Recent progresses on atomic physics with highly charged ions in Lanzhou

X. Ma¹, X. L. Zhu¹, S. F. Zhang¹², B. Li¹², S. Y. Xu¹², L. J. Meng¹², W. T. Feng¹², D. C. Zhang¹, D. B. Qian¹, H. P. Liu¹, S. C. Yan¹², L. T. Sun¹, J. Y. Li¹, X. L. Tu¹², M. Wang¹, Z. G. Hu¹, H. S. Xu¹, G. Q. Xiao¹, H. W. Zhao¹, J. W. Xia¹, Y. J. Yuan¹, W. L. Zhan¹

¹Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, 730000, China
²The Graduate University of the Chinese Academy of Sciences, Beijing, 100049, China

E_mail: x.ma@impcas.ac.cn

Abstract. Storage rings, dedicated small accelerators and experimental setups have been established during past few years in Lanzhou China. The commissioning of the heavy ion Cooler Storage Rings gained great success. These advances give good opportunities for atomic physics researches using highly charged ions. The current status of the accelerators, some experimental setups will be introduced. Examples of some research results will be selected and reported. The future aspects of atomic physics related to ion–matter interactions will be outlined.

1. Introduction
The interactions between highly charged ions and gas phase atoms/molecules, electrons, surfaces, solid materials, as well as bio-materials attract more and more interests in recent years, many new developments are reported. Highly charged ions can be produced in electron cyclotron resonance (ECR) ion source, electron beam ion trap/source (EBIT/S), and high energy accelerators. With the advent of heavy ion storage rings, new possibilities are open for atomic and nuclear physics researches with highly charged ions [1,2]. Here, we report the recent progresses on the cooler storage rings, dedicated small accelerators and experimental setups established for atomic physics researches during past few years in Lanzhou, China.

2. A platform for multi-discipline researches with highly charged ions
With the increasing interest in the application of low- and intermediate energy highly charged ions, a dedicated platform for multi-disciplinary researches with highly charged ions has been constructed at the Institute of Modern Physics (IMP) in Lanzhou, where the projectile energy is extended to 320q keV (where q is the projectile charge state). The new facility includes a 320kV high voltage platform, transportation beam-lines, and five experimental terminals. To reduce the power load to the platform, an all permanent ECR ion source was designed, which has a dimension of magnetic body of Ø650 mm × 562 mm. The overall magnetic field has been measured and compared to the theoretical results, good agreement was obtained. The injection magnetic field of the source is 1.28 T and the extraction magnetic field is 1.07 T, the details of the magnetic design can be found in reference [3].
The beam lines are equipped with five experimental terminals: (1) ultra-high vacuum chamber for surface studies, (2) reaction microscope for atomic physics collision dynamics as well as spectroscopy with atomic or molecular target beams [4], (3) multi-purpose experimental terminal for material science, the design is flexible and allows the external users to bring their own set-ups for experiments, (4) atomic physics terminal for atomic collision and micro-capillary experiments, and (5) a terminal for biophysics searches, respectively.

The commissioning of the platform was successful. Ions such as Ar^{q+} (8<q<16), Xe^{q+} (10<q<30), Ne^{6,7,8+}, C^{4,5+}, and O^{3,5,6+}, etc were provided for the experimental studies of atomic collisions, ion-surface, ion-solid, and ion-capillary array interactions. Recently the extraction of highly charged metallic ions was tested for lead. Figure 2 shows the intensity distributions of different charge states for Pb ions at 350W. The Pb^{31+} ions were observed and further optimization is being under progress.

![Figure 1. Typical charge state distribution spectrum for highly charged Pb ions.](image)

3. Physics programs at the cooler storage ring

The project of cooler storage rings at Heavy Ion Research Facility in Lanzhou (HIRFL-CSR) have been completed at the Institute of Modern Physics (IMP) [5], the facility will provide heavy and highly charged ions up to bare uranium with high quality. The 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 2. 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 for heavy ions and the energy up to GeV/u for light ions in the CSRm. The ions then can be extracted to produce radioactive ion beams (RIBLL) or after stripping, 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, and the density of internal target reached several 10^{12} atoms/cm^2. Both rings are equipped with new generation electron coolers [6]. The 7 MeV/u C^{4+} and 22 MeV/u Ar^{8+} after stripping to C^{6+} and Ar^{16+} respectively, have been injected into the CSRm, cooled, and accelerated up to 1000MeV/u, up to 2x10^9 ions are stored. The 2.9 MeV/u Xe^{27+} ions have also been injected into the CSRm cooled and accelerated up to 235 MeV/u, and 1x10^8 ions have been stored.
The researches of highly charged ions are making progresses in last few years, see e.g. [7,8]. 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 (DR)
- Nuclear properties investigated by atomic spectroscopy
- Mass measurements for radioactive ions far from stability
- Laser cooling of heavy ion beams
- Molecular ions related processes

![Figure 2. Schematic overview of HIRFL-CSR and some experimental areas.](image)

### 4. Examples of some recent results

One experiment performed at the reaction microscope at 320kV platform was the state-elective studies for electron capture. The population to different quantum states for electron capture with the different impact parameter for He\(^{2+}\) on helium collision is shown in Figure 3, the strong dependence on impact parameters was demonstrated. The uppermost panel corresponds to a large transverse momentum of \(8 < p_{\perp} \leq 10\) a.u., and the lowermost panel corresponds to a small transverse momentum of \(0 < p_{\perp} \leq 2\) a.u. (small scattering angle, larger impact parameters \(b\)). It clearly shows that electron is mainly captured into the excited state for small impact parameter collisions, and that electron prefers the ground state at large impact parameters. The highly differential results tested stringently theoretical models [7,8].

The CSRe can be used as high-resolution mass analyzer, and the masses are determined from the precise measurement of their revolution frequencies. The CSRe was set to isochronous mode for
commissioning run of mass measurement [9]. The fragments of $A/q = 2$ from fragmentation of 368MeV $^{36}$Ar projectile were measured by their revolution frequencies. The mass spectrum is shown in figure 4. A mass resolution $\Delta m / m$ was estimated to be $10^{-6}$.

In summary, the developments in accelerators and experimental equipments provide good opportunities for atomic physics related to ion–matter interactions. The facilities are open to outside users.

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