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Highly-Charged Ion Beam for Study of Cluster Physics

Masashi Imanaka, Tetsuro Kurita*, Takahide Nakagawa**, Haruka Sasaki, Sang-Gon Lee, Ichiro Arai and Sang-Moo Lee
Institute of Physics, University of Tsukuba, Tsukuba, Ibaraki 305-8577, Japan
Fax: 81-298-53-2565, e-mail: imany@tac.tsukuba.ac.jp
*The Wakasawan Energy Research Center, Nagatani, Tsuruga, Fukui 914-0192, Japan
Fax: 81-770-24-5605, e-mail: tkurita@werc.or.jp
**RIKEN, Hirosawa 2-1, Wako, Saitama 351-0198, Japan
Fax: 81-48-461-5301, e-mail: nakagawa@postman.riken.go.jp

We have developed a super-conducting electron cyclotron resonance (ECR) ion source for the study of cluster physics. With use of a liquid He free refrigerator, a magnetic filed of 3T at maximum has been achieved for the confinement of ECR plasma. It has successfully provided an intense beam of highly-charged ions, e.g., 9.6eμA of Xe^{30+}, 5.7eμA of Xe^{32+} and 0.9eμA of Xe^{36+}. The beam is applied to the study of cluster physics such as (1) fissions of a highly charged clusters produced by a collision between a highly-charged ion and a neutral cluster and (2) cluster formation in sputtering of bulk surface with a highly-charged ion.

Key words: electron cyclotron resonance ion source, highly-charged ion, cluster, fission, sputtering

1. INTRODUCTION

We are planning two series of experimental studies in cluster physics. The first is a study of fission phenomena in highly charged clusters. We are going to study more large-sized and highly-charged clusters than those studied in the conventional experiments. The second is a study of cluster formation in sputtering of bulk surface with a highly-charged ion (HCI). As a source of HCI beam for such experiments, we have developed a liquid He free super-conducting electron cyclotron resonance (ECR) ion source named SHIVA and successfully extracted intense beams of various heavy ions[1-3]. In this contribution, we introduce the planned experimental studies of cluster physics and the developed ECR ion sources SHIVA.

2. FISSION OF HIGHLY-CHARGED CLUSTER

In 1882, L. Rayleigh theoretically discussed about the stability of a charged liquid drop and predicted that a q-fold charged droplet would become unstable with respect to the quadruple deformations at the critical size at which its Coulomb energy E_C equals twice its surface energy E_S[4], i.e.,

$$E_C = 2E_S \quad . \qquad (1)$$

In the case of highly-charged clusters, its surface energy and Coulomb energy are written by

$$E_S = 4\pi\left(r_S n^{1/3}\right)^2 \sigma \quad ,$$

and

$$E_C = \frac{e^2 q^2}{2 r_S n^{1/3}} \quad , \quad (2)$$

where r_S , q and n is Wigner Seitz radius, charge state and size of clusters and σ is the bulk surface tension of the respective element. Therefore, the critical size is

$$n_{crit} = \frac{e^2 q^2}{16\pi r_s^{\ 2} \sigma} \quad . \quad (3)$$

Recently, F. Chandezon and coworkers observed fission phenomena for the sodium cluster with $q \leq +10$

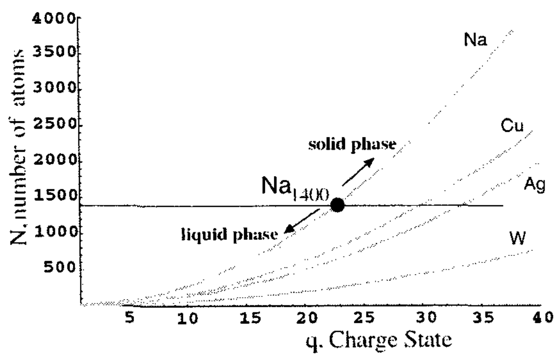

Fig. 1. The critical size n_{crit} as a function of the charge state of clusters for various materials.

