Proc. 15th Int. Symp. Origin of Matter and Evolution of Galaxies (OMEG15)
JPS Conf. Proc. **31**, 011012 (2020)
https://doi.org/10.7566/JPSCP.31.011012

Recent progress of research with KISS and MRTOF

Hiroari Miyatake for KISS/MRTOF collaboration

Wako Nuclear Science Center, Institute of Nuclear and Particle Studies, High Energy Accelerator Research Organization, Hirosawa 2-1, Wako, Saitama 351-0198, Japan

**E-mail: hiroari.miyatake@kek.jp*

(Received September 15, 2019)

KISS (KEK Isotope Separation System) project aims at finding an astrophysical condition for synthesizing isotopes of heavy elements under a rapid neutron-capture (r)-process, which forms the third peak in the solar abundance pattern. So far, we have performed measurements of lifetimes, decay schemes, and hyperfine structures of some platinum, iridium, and osmium isotopes by using multi-nucleon transfer reactions, in-gas-cell laser ionization, and decay spectroscopic techniques. In addition to the KISS activities, comprehensive mass measurement project with MRTOF (Multi-Reflection Time-Of-Flight spectrograph) has been started. Some of MRTOF's have already been installed not only at KISS but also at GAs-filled Recoil Ion Separator (GARIS II) of Riken RI-Beam Factory (RIBF), the latter of which are going to measure masses of super-heavy isotopes.

KEYWORDS: Nuclear spectroscopy, ISOL technique coupled with laser resonance ionization, Nuclear mass measurements with MRTOF, rapid neutron-capture process, Experimental nuclear astrophysics, Super heavy nuclei

1. Nuclear spectroscopies with KEK Isotope Separation System (KISS)

KISS is an Isotope Separator On-Line (ISOL) based on an argon-gas-cell and a laser ion source. It has been installed at Riken RI-beam factory and operated since 2016 [1]. One of major project with KISS is an experimental research on an origin of the rapid neutron capture process in astrophysical heavy-element synthesis. KISS has been used for decay- and laser- spectroscopies of neutron-rich Pt-, Ir-, and Os-isotopes produced through the multi-nucleon transfer reactions. These isotopes are sitting on the way of decaying back from waiting nuclei of progenitors for the third peak (at around A~195) in the r-process elemental abundance pattern.

1.1 Decay-spectroscopies of neutron-rich Pt-, Ir-, and Os-isotopes with KISS

So far, lifetimes of 12 isotopes, including newly measured ^{198}Os ($t_{1/2}$=2.0(5) min.) [2], have been observed by detecting β-rays with multi-segmented proportional gas counters (MSPGC) [3]. Fig. 1 indicates measured and reported (NNDC) [4] half-lives of osmium isotopes together with predictions of various models. They are generalized energy-density functional theory with continuum quasiparticle random-phase approximation (DF3) [5], finite-range droplet model with QRPA (FRDM) [6], and the gross theory with the KTUY mass model (KTUY) [7]. All the models are taking both strengths of allowed GT and FF transitions into account. However, any model does not reproduce well the measurements in the entire mass range. Therefore, further experimental study is needed to improve the models.

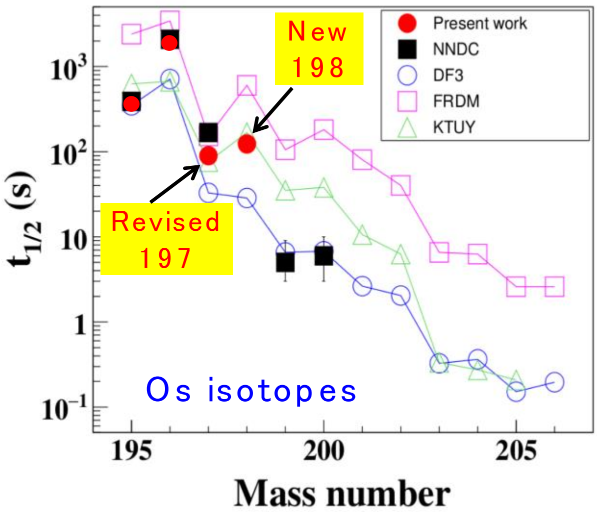

Fig. 1. Half-life systematics in osmium isotopes. Red circles and black squares indicate measured and reported values, respectively. Blue circles, pink squares, and green triangles are various model predictions as explained in the text.

