Research activities of KEK RNB group at RIBF

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How are gold and platinum elements synthesized in the universe? This is one of the important questions in fundamental science of the 21st century. The KISS project aims at finding the astrophysical origin of such heavy-element synthesis through the experimental nuclear physics.[1)] This is a challenging and next-step project based on the scientific expertise of the Tokai Radioactive Ion Accelerator Complex (TRIAC), which was the first-generation Radioactive Nuclear Beam (RNB) facility of the post-acceleration scheme operated at the KEK Tokai campus.[2)] The project was encouraged to proceed in the international review committee held in FY2009. Since then, KEK Isotope Separation System (KISS) was installed in experimental halls of the Nishina building at RIBF and has been utilized various experiments under the collaboration between RNC/RIKEN and IPNS/KEK. The first ceremonial meeting for this collaboration was held in October 2011.

According to the scenario of the rapid neutron capture (r-)process,[3)] waiting nuclei as progenitors of the stable heavy elements around $A = 195$ can provide crucial information on the astrophysical circumstance through their masses, lifetimes, decay schemes, and neutron capture rates,[4)] although these nuclei in the vicinity of the waiting region are still far to access.

We have proposed multi-nucleon transfer (MNT) reactions of intense neutron-rich heavy-ion beams as production tools.[5)] Produced nuclei are stopped immediately in the KISS argon gas cell to be neutral atoms for further A- and Z-separation by applying the laser resonance ionization and dipole magnetic field (Fig. 1).[6)] The commissioning of KISS was performed from 2011 to 2014 to confirm the A- and Z-separation of RIs reasonably extracted from the gas cell.[7)] Apart from the KISS R&D, In-Gas Laser Ionization and Spectroscopy network (IGLIS-net[8)]) has been launched in 2012 as an international information network of the physics subjects and techniques related to IGLIS with 15 groups and institutes worldwide. Further, the Wako Nuclear Science Center (WNSC) was established as a formal branch of IPNS, KEK at the RIKEN Wako campus in April 2015 for supporting user activities.

A new research activity on the nuclear mass measurements has been started in our group in FY2015 based on the joint R&D works with RNC of the Multi-Reflection Time-Of-Flight mass spectrograph (MRTOF).[9)] The resolving power of MRTOF can reach the level of approximately 105 even for heavy-isotope measurements within a relatively short analyzing time less than 10 ms. It is a powerful tool not only for nuclear astrophysics but also for nuclear physics in a broad range of the nuclear chart.

As the first series of measurements (called the SHE-mass project), MRTOF was set at the focal plane

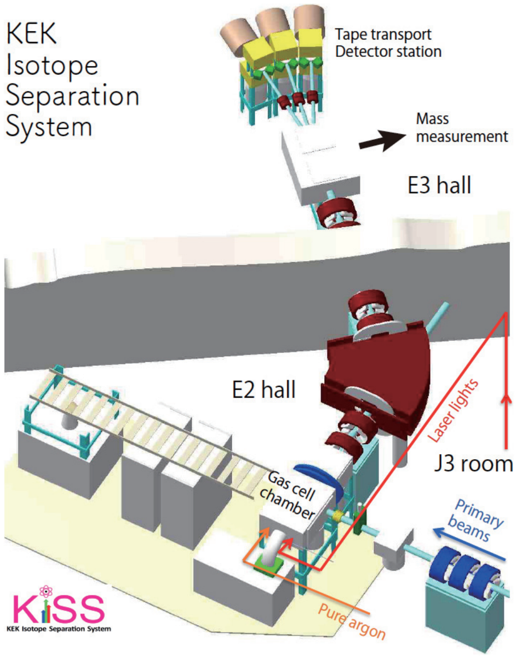

Fig. 1. Schematic drawing of KISS.

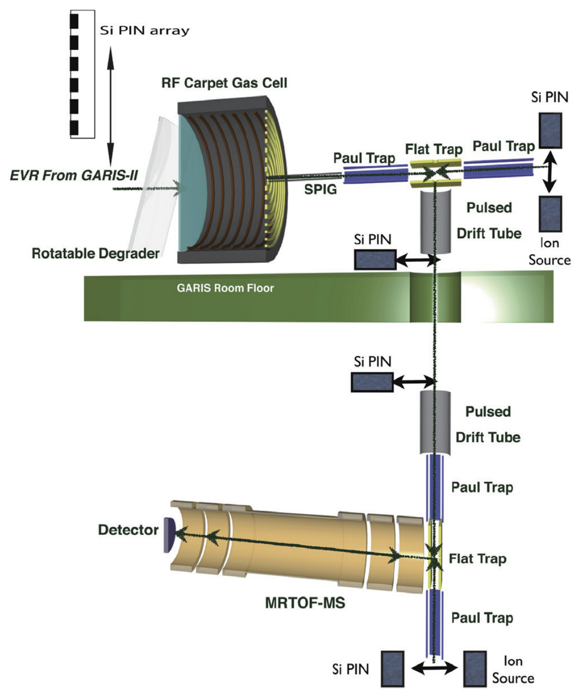

Fig. 2. Schematic drawing of the MRTOF system set at GARIS II.