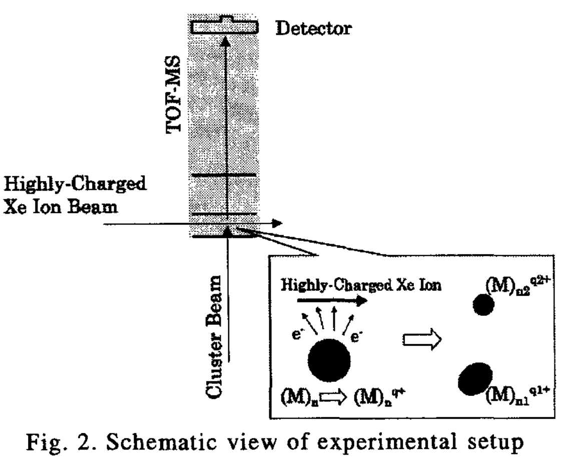

Fig. 2. Schematic view of experimental setup for cluster fission.

and $n \leq 500$[5]. We are currently planning a new project to observe fission phenomena for large-sized clusters such as $n \leq 5000$. Because the critical size of cluster fission is proportional to q^2 as shown in Equation 3, it is necessary to produce clusters in more highly-charged state ($q \leq +20$) for the observation fission phenomena in large-sized metal clusters. If we achieve such experiments successfully, we can observe a change of fission mechanism associated with a phase transition from a liquid to a solid in clusters (see Fig. 1) for the first time in the world.

For making the fission reaction, one of the most effective ways is a soft peripheral collision of highly-charged Xe ions[6]. Fig. 2 shows an experimental setup of cluster fission. A cluster beam is generated by a magnetron sputter-type cluster source[7], which can produce a cluster composed of a few thousand atoms. A highly-charged Xe ion is produced by the ECR ion source SHIVA. Thorough a soft peripheral collision with the highly-charged Xe ion, a multiply ionized cluster is generated. Masses of the fragments produced through the fission are measured by a time-of-flight mass spectrometry (TOF-MS) system.

3. CLUSTER FORMATION IN SPUTTERING OF BULK SURFACE WITH HIGHLY-CHARGED ION

We have measured the abundance spectra of clusters for various metals produced by the bombardment of 6keV neutral Xe atoms[8]. Applying a scaling plot for those spectra, we have found that all spectra coincide with each other. Guided by the observation of this remarkable regularity, a bond percolation model assuming a mechanical break-up of the sputtered surface has been examined. The model has successfully reproduced all the spectra resulting in an effective percolation rate p for each material. The percolation rates were strongly correlated with the melting temperatures of bulk materials, and the correlation among them was written by the equation

$$p = P_0 \exp\left(-\frac{D'}{k_B(e-1)T_m}\right) , \quad (4)$$

where P_0 is normalization constant, D' is an effective dissociation energy of bond, k_B is the Boltzmann constant, and T_m is a melting temperature of bulk material (see Fig. 3).

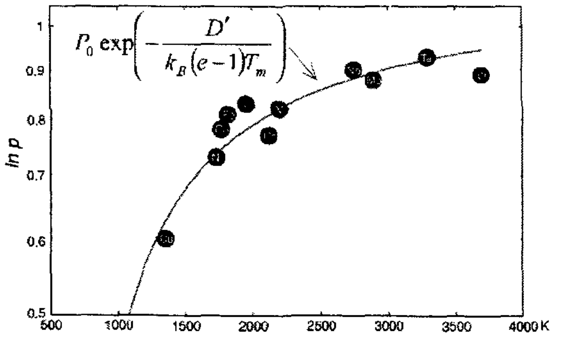

Fig. 3. Correlation between the melting temperature T_m and the concentration of broken bonds p for various metals; a model calculation (solid line) and experimental results (symbols)

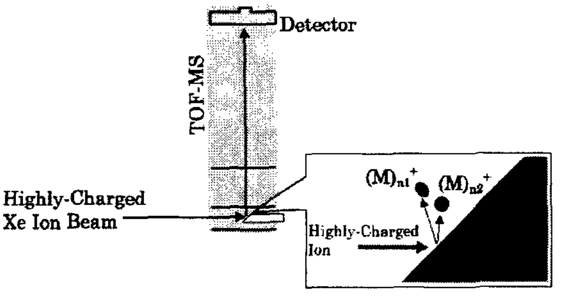

Fig. 4. Schematic view of experimental setup for cluster formation through collision of slow HCI with various metal surfaces.