During the lifetime measurements with β-rays, γ-rays have been also measured with super-clover (SC-) Ge-detectors. MSPGC is covered by four of SC-Ge's with close geometry to the focal plane of KISS. Fig. 2 shows a preliminary result of the measured X-and γ-rays coincident with MSPGC signals. Half-lives of these transitions are similar to 45 sec within the statistical errors. They are shorter than the ground state of ^{195}Os ($t_{1/2}$=6.5 min.). Considering characteristic X-rays of osmium, these transitions are assigned as de-excited transitions from new isomeric state in ^{195}Os [8]. It is expected that isomers originated from $i_{13/2}$-neutron orbit can be found in the decay region of waiting nuclei [9] and they would play an important role to form the final abundance pattern in the cold r-process scenario [10].

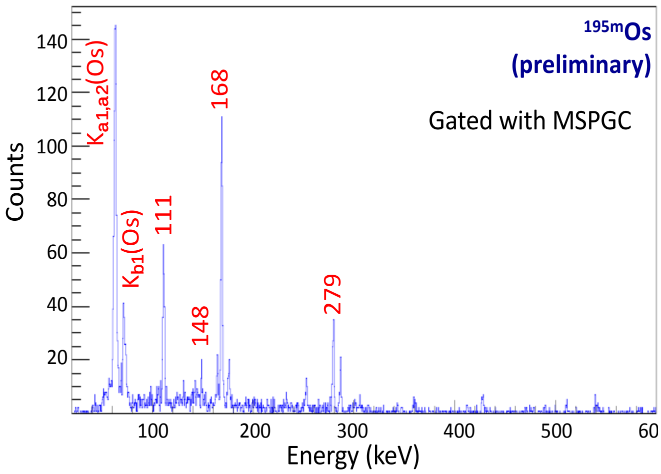

Fig. 2. Measured X- and γ-rays relevant to newly observed isomeric state in ^{195}Os. Those transitions are coincident with MSPGC and have shorter half-lives around 45 sec shorter than ^{195g}Os ($t_{1/2}$=6.5 min.).

1.2 β-delayed fissions in the trans-uranium region

After successful observation and discussion on the multi-messenger object, GW170817, a fission cycling in the r-process has been shed light as an important probe to find out heavier element synthesis than lanthanides in light-curve measurements of

Kilonovae [11]. On the other hand, it has been still uncertain to estimate quantitatively the fission barrier heights and fission fragment distributions due to small amount of relevant data in the neutron-rich heavy isotopes closed to the r-process path. We are going to measure fissions of such neutron-rich isotopes with KISS by applying multi-nucleon transfer (MNT) reactions of trans-uranium target and neutron-rich stable (or radioactive) beams. Fig. 3 indicates expected yield of unknown neutron-rich isotopes produced by MNT reactions of ^{238}U beams (500 pnA, 8 MeV/A) and ^{248}Cm target based on the Grazing calculation [12]. Systematic measurement of fission barrier height could be performed for some of unknown nuclei, sitting in the neutron-rich side of the stability line, by detecting β-delayed fissions.

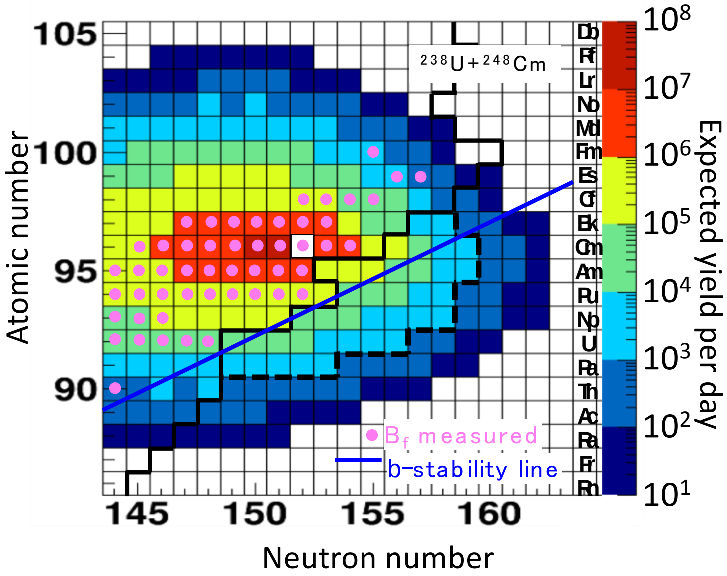

Fig. 3. Expected production yields of neutron-rich isotopes through MNT reactions of ^{238}U and ^{248}Cm. Fission barrier heights (Bf) could be measured for unknown isotopes in the neutron-rich side of the stability line.

