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# Nuclear spectroscopy of r-process nuclei using KEK Isotope Separation System

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**Abstract.** We developed KEK Isotope Separation System (KISS) for the nuclear spectroscopy of the nuclei in the vicinity of  $N = 126$ . The spectroscopy is important to identify the explosive astrophysical environment for the formation of the third peak in the observed solar  $r$ -abundance pattern. We report the experimental results of in-gas-cell laser ionization spectroscopy and  $\beta$ -decay spectroscopy for the nuclei in the vicinity of  $^{198}\text{Pt}$ .

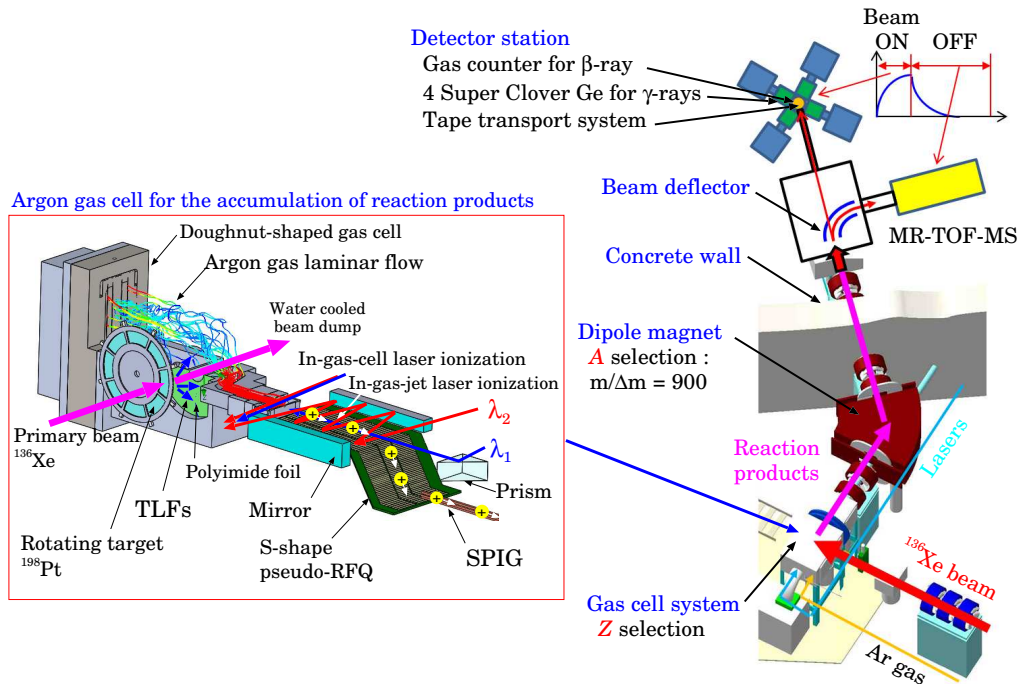
## 1. Introduction

The study of the  $\beta$ -decay half-lives and nuclear masses of waiting-point nuclei with  $N = 126$  is crucial to understand the explosive astrophysical environment for the formation of the third peak in the observed solar abundance pattern, which is produced by a rapid neutron capture process (r-process) [1]. For the nuclear spectroscopy in this heavy region, we have developed KEK Isotope Separation System (KISS) [2, 3, 4]. KISS is an argon-gas-cell-based laser ion source combined with an on-line isotope separator [5, 6, 7, 8, 9, 10]. The nuclei around  $N = 126$  are produced by multi-nucleon transfer reactions (MNT) [11] of  $^{136}\text{Xe}$  beam and  $^{198}\text{Pt}$  target [12]. We developed and installed high-efficiency detector system, which consists of new gas counter (MSPGC) [13] and Super Clover Ge detectors (SCGe) for  $\beta$ -particle and  $\gamma$ -ray detection, respectively. These enabled us to perform  $\beta$ -delayed  $\gamma$ -ray spectroscopy of  $^{195,196,197,198}\text{Os}$  for the half-life measurements and study of  $\beta$ -decay schemes [14], and in-gas-cell laser ionization spectroscopy of  $^{199g,199m}\text{Pt}$  [15] and  $^{196,197,198}\text{Ir}$  [16] for determining the magnetic moments and the change of the charge-radii (deformation parameters) successfully. Here, we report the present status and experimental results at KISS, and future plan of KISS activities.