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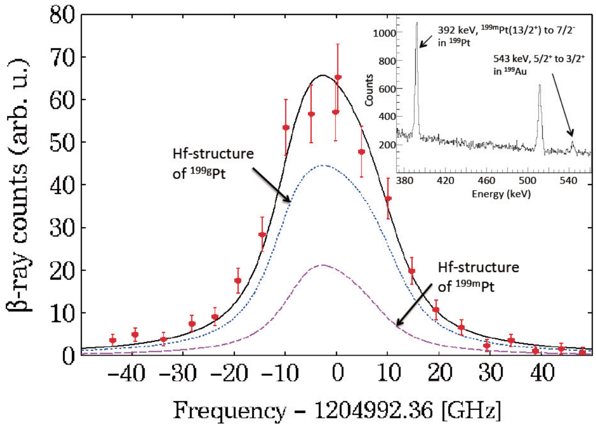

Fig. 3. Hyperfine (Hf-) structures of ${}^{199\mathrm{m},\,199\mathrm{g}}$Pt obtained with β-transitions of ${}^{199\mathrm{g}}$Pt. Short and long dotted lines indicate contributions of ${}^{199\mathrm{g}}$Pt and ${}^{199\mathrm{m}}$Pt, respectively. The Hf-structure of ${}^{199\mathrm{m}}$Pt is independently determined by the internal γ-transition (392 keV) from ${}^{199\mathrm{m}}$Pt shown in the inset.

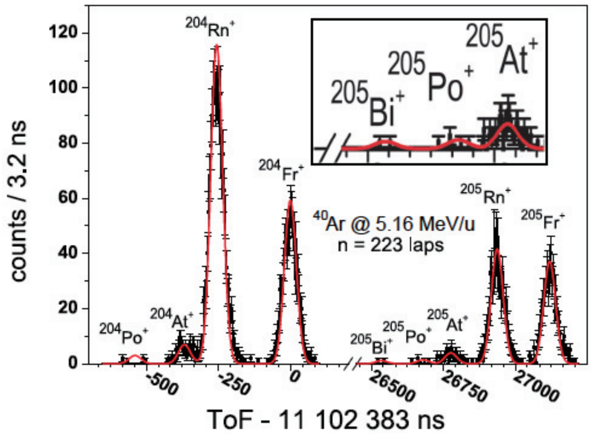

Fig. 4. Time-of-flight spectrum measured in the nuclear fusion reactions of ^{169}Tm and ^{40}Ar. Isotopes shown in the figure are clearly identified by comparison with tof-spectrum of a different number of flight laps, $n = 224$. RI of ^{205}Bi was clearly identified within an error of 1 MeV/c^2 by two detected events, as shown in the inset.

of GARIS II to determine the masses of evaporation residues in nuclear fusion reactions,[10] as shown in Fig. 2.

Thus far, a number of experimental subjects have been approved at RIBF-PAC, and their experiments have been performed with KISS and MRTOF devices. Those are RRC29, RRC37, RRC40, RRC41, RRC44, and RRC45 for the KISS experiments and LINAC07, LINAC23, and LINAC24 for the MRTOF experiments. KISS experimental subjects approved thus far include lifetime measurements of nuclei in the vicinity of the waiting region and decay- and laser-spectroscopies of isomeric and ground states in neutron-rich heavy nuclei. Subjects using MRTOF are devoted to the mass measurements of very heavy elements and proton-rich nuclei with astrophysical interests concerning X-ray bursters.

Figure 3 shows the first result of the hyperfine structures of ${}^{199\mathrm{g}}$Pt and ${}^{199\mathrm{m}}$Pt firstly measured in the recent KISS experiment (RRC41).[11] The magnetic moment and shift of the charge-radii of each state were clearly obtained. This experiment has been successfully performed under the collaboration between IBS and KEK, in which we have constructed a gamma-ray measurement system with super-clover Ge detectors from IBS and a mass measurement system with MRTOF in FY2016. The former system is already available, and the latter will be ready in FY2017 for KISS experiments and at the RAON facility[12] in future.

Figure 4 shows the first result of the SHE-mass project (LINAC07),[13] which reveals unique MRTOF characteristic as a mass spectrograph having a certain mass range with high sensitivity for a small amount of RIs. A typical mass-determination uncertainty is approximately 100 keV/c^2 for 100 detected ions in this mass region. Thus far, measurements have been performed for more than 80 isotopes, including new mass determinations of six isotopes of mendelevium ($Z = 101$) and einsteinium ($Z = 99$) elements.[14]

Based on the current research activities, WNSC has proposed an upgrade plan of the KISS project, which is KISS Stage II for a comprehensive study of element synthesis with precise nuclear spectroscopy covering the whole region of the nuclear chart.[15] It can be realized by the present KISS upgrade for accepting intense HI-beams and by installation of a pure RI spectroscopy line at the SLOWRI facility being commissioned.[16]

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