2. Mass measurements with Multi-Reflection Time-Of-Flight Mass Spectrometry (MRTOF)

The MRTOF has been firstly utilized on-line experiments at a focal plane of GARIS-II [13] and successfully operated to determine masses more than 80 isotopes including trans-uranium elements [14]. Based on this expertise, comprehensive mass measurement project has been started since 2017 at RIBF. It aims at measuring nuclear

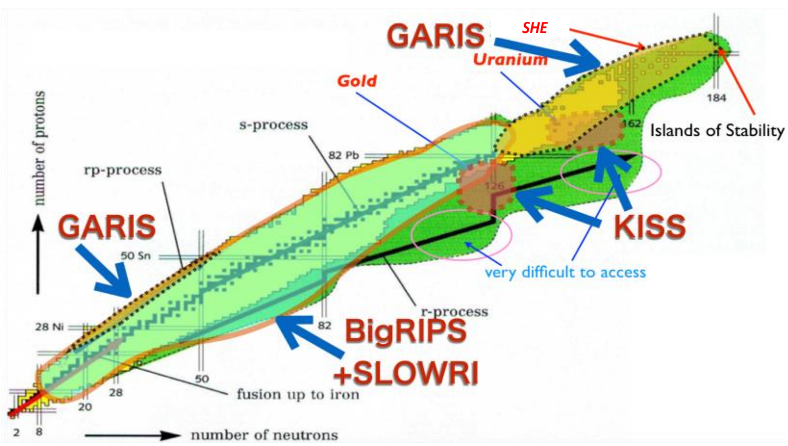

Fig. 4. Nuclear map indicating areas of nuclear mass measurements with MRTOF's being installed at facilities, GARIS, KISS, BigRIPS-ZDS (Zero-Degree Spectrometer), and SLOWRI, at RIBF.

masses of isotopes available at RIBF by installing some of MRTOF's at major experimental facilities, GARIS-II/-III, KISS, BigRIPS-ZDS, and SLOWRI [15]

2.1 Comprehensive mass measurement

Fig. 4 shows a nuclear map indicating expected areas of mass measurements with dedicated systems including MRTOF at relevant facilities. The systems consist of similar devices: a helium gas-cell ion cooler (GCCB) for stopping and cooling down isotopes, a multi-trap ion buncher (Flat trap) for trapping and ejecting ions to the MRTOF, and an ion-guide set between them for transporting ions [13]. The first MRTOF system has been constructed at GARIS-II to measure masses of evaporation residues of nuclear fusion reactions. This system is powerful for mass measurements of neutron deficient isotopes of light to heavy elements with its high precision of $\delta m/m{\sim}10^{-8}$ and feasibility for short-lived isotopes of $t_{1/2}{\sim}10$ ms [14]. It was utilized the first campaign of a SHE-mass project, as mentioned in the next subsection, and was moved to other experimental hall together with GARIS-II. The system has been improved its transport efficiency by about one order of magnitude compare to the previous setup by replacing relatively long transport line between GCCB and Flat trap.

The half-sized MRTOF, called as "mini-MRTOF" has been installed at KISS facility [1] to perform mass measurements of neutron-rich isotopes produced by MNT reactions. Its characteristics has been investigated under the IBS-KEK collaboration, so far. Typical mass resolving power of around 150,000 has already been achieved during recent R&D works. The first experiment is scheduled in this year, 2019.

At a focal plane of the Zero-Degree Spectrometer (ZDS), which directly connects to BigRIPS, another MRTOF system has been prepared together with different type of GCCB [16]. Many radioactive isotopes will be available at ZDS for mass measurements by the help of projectile-fragmentation reactions and/or in-flight fissions of intense uranium beams.

2.2 SHE-mass project

In the comprehensive mass measurement project, direct mass measurements of super heavy isotopes are intensively prepared and performed at SHE-mass project at GARIS-II and GAIS-III, which is similar device of

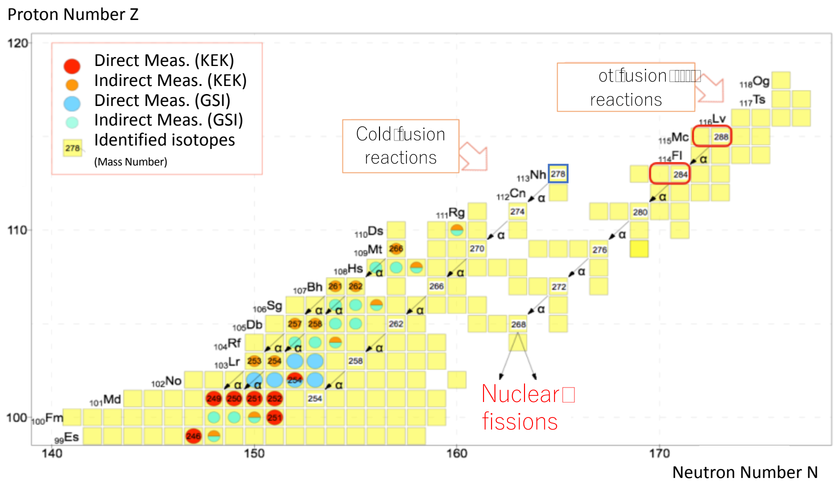

Fig. 5. Nuclear map indicating super heavy isotopes so far synthesized and identified. Red (orange) circles are directly (indirectly) mass determined isotopes at the first campaign of the SHE-mass project. Isotopes covered b y red squares are candidates to be measure the masses in near future.