## 2. KISS

Figure 1 shows a schematic layout of KISS installed at the RIBF facility in RIKEN. It consists of a gas-cell system shown in the red box in Fig. 1, a laser system, a mass-separator system and a detector station for  $\beta$ -decay spectroscopy.





**Figure 1.** Schematic view of KISS, and the KISS gas cell shown in the red box.

### 2.1. KISS gas cell system

Primary beam of  $^{136}\text{Xe}^{20+}$  with an energy of 10.75 MeV/nucleon and an intensity of 50 pA irradiated an enriched  $^{198}\text{Pt}$  (purity 91.63% and thickness 12.5 mg/cm<sup>2</sup>) target for the MNT reactions [12]. Then, the primary beam passed through a doughnut-shaped gas cell [4] (see Fig. 1) without entering the gas cell. Finally, the beam was stopped at a water cooled beam dump, which was placed far from the KISS gas cell.

The doughnut-shaped gas cell (see Fig. 1) was developed to increase production yields by suppressing the plasma effect induced by the primary beam and by increasing the primary beam intensity for the production. Using the new gas cell, we can successfully obtain one order of magnitude higher production yields than that obtained by using the old-type gas cell. Only the target-like fragments (TLFs) can be implanted into the gas cell with high efficiency, owing to the characteristic large emission angles of TLFs [2, 3]. Then, the TLFs neutralized in the argon gas were transported toward the exit by a optimized argon gas laminar flow [4]. We employed two kinds of two-color two-step laser resonance ionization techniques for selecting the atomic number  $Z$ . One is in-gas-cell laser ionization technique for  $\beta$ - $\gamma$  spectroscopy and hyperfine structure measurements, and the other is in-gas-jet laser ionization technique [17] for precise hyperfine structure measurements and mass measurements of ground and isomeric states.

The laser-produced singly charged ( $q = 1$ ) ions were transported through a S-shaped pseudo-RFQ (S-RFQ) and sextupole ion guide (SPIG) [18], and were accelerated with an energy of 20 kV. Their mass-to-charge ratio ( $A/q$ ) was selected by a dipole magnet with  $m/\Delta m = 900$ . Finally, one kind of isotope was transported to the detector station placed at the neighboring experimental hall for the decay measurements. Recently, we installed a new branch for mass measurements by using a Multi-Reflection Time-of-Flight Mass Spectrograph (MRTOF-MS).

## 2.2. Detector station

The detector station has a tape transport device to avoid radioactivity from the decay chains of the separated nuclides under the pulsed beam operation of KISS. An aluminized Mylar tape was moved at the end of each measurement cycle to remove unwanted radioactivity from the detection area.

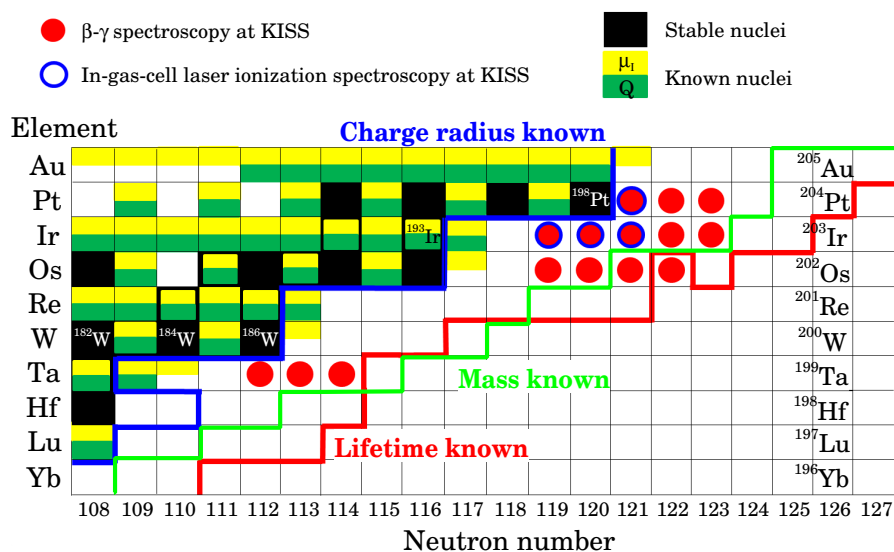
We developed high-efficiency and low-background gas counter, named multi-segmented proportional gas counter (MSPGC) [13] which consists of 32 counters (16 pairs of telescope), in order to perform  $\beta$ - $\gamma$  and laser spectroscopic studies by detecting  $\beta$ -particles emitted from rare reaction products. The absolute detection efficiency of the 16 telescope pairs in the MSPGC is as high as about 50% (multiplicity  $M = 2$ : one telescope fired event) for  $\beta$ -particles with  $Q_\beta = 1$  MeV because of a lower energy threshold of around 100 keV than that of typical plastic-scintillator  $\beta$  telescopes. The background rate was successfully reduced to be 0.1 cps from 1 cps.

