,
cooled and accelerated to the high energy range of 100–600 MeV/u in the CSRm, and then
extracted to produce radioactive ion beams (RIB) or after striping, injected into the CSRe.
The secondary beams can be injected into the CSRe for internal-target experiments or
extracted for external experiments. High precision spectroscopy can be performed in the
CSRe at the internal target as well as at the electron cooler.
The planned programs closely related to atomic physics are the following:
• High precision X-ray spectroscopy for few-electron heavy ions
• QED effects in strong Coulomb fields
• Polarization measurements of hard X-rays
• Collision dynamics at relativistic velocities
• Laser assisted recombination processes (ion-e, ion-atoms)
• Dielectronic recombination processes
• Nuclear properties investigated by atomic spectroscopy
• Mass measurements
• Molecular ions related processes

The construction and the installation of the two rings has been finished, the electron coolers have been tested, the density of internal target reached several $10^{12}$ atoms/cm$^2$. The ions from SSC have been injected into the CSRm, and circulating at least for one turn. More efforts are made presently to optimize the operation parameters in order to have closed orbit.

8. Summary
In this paper we report on the progress of atomic physics researches at the Institute of Modern Physics, which covers both the studies on ion-atom/molecule collisions, ion-cluster interaction, negative ion formation, state-selective electron capture, and the installation of a new experimental area at moderate ion energies dedicated to atomic researches, as well as the advances of the cooler storage rings at HIRFL. It is clear that, based on the facilities already existing or soon ready to operate, atomic researches will provide a high potential for studying the collision dynamics from femto-second to atto-second regime.

![Fig. 7. The layout of HIRFL and the cooler storage rings complex](image)

**SFC**: several to 10 AMeV  
**SSC**: tens to 100 AMeV  
**CSRm**: 1.1 AGeV ($^{12}$C$^{6+}$), 2.8 GeV(p)  
**CSRe**: 0.76 AGeV ($^{12}$C$^{6+}$)

Fig. 7. The layout of HIRFL and the cooler storage rings complex

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