IL NUOVO CIMENTO **39 C** (2016) 359
DOI 10.1393/ncc/i2016-16359-9

COLLOQUIA: SEA2016

Nuclear spectroscopy of r-process nuclei around $N = 126$ using KISS

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received 28 November 2016

Summary. — The beta-decay properties and atomic mass of nuclei with neutron magic number of $N = 126$ are considered critical for understanding the production of heavy elements such as gold and platinum at astrophysical sites. We will produce and measure the half-lives and masses of the nuclei with $Z = 74$–77 around $N = 126$ by using the multinucleon transfer (MNT) reaction of ^{136}Xe/^{238}U beams and ^{198}Pt target system. For this purpose, we have constructed the KEK Isotope Separation System (KISS) at RIKEN RIBF facility. KISS consists of an argon gas cell based laser ion source (atomic number selection) and an isotope separation on-line (ISOL) (mass number selection), to produce pure low-energy beams of neutron-rich isotopes around $N = 126$. We performed the on-line tests to study the basic properties of the KISS and, successfully extracted laser-ionized nuclei around $N = 126$.

1. – Introduction

Most of the heavy elements are considered to be produced in a rapid neutron capture process (r-process). The detailed process of the production and the astrophysical site of r-process are not fully understood. The β-decay properties and masses of nuclei with $N = 126$ are considered to be critical for understanding astrophysical sites for the production of the heavy elements [1]. We plan to measure the half-lives and masses of nuclei with around $N = 126$, especially ^{200}W, ^{201}Re, ^{202}Os and ^{203}Ir ($Z = 74$–77, $N = 126$) as a first step. These nuclei could be produced by multinucleon transfer (MNT) reaction [2]

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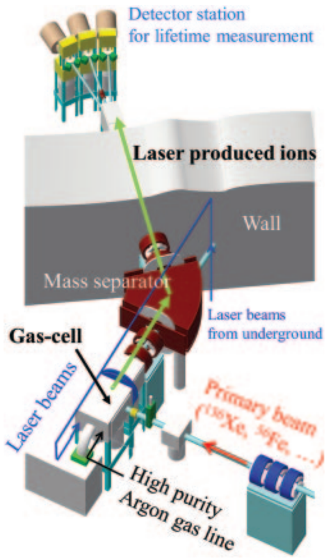

Fig. 1. – Schematic view of KISS.

between an energetic stable isotope beam ^{136}Xe around 10 MeV/nucleon and a ^{198}Pt target system [3, 4].

For the experiments, we have constructed the KEK Isotope Separation System (KISS) at RIKEN RIBF facility [5]. KISS consists of an argon gas cell combined with laser resonance ionization technique (atomic number Z selection) and of an isotope separation on-line (ISOL) (mass number A selection) [6-11], for the production of pure low-energy beams of neutron-rich isotopes around $N = 126$ and the study of their β-decay properties.

We performed the on-line experiments to study the basic properties of the KISS, and to measure the extraction efficiency from the gas cell and the extracted beam purity, using ^{136}Xe beam and ^{198}Pt target system.

In the report, we introduce the overview of KISS system in sect. **2**, the results of the KISS experiments in sect. **3**, future plans in sect. **4**, and the summary in sect. **5**.

2. – KISS

Figure 1 shows a schematic layout of KISS constructed in the RIKEN experimental rooms. It consists of a gas-cell system, a laser system, a mass-separator system, and a detector system for β-decay spectroscopy. The details of KISS can be found in ref. [5].

The gas-cell system employs differential pumping to reduce the pressure in the vacuum chamber from 50 kPa to several 10^{-4} Pa in order to enable extraction of isotopes as an ion-beam with sufficiently low emittance and high efficiency as shown in fig. 2. Each room was connected with a sextupole ion-guide (SPIG) [12]. The design of the gas cell was optimized to accumulate the reaction products with a high stopping efficiency, and to transport them by a fast and efficient laminar flow [5].

The laser system consists of two frequency-tunable dye lasers pumped by two excimer (XeCl, 308 nm) lasers, and is installed in a separate room below the KISS gas cell system. A search for efficient ionization schemes of heavy elements [13, 14] at off-line tests is in

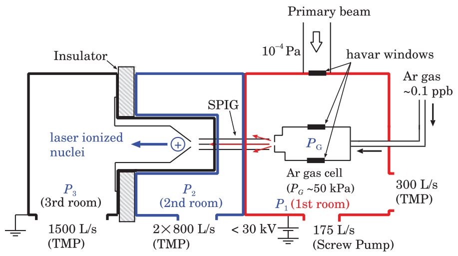

Fig. 2. – Schematic view of the gas-cell system. The boundaries of the first, second and third rooms for differential pumping are indicated by the thick red, blue and black lines, respectively.

progress. We already searched for those of Ta, Re, Os, Ir and Pt (Z = 73, 75, 76, 77 and 78).

The configuration of mass-separator system is a QQDQQ. Here, Q and D denote quadrupole and dipole magnets, respectively. The measured mass resolving power was 900, which is enough high for our project.

The detector station has a tape transport device for decay measurements using a pulsed beam from the separator. Three sets of two layered plastic scintillator telescopes for β-rays followed by germanium detectors for γ-rays cover the implantation point. The detection efficiency and the background rate were 46% for $Q_\beta = 2$ MeV and 0.1 cps, respectively.