Four Super Clover Ge detectors were installed to detect  $\beta$ -delayed  $\gamma$ -rays and  $\gamma$ -rays of de-excitation transitions from isomeric states. By using  $\gamma$ -rays from  $^{152}\text{Eu}$  and  $^{133}\text{Ba}$ , the absolute detection efficiency for  $\gamma$ -rays with an energy of 400 keV was measured as high as 14% owing to the close setup geometry of approximately 50 mm from the implantation position on the tape.

## 3. Experimental results

The present status of  $\beta$ - $\gamma$  (red closed circle) and in-gas-cell laser (blue open circle) spectroscopy in the vicinity of  $N = 126$  at KISS are shown in Fig 2. The blue, green, and red lines indicate the borders for charge-radius, mass, and lifetime known regions, respectively. Color codes indicate the stable nuclei, and nuclei whose magnetic dipole moment ( $\mu_I$ ) and electric quadrupole moment ( $Q$ ) were measured. By using enriched  $^{198}\text{Pt}$  and natural tungsten targets, we extracted 15 neutron-rich nuclei from the KISS gas cell until now, and performed  $\beta$ - $\gamma$  spectroscopy. We can access the neutron-rich nuclei of refractory elements by selecting appropriate production targets at KISS. We plan to perform the laser spectroscopy for these nuclei as well as the  $\beta$ - $\gamma$  spectroscopy and mass measurements intensively and systematically.

In the following section, we introduced the  $\beta$ - $\gamma$  spectroscopy of  $^{198}\text{Os}$  and the measurements of HFS spectra of  $^{199g,199m}\text{Pt}$ .



**Figure 2.** Present status of  $\beta$ - $\gamma$  and laser ionization spectroscopy performed at KISS.

### 3.1. $\beta$ - $\gamma$ spectroscopy of osmium isotopes

We extracted  $^{196g}\text{Os}$  ( $T_{1/2} = 34.9 \pm 0.2$  min [19]) by using newly established laser ionization scheme of osmium isotopes [20] to confirm the firm extraction of osmium isotopes from the KISS gas cell, and clearly identified  $^{196g}\text{Os}$  from the measured half-life  $T_{1/2} = 35.3 \pm 1.4$  min and  $\beta$ -delayed  $\gamma$ -ray spectrum.

Then, we extracted  $^{197,198}\text{Os}$  and their daughter nuclei  $^{197,198}\text{Ir}$  in series, as laser-produced ions, and performed their  $\beta$ - $\gamma$  spectroscopy. The details were reported in Ref. [14]. For the first time, the  $\beta$ -decay half-life of  $^{198g}\text{Os}$  was measured to be 125(28) s, and the half-life of  $^{197g}\text{Os}$  was revised to 91(8) s.

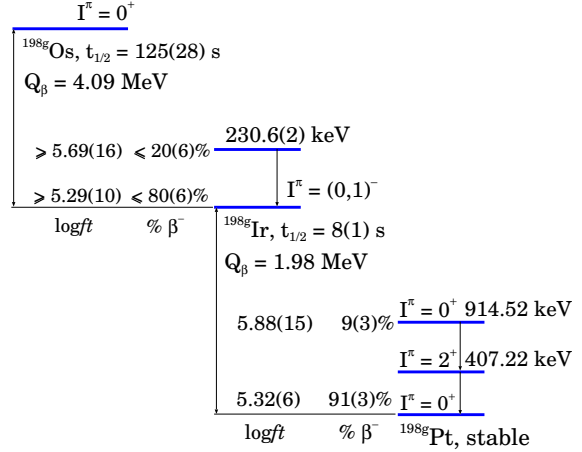
The  $\beta$ -decay schemes of  $^{198g}\text{Os}$  and  $^{198g}\text{Ir}$  were partially established from this spectroscopic studies as shown in Fig. 3, for the first time. The  $\gamma$ -ray intensity per  $\beta$ -decay of  $^{198g}\text{Os}$  was determined to be 20(6)% for the 230.6-keV transition. The  $\beta$ -decay branching ratios to  $^{198g}\text{Ir}$  and the excited states of  $^{198}\text{Ir}$  were tentatively evaluated to be  $\leq 80(6)\%$  and  $\leq 20(6)\%$  with  $\log(ft) \geq 5.29(10)$  and  $\log(ft) \geq 5.69(16)$ , respectively. The  $I^\pi$  value of  $0^-$  or  $1^-$  for  $^{198g}\text{Ir}$  was suggested from the analogy of  $^{196g}\text{Os}$   $\beta$ -decay chains [21] reported as FF transitions with small  $\log(ft) \sim 5.3$ . As the result, the first-forbidden transitions of  $\nu(3p_{3/2})$  or  $\nu(2f_{5/2}) \rightarrow \pi(2d_{3/2})$  are suggested to be dominant.

