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Beta-decay spectroscopy of r-process nuclei around $N = 126$

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Abstract. KEK Isotope Separation System (KISS) has been developed at RIKEN to study the β-decay properties of neutron-rich isotopes with neutron numbers around $N = 126$ to understand the astrophysical site of r-process. These nuclei will be produced by multi-nucleon transfer reactions in neutron-rich heavy ion collisions between ^{136}Xe beam and ^{198}Pt target. The KISS consists of an argon gas cell combined with a laser resonance ionization technique for atomic number selection, of an ISOL mass-separation system and of a detector system for the β-decay spectroscopy of nuclei around $N = 126$. The argon gas cell of KISS is a key component for thermalizing (stopping and neutralizing) and accumulating the unstable nuclei, and selectively ionizing them by using laser. We have performed off- and on-line experiments to study the basic properties of the gas cell as well as KISS. We successfully extracted the laser-ionized stable ^{198}Pt atoms from the KISS at the commissioning on-line experiments. We furthermore extracted laser-ionized unstable ^{199}Pt atoms and confirmed that the measured half-life was in good agreement with the reported value. Now KISS is ready for lifetime measurements of Pt, Ir, and Os isotopes around $N = 126$.

1 Introduction

The heavier elements than iron are considered to be produced in a rapid neutron capture process (r-process), which goes through very neutron-rich nuclei. The β-decay properties of nuclei with $N = 126$ are considered to be critical for understanding astrophysical sites for the production of the heavy elements such as gold and platinum [1]. In order to reveal the astrophysical site, we plan to measure the half-lives of nuclei with around N =126, especially ^{200}W, ^{201}Re, ^{202}Os and ^{203}Ir ($Z = 74-77$, $N = 126$) as the first step. These nuclei will be produced by multi-nucleon transfer (MNT) reaction [2] between an energetic stable isotope beam ^{136}Xe around 10 MeV/nucleon and a ^{198}Pt target [3, 4].

For the measurements, 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 selection) and of an isotope separation on-line (ISOL) (mass number selection)

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[6–11], to produce pure low-energy beams of neutron-rich isotopes around $N = 126$ and to study their β-decay properties.

We performed the off- and on-line tests to study the basic properties of the KISS, and then conducted the on-line experiments to study the thermalization and neutralization processes of reaction products in the gas cell, and to measure the extraction efficiency from the gas cell and the extracted beam purity.

In the report, we introduce the overview of KISS system in Sect. 2, the results of the KISS commissioning on-line experiments in Sect. 3, development of ion extraction system for increasing the extraction efficiency in Sect. 4, and the summary in Sect. 5.

2 Over view of KISS

Figure 1 shows the comparison between the measured and calculated production cross sections of isotones with $N = 126$. The MNT reaction system between ^{136}Xe beam and ^{198}Pt target is the best for the productions of the isotones with $Z < 79$. Considering the production yields and the efficiency for the isotope identifications, the MNT reaction system with KISS would be more than three orders of magnitude efficient for the β-decay spectroscopy in this region than the projectile fragmentation reaction system.

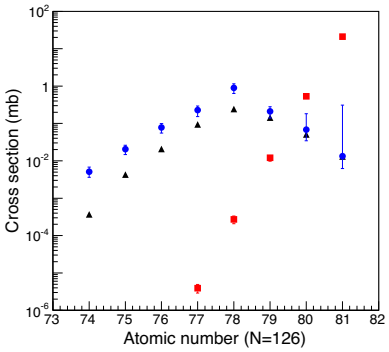

Figure 1. Comparison between the measured cross sections by a projectile fragmentation reaction of ^{208}Pb+^{9}Be at GSI [12] (red square) and by the MNT reaction of ^{136}Xe+^{198}Pt at GANIL [4] (blue circle), and the GRAZING calculation [13, 14] for the MNT reaction (black triangle).

Figure 2 shows a schematic layout of KISS. It consists of a gas-cell system, a laser system, a mass-separator system, and a detector system for β-decay spectroscopy. Overview of KISS was introduced in this report, and the details of KISS can be found in Ref. [5].