3. – Experimental results

The primary ^{136}Xe beam with the energy of 10.75 MeV/A and the intensity up to 20 pnA was provided by RIKEN ring cyclotron. The thermalized and neutralized reaction products such as ^{198,199}Pt atoms were selectively re-ionized by laser resonance ionization technique in the gas cell, and the ions were extracted and detected after mass separation by measuring ion rate using a Channeltron detector for stable nuclei and using β-ray telescopes for unstable nuclei.

We measured mass distributions with and without ionization-laser irradiation as shown in fig. 3 in order to investigate how much laser-produced $^{198}Pt^+$ ions form impurity molecular ions with H_2O, Ar_2 and hydrocarbons under the argon plasma induced by the primary beam irradiation. Figure 3 shows the mass spectrum of laser ionized ^{198}Pt atoms. Blue and red lines indicate the mass distributions measured with and without the laser irradiation. The prominent peak of $^{198}Pt^+$ was observed successfully, and there were no molecular ion peaks because of the dissociation of the molecular ions by using three stage SPIG system [15].

Plasma in the gas cell induced by the primary beam is reported to reduce the ionization efficiency and selectivity [8], therefore, the extraction efficiency from the gas cell depends on the primary beam intensity slightly. The extraction efficiency of $^{198}Pt^+$ ions were measured as a function of primary beam intensity. The extraction efficiency was defined as S/I. Here, S presents the numbers of the detected $^{198}Pt^+$ ions. I denotes the ^{198}Pt atoms emitted from the target by elastic scattering (17 barn). The measured efficiencies for $^{198}Pt^+$ ions were about 0.15%. The efficiency was independent of the primary beam intensity, owing to the specially designed structure of the gas cell [5]. The measured beam purity was $> 99.5\%$ for $^{198}Pt^+$, which are enough high for the β-decay lifetime measurements.

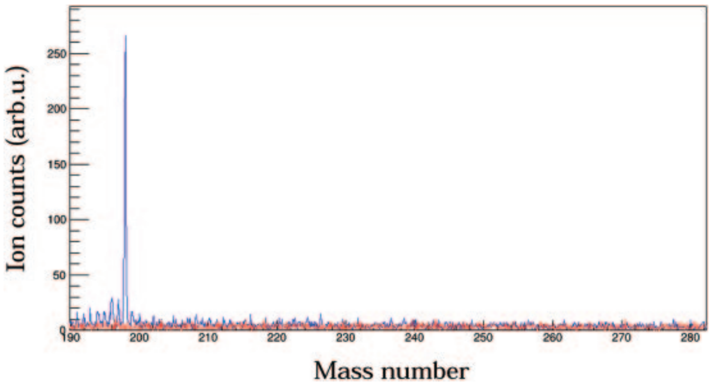

Fig. 3. – Mass spectra measured with and without the laser irradiation to ^{198}Pt atoms.

We extracted laser-ionized $^{199}\mathrm{Pt}^+$ ($t_{1/2} = 30.8(2)\,\mathrm{min}$) and $^{196}\mathrm{Ir}^+$ ($t_{1/2} = 52(1)\,\mathrm{s}$), and measured the lifetimes to be 31.3(15) min and 67(13) s, respectively, which were in good agreement with the previous reported values [16]. Thus, it is feasible to measure the lifetimes of unstable nuclei around $N = 126$ with the present extraction efficiency and purity.

It is possible to study the hyperfine structure (HFS) through the investigation of the excitation transition in the laser resonance ionization process. The change of the charge radius and electromagnetic moments can be measured from the HFS study, and the nuclear wave-function and deformation can be investigated from the measured values. We performed the in-gas cell laser ionization spectroscopy (IGLIS) of ^{199}Pt in order to determine the change of charge radius and magnetic dipole moment, and the analysis is in progress. The systematic study of HFS of nuclei in this region will be performed at KISS.

4. – Future plan

In order to increase the production yields of the nuclei around $N = 126$ and perform the nuclear spectroscopy such as lifetime, mass measurement and β-γ spectroscopy extensively, we have developed a doughnut-shaped gas-cell for increasing available primary beam intensity, gas counter for β-rays detection, Ge arrays for γ-rays detection, and MR-TOF system for mass measurement, respectively.

KISS was open for external user program from RIKEN NP-PAC in 2015. There were 21 LoI in these two years. In order to perform the proposed experiments, it is necessary to promote the above-mentioned R&D works as soon as possible. We expect that the user programs such as β-γ spectroscopy and mass measurements can be performed from 2017.

5. – Conclusions

We constructed the KEK Isotope Separation System (KISS) at RIKEN to study the β-decay properties and masses of neutron-rich isotopes with neutron numbers around $N = 126$ for applications in astrophysics. On-line performance test of the gas cell system and the KISS was performed using ^{136}Xe beam accelerated by RIKEN ring cyclotron.

We can successfully extract laser ionized atoms of $^{198,199}Pt^{+}$ and $^{196}Ir^{+}$, and measure the extraction efficiency of about 0.15%, which was independent of the primary beam intensity. It is feasible to perform nuclear spectroscopy and in-gas-cell laser ionization spectroscopy at KISS. To extend nuclear spectroscopy in this region toward more neutron-rich nuclei, we have developed the doughnut-shaped gas-cell, new gas counter for β-rays detection, Ge arrays, and MR-TOF system.

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This experiment was performed at RI Beam Factory operated by RIKEN Nishina Center and CNS, the University of Tokyo. The authors acknowledge the staff of the accelerator for their support.

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