So far, many studies for interactions of slow HCIs with solid surfaces have been performed. Hamza et al. have experimentally shown an $(UO_x)_n^+$ formation from UO_2 surface with incidence of HCIs and a power low decay of partial cluster yield[9]. It has been also shown that at the highest charge states of incident ions, the power law exponent approaches –2, which is a limit given by theories such as the shock wave model[10] and equilibrium model[11].

Unfortunately, no studies have ever tried to observe a cluster emission from metal surface with incidence of HCIs. We are now planning experiments for cluster formation through interaction between slow (up to a few keV/amu) HCI and variety of metal surfaces systematically. In the experiments, we will be able to observe new phenomena absent in case of neutral projectiles, e.g., a potential energy effect of HCIs and an effect of electrical and thermal properties of target material such as ionization potentials and melting points.

Fig. 4 shows a schematic view of experimental setup for planning experiments. The HCIs beam(1-10keV) produced by the ECR ion source SHIVA is injected to the solid metal surface. Thorough the interaction of HCIs beam with the solid metal surface, monomers, clusters and their ions are sputtered or ablated. The mass of positive ions will be extracted by the electronic field and measured by the TOF-MS system.

4. SUPERCONDUCTING ECR ION SOURCE (SHIVA)

4.1 Design of SHIVA

To produce an intense beam of highly charged heavy ions, we have constructed a liquid He free superconducting ECR ion source named SHIVA (Super conducting without liquid He electron cyclotron resonance Ion source for Various Atomic cluster physics experiments).

For structural details of the ion source, see the figures in Ref. [1][3]. Fig. 5 shows a cross-sectional view of SHIVA. The super-conducting solenoid coils are cooled down below 5K by using a Gifford McMahon type refrigerator, which keeps the super-conducting without liquid He. These solenoid coils are used to supply the mirror magnetic field to confine the plasma in the axial direction. The hexapole magnet, which consists of 24 segments of permanent magnets, is used to confine the

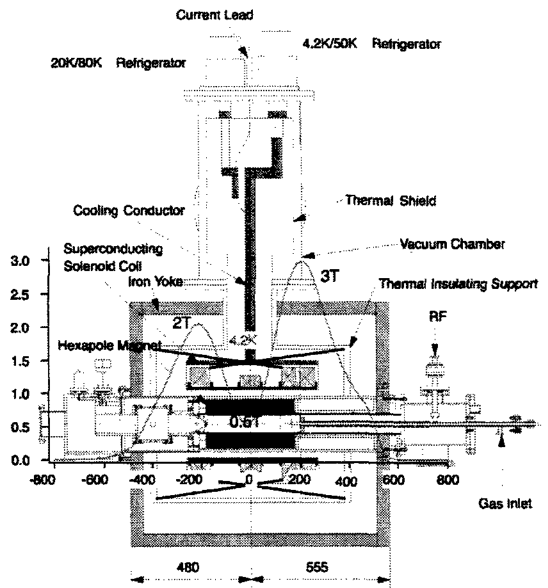

Fig. 5. Cross sectional view of liquid He free SC-ECRIS SHIVA

plasma in the radial direction. The maximum magnetic field strength of mirror magnetic field is 3 and 2T at microwave injection side (B_{inj}) and at the beam extraction side (B_{ext}), respectively. The minimum magnetic field strength of mirror magnetic field (B_{center}) is about 0.3T. The inner and outer diameters of the hexapole magnet are 80 and 174mm, respectively. The maximum magnetic field strength at the inner surface of the plasma chamber is 1T. The inner diameter of the plasma chamber is 72mm. To protect the hexapole magnet from demagnetization by high temperature, the plasma chamber wall has a double wall structure to allow to flow