As shown in Fig. 3, 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. Each room was connected with a sextupole ion-guide (SPIG) [15] which is used to transport ions from high pressure region to low pressure region by cooling the beam emittance. 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]. Detailed geometry and basic performances were reported in Ref. [5]. The extraction efficiency was

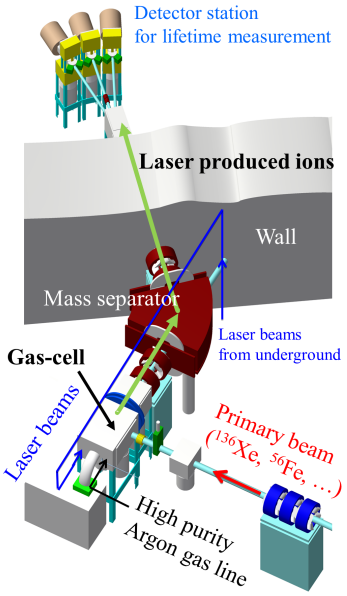

Figure 2. Schematic view of KISS.

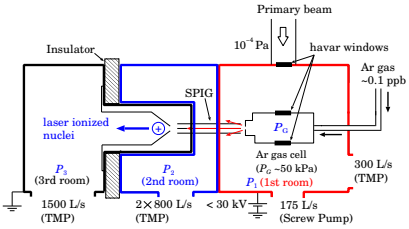

Figure 3. Schematic view of the gas-cell system. The boundaries of the first, second and third rooms for differential pumping are indicated by the thick red, blue and black lines, respectively.

estimated to be about 5% for ^{200}W ($Z = 74$, $N = 126$) nuclei with a half-life time of 801 ms predicted by the KUTY mode [16]. ^{200}W nuclei is located most far from the stability line in the project.

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 [17, 18] at off-line tests is in progress.

The mass-separator system has a QQDQQ configuration, in which 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 1.1 cps, respectively. In order to measure the lifetime of nuclei produced with low reaction rate, a background rate of β-ray telescopes should be lower than the extracted beam rate. In order to reduce the background rate down to 0.1 cps, geometry-modified new β-ray telescopes with the same detection efficiency as the previous ones were developed and installed in the KISS detector system.

3 Result of on-line tests

The absolute extraction efficiency and selectivity of KISS can be evaluated only at an on-line test by measuring the intensities of atoms implanted in and extracted from the gas cell. In addition, plasma in the gas cell induced by the primary beam is reported to reduce the ionization efficiency and selectivity [8]. In order to measure the absolute extraction efficiency and selectivity under the plasma,

we performed an on-line test using the ^{136}Xe beam and ^{198}Pt target, and measure the efficiency and selectivity as a function of the primary beam intensity. 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.

We measured mass distributions with and without ionization-laser irradiation as shown in Fig. 4 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 4 shows the mass spectrum of laser ionized ^{198}Pt atoms. Red and blue lines indicate the mass distributions measured with and without the laser irradiation. The ^{198}Pt$^+$ ions were found to form the impurity molecular ions of $^{198}PtH_2^+$, $^{198}PtH_2O^+$ and $^{198}PtAr_2^+$ with the relative intensities of 1, 1, and 6 normalized to the intensity of ^{198}Pt$^+$ ions, respectively. There were the efficiency reduction of a factor of about 1.5 due to the molecular formation. By dissociate molecular ions at SPIG [9], it is possible to recover the extraction efficiency as single ions of ^{198}Pt$^+$.

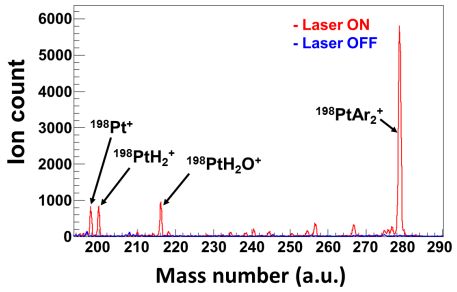

Figure 4. Mass spectra measured with and without the laser irradiation to ^{198}Pt atoms.

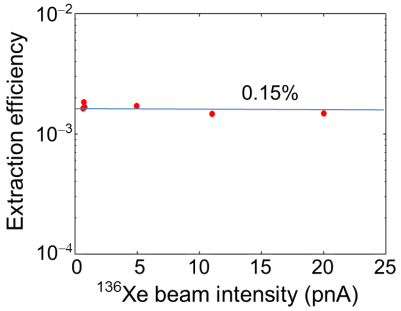

Figure 5. Measured extraction efficiency as a function of primary beam in the case of $^{198}PtAr_2^+$. The solid line is guide for the eyes.

The extraction efficiencies of $^{198}PtAr_2^+$ (mass number $A = 278$) ions, which were most intense peak in Fig. 4, were measured as a function of primary beam intensity as shown in Fig. 5. The extraction efficiency was defined as S/I. Here, S presents the numbers of the detected $^{198}PtAr_2^+$ ions. I denotes the ^{198}Pt atoms emitted from the target by elastic scattering (17 barn). The measured efficiencies for $^{198}PtAr_2^+$ ions were about 0.15%. The efficiencies were independent of the primary beam intensity, as shown in Fig. 5, owing to the specially designed structure of the gas cell [5]. The measured beam purity was > 99.5% for $^{198}PtAr_2^+$, which are enough high for the β-decay lifetime measurements.