We performed precise  $\beta$ - $\gamma$  spectroscopy of  $^{195}\text{Os}$ , and establish its  $\beta$ -decay scheme for the first time. New long-lived isomeric state on  $^{195}\text{Os}$  was found in the measurement. The details were reported in Ref. [22].

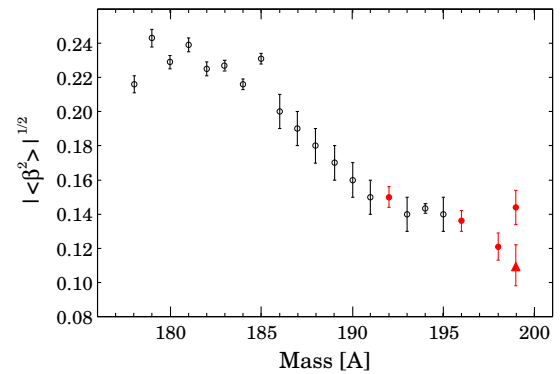
### 3.2. In-gas-cell laser ionization spectroscopy

Nuclear spin and electromagnetic moments are important values to discuss nuclear structures. These values can be determined through the investigation of hyperfine splitting [15, 23, 24] by an in-gas-cell laser spectroscopy technique. Because the broad HFS spectra measured by in-gas-cell laser ionization technique is mainly governed by the magnetic dipole moment. Therefore, we can determine the  $\mu_I$  value within 10% uncertainty [15, 23, 24], and measure the isotope shift to evaluate the nuclear deformation parameter based on droplet model [25].

The measurements of HFS spectra of  $^{199g,199m}\text{Pt}$  were performed by the in-gas cell laser ionization technique [15], and Table 1 shows the present results. From the measured isotopes shifts, the change of charge radii  $\delta\langle r^2 \rangle^{A,194}$  and nuclear deformation parameters  $|\langle \beta^2 \rangle|^{1/2}$  for  $^{199g,199m}\text{Pt}$  were deduced based on the droplet model as shown in Fig. 4. The  $|\langle \beta^2 \rangle|^{1/2}$  for  $^{199g}\text{Pt}$  and  $^{199m}\text{Pt}$  were



**Figure 3.**  $\beta$ -decay scheme of  $^{198}\text{Os}$  [14].



**Figure 4.** Systematics of nuclear deformation parameters  $|\langle \beta^2 \rangle|^{1/2}$  for platinum isotopes. Present values are indicated by red circles ( $^{192g,196g,198g,199g}\text{Pt}$ ) and triangle ( $^{199m}\text{Pt}$ ).

evaluated to be 0.144(10) and 0.110(12). From the systematic trends of the deformation parameters for  $^{193g-199g}\text{Pt}$  and isomeric state with  $I^\pi = 13/2^+$ ,  $^{199g}\text{Pt}$  and  $^{199m}\text{Pt}$  were, respectively, oblately and prolately deformed. The details of the discussion were reported in Ref. [15].

**Table 1.** Results of the in-gas-cell laser ionization spectroscopy of  $^{199g,199m}\text{Pt}$  [15].

Nuclide	$I^\pi$	$\mu_I$ ( $\mu_N$ )	$\delta\langle r^2 \rangle^{A,194}$ ( $\text{fm}^2$ )	$ \langle \beta^2 \rangle ^{1/2}$
$^{199g}\text{Pt}$	$5/2^-$	+0.75(8)	0.268(34)	0.144(10)
$^{199m}\text{Pt}$	$13/2^+$	-0.57(5)	0.166(30)	0.110(12)

#### 4. Future plan at KISS

In order to promote the further spectroscopic studies of more neutron-rich nuclei at KISS, we have been developing MRTOF-MS system for mass measurement and new narrow-band laser system for the precise in-gas-jet laser ionization spectroscopy.