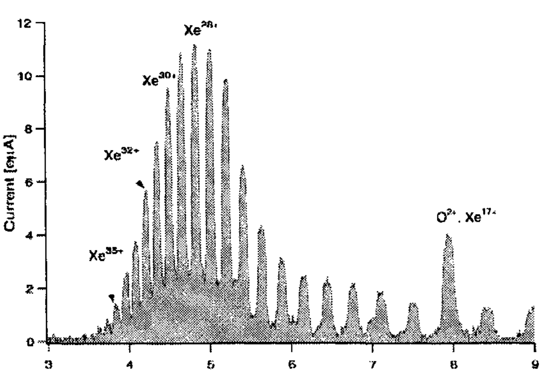

Fig. 6. Typical charge state distribution of Xe ions obtained from SHIVA

Gas	$^{136}Xe(90\%enriched)+O_2$
B_{inj}	1.85T
B_{center}	0.4T
B_{ext}	1.24T
Extraction voltage	15kV
Microwave frequency	14.5GHz
Injected microwave power	760W
Biased electrode voltage	-225V

Table I. Main parameters of the ion source for producing Xe^{32+} ions

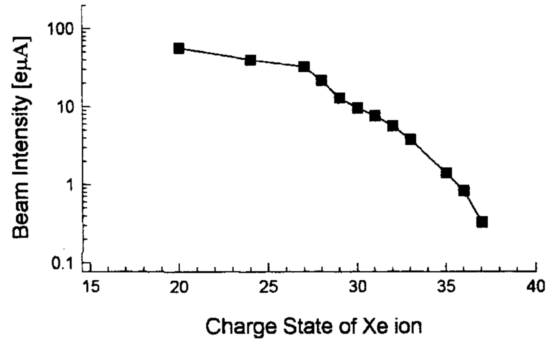

Fig. 7. Best result for producing Xe ions in SHIVA.

cooling water. The injected microwave frequency is 14.5GHz. The maximum power is 2kW.

A thin aluminum cylinder (1mm thickness) is inserted into the plasma chamber of SHIVA. The aluminum cylinder can help to increase the plasma density due to secondary electrons emitted from its surface by electron impact[12]. In addition, a negatively biased electrode (30mm diameter and 5mm thickness) placed in the plasma chamber is utilized for increasing the beam intensity. This insertion of biased electrode is often used in many ECR ion sources[13] and its effectiveness has also been confirmed in case of SHIVA[3,14].

4.2 Production of highly charged Xe ion and its performance

For production of Xe ions, we used enriched ^{136}Xe gas (enrich of 85%). It was reported that oxygen gas was effective to obtain more intense beam (mixing gas method) generally in case of producing an ion of the atom heavier than neon[15]. Therefore, we used an oxygen gas as a mixing gas.

Fig. 6 shows a typical charge distribution of highly charged Xe ions when the ion source was tuned to produce Xe^{32+} ions[3]. The main parameters of the ion source are listed in Table I. Under these conditions, we obtained 9.6eμA of Xe^{30+}, 5.7eμA of Xe^{32+} and 0.9eμA of Xe^{36+} with 760W of RF power. The best result obtained so far is shown in Fig. 7. As expected, intense beam of highly charged Xe ions has been successfully produced from SHIVA.

5. CONCLUSION

We have succeeded to produce an intense beam of highly charged Xe ions from the super-conducting ECR ion source SHIVA. Due to this success, it has been possible for us to perform new series of cluster physics experiments, such as (1) fissions of a highly charged clusters produced by a collision between a highly-charged ion and a neutral cluster and (2) cluster formation in sputtering of bulk surface with a highly-charged ion.

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