We extracted laser-ionized ^{199}Pt$^+$ ($t_{1/2}$ = 30.8(2) min) that mainly formed $^{199}PtAr_2^+$ molecular ions like ^{198}Pt$^+$ did. Figure 6 shows the measured lifetime extracting $^{199}PtAr_2^+$ molecular ions. The measured lifetime $t_{1/2}$ = 33(4) min was in good agreement with the reported value [19]. Thus, the molecular formation does not affect the lifetime measurement of unstable nuclei.

4 Improvement of SPIG for higher extraction efficiency

To increase the extraction efficiency, we have developed a new extraction system, which consists of two stage SPIG system having different geometries for SPIG1 (8 mm in diameter and 83 mm in

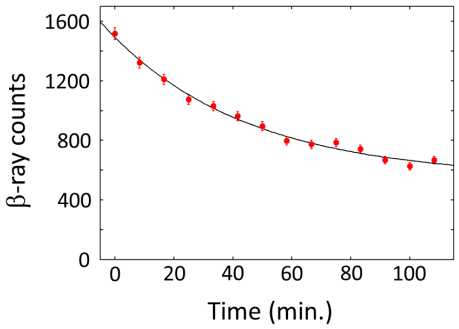

Figure 6. Lifetime measurement of unstable nucleus ^{199}Pt.

length) and SPIG2 (3 mm in diameter and 118 mm in length) as shown inf Fig. 7-(a). The geometry of the SPIG2 is similar to the former single SPIG (3 mm in diameter and 200 mm in length) used at the present on-line measurements. By increasing the inner diameter of the first SPIG, we intended to capture the laser ionized atoms emitted with large angles from the gas-cell exit-orifice of 1 mm in diameter. We also intended to dissociate the molecular ions by applying the DC voltage between the first and the second SPIGs where the gas pressure is much lower than that at the gas cell exit. A relatively low DC voltage compared to the Ref. [9] enables to dissociate the molecular ions at the connection point of two SPIGs. Figures 7-(a) and (b) show the schematic view of modified SPIG configuration and the measured mass distributions using iridium filament placed in the gas cell with the pressure of 45 kPa, respectively. The red and blue lines indicate the measured mass distributions with $V_{DC} = 0$ V and -30 V for the second SPIG, respectively. We can clearly observe the dissociation of the molecular ions of laser-produced iridium. More than 90% of extracted laser-produced iridium was recovered as singly charged iridium ions. Considering the molecular-ion formation-probability in the case of platinum as shown in Fig. 4, the extraction efficiency would be recovered with a factor of about 1.5. The performance of the large acceptance of the first SPIG will be studied at an on-line experiment by measuring the extraction efficiency.

5 Summary

We constructed the KEK Isotope Separation System (KISS) at RIKEN to study the β-decay properties 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 measure the extraction efficiency of about 0.15%, which was independent of the primary beam intensity. The lifetime of radioactive ^{199}Pt nucleus, which was an unstable-nucleus extracted from KISS for the first time, was successfully measured. Considering the production rates of nuclei around $N = 126$ calculated by the GRAZING code, we will be able to measure lifetimes of 7 different isotopes. Hereby, an efficiency of 0.1%, beam purity of > 99.7%, and a primary beam intensity of 20 pnA were assumed. To extend this study to more neutron-rich nuclei, we have some development plans. We will develop a new sextupole ion guide with a large angular acceptance for increasing the extraction efficiency, and a new low-background β-ray telescopes with the counting rate of a few cph.

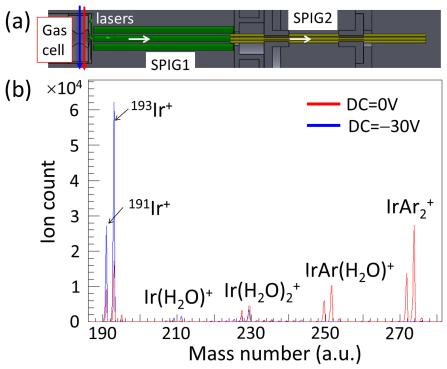

Figure 7. (a) Schematic view of modified SPIG configuration and (b) measured mass distribution with and without dissociation DC voltage.

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