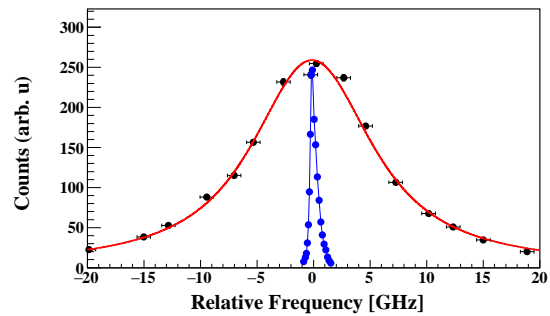
##### 4.1. MRTOF-MS at KISS

A new branch at the KISS beam line was installed as shown in Fig. 1 for mass measurements in this heavy region by using a MRTOF-MS. We can transport KISS beam to the MRTOF-MS by using an electric deflector for producing pulsed beam during the decay curve measurement at the decay station. Half-lives and masses can be simultaneously measured in one experiment. The MRTOF-MS has been successfully developed and applied for mass measurements [26, 27, 28, 29]. Now the MRTOF-MS is ready for mass measurements at KISS.

##### 4.2. In-gas-jet laser ionization spectroscopy

To determine electromagnetic moments and isotope shifts with higher precision, we have developed an in-gas-jet laser ionization spectroscopy technique [17]. We installed De Laval nozzle to make gas jet with uniform velocity distribution, S-shaped pseudo-RFQ (S-RFQ) for collinear laser spectroscopy, and a new narrow-band laser system. The laser system consists of pumping laser of Nd:YAG (EdgeWave, 355nm, 60W), narrow-band seed laser (TOPTICA, DLC DL PRO HP), and dye-amplifier (Sirah). In the case of in-gas-jet laser ionization technique, the widths caused by the pressure broadening and Doppler broadening are drastically reduced from  $\Gamma_p = 10$  GHz to 0.05 GHz in FWHM and from  $\Gamma_D = 1.1$  GHz to 0.4 GHz in FWHM, respectively, owing to the spectroscopy in low-pressure and low-temperature gas-jet. Owing to a narrow-band laser system, the laser bandwidth becomes  $\Gamma_L = 0.1$  GHz from 3.4 GHz in FWHM. Finally, the resolution will be improved to be approximately  $\Gamma = 0.5$  GHz in FWHM.

Figure 5 shows HFS spectra of  $^{198}\text{Pt}$  ( $I^\pi = 0^+$ ) and  $^{194}\text{Pt}$  ( $I^\pi = 0^+$ ) measured by in-gas-cell and in-gas-jet laser ionization techniques, respectively, under the gas cell pressure of 80 kPa (background gas-pressure 50 Pa). No HFS splitting was observed due to  $I^\pi = 0^+$  of both isotopes. Therefore, each width shows the intrinsic resolution obtained by each technique. The



**Figure 5.** HFS spectra of  $^{198}\text{Pt}$  ( $I^\pi = 0^+$ ) and  $^{194}\text{Pt}$  ( $I^\pi = 0^+$ ) measured by in-gas-cell and in-gas-jet laser ionization techniques, respectively. Horizontal axis shows the deviation from each  $\lambda_1$  of the applied ionization schemes.



widths by in-gas-cell and in-gas-jet laser ionization techniques were measured to be 12.5(5) GHz and 0.6(1) GHz in FWHM, respectively. We drastically improved the resonance width by applying in-gas-jet laser ionization technique. Now we are optimizing the setup of in-gas-jet laser ionization spectroscopy for an on-line experiment.

## 5. Summary

The KEK Isotope Separation System (KISS) was installed at RIKEN to study the  $\beta$ -decay properties of neutron-rich isotopes with neutron numbers around  $N = 126$  for applications in astrophysics. We can successfully extract the neutron-rich isotopes produced by the MNT reactions from the KISS gas cell, and performed  $\beta$ - $\gamma$  and laser spectroscopic studies. We measured half-life of  $^{198}\text{Os}$  for the first time, and performed  $\beta$ - $\gamma$  spectroscopic studies of, especially, osmium isotopes. By using in-gas-cell laser ionization technique, we measured the HFS spectra of  $^{199g,199m}\text{Pt}$  and  $^{196,197,198}\text{Ir}$  isotopes, and determined the  $\mu_I$  values and nuclear deformation parameters successfully. As the further spectroscopic studies at KISS, we plan to perform mass measurements by using MRTOF-MS and precise in-gas-jet laser ionization spectroscopy.

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