GARIS-II and will be ready at RIBF, soon. Fig. 5 indicates so far discovered super heavy isotopes, produced through two types of reactions, so called as cold- and hot-fusion reactions [17]. Based on the measured mass information, absolute masses of isotopes produced by cold-fusions can be investigated indirectly by taking account of sequential α-decay energies. For example, mass of ^{278}Nh can be investigated by applying this method. On the other hand, masses of isotopes produced by hot-fusion reactions have not been investigated due to spontaneous fissions on the way of sequential decays. SHE-mass project is aimed at measuring masses of evaporation residues of hot-fusion reactions by MRTOF. This subject has already been approved at RIBF and relevant experiments has been started.

Newly developed time pickup counter, called as α-TOF [18], has been set at the focal plane of MRTOF system at GARIS-II. The times-of-flight of ions are measured by injecting ions from MRTOF to this counter. Since analytes are usually α-decaying isotopes in this mass region, α-TOF can not only generate arrival timings of ions with enough short time width (~200 ps), but also successively detect α-particles with their energies and emission timings. This correlation between the ion-arrival timing, α-decay timing, and its decay energy allows to perform clear determination of ground state masses and lifetimes of super heavy isotopes even in the case of complex TOF measurement with low-energy isomers.

3. Conclusion

KISS project with nuclear astrophysical interests, especially on the heavy-element synthesis by the rapid neutron-capture process, has been proceeded at RIBF since 2016. So far lifetimes of 12 isotopes in the Pt, Ir, and Os elements have been determined together with the decay-schemes. It is necessary that further experimental studies are needed to solve discrepancy of measured half-lives and theoretical predictions in the osmium isotopes for making reliable descriptions of progenitors for the r-process third abundance peak.

Nuclear mass measurement project has already been started with using MRTOF device. Comprehensive measurements for any isotopes available at RIBF will be feasible by installing the MRTOF systems to appropriate facilities. Systems at KISS and GARIS-II has been ready to perform experiments for isotopes being produced through MNT and fusion reactions, respectively. Another system at ZDS connecting to BigRIPS is under commissioning.

Acknowledgment

Relevant researches were performed at the RI Beam Factory (RIBF) operated by RIKEN Nishina Center and CNS, University of Tokyo. The author acknowledges the RIKEN accelerator staff for their support. This work was also supported by JSPS KAKENHI Grant Nos. JP23244060, JP24740180, JP26247044, JP15H02096, JP17H01132, JP17H06090, and JP18H03711.

References

[1] Y. Watanabe et al., Nuclear physics News **28**, 25 (2018). and Y. Hirayama et al., 10.1016/j.nimb.2019.04.035
[2] Y. Hirayama et al., Phys. Rev. C**98**, 014321 (2018).
[3] M. Mukai et al., Nucl. Insrtum. Meth. A**884**, 1 (2018) and 10.1016/j.nimb.2019.04.036.
[4] https://www.nndc.bnl.gov/
[5] I.N. Borzov, Phys. Rev. C**67**, 025802 (2003).
[6] P. Möller et al., Phys. Rev. C**67**, 055802 (2003).
[7] H. Koura et al., Prog. Theor. Phys. **113**, 305 (2005).
[8] Md. Ahmed, Doctor thesis, Tsukuba University (2018).
[9] A.K. Jain et al., Nuclear Data Sheets **128**, 1(2015).
[10] S. Wanajo, AstroPhys. J. **666**, L77 (2007).
[11] S. Wanajo, Astrophys. J. **868**, 65 (2018).
[12] Program GRAZING, http:/www.to.infn.it/~nanni/grazing/
[13] P. Schury et al., Phys. Rev. C**95**, 011305 (2017).
[14] Y. Ito et al., Phys. Rev. C**120**, 152501 (2018), M. Rosenbusch et al., Phys. Rev. C**97**, 0643067 (2018), and S. Kimura et al., Int. J. Mass Spect. **430**, 134 (2018).
[15] http://www.nishina.riken.jp/RIBF/index.html
[16] M. Rosenbusch et al., 10.1016/j.nimb.2019.05.058
[17] Yu.Ts. Oganessian and V.K. Utyonkov, Nucl. Phys. A944, 62 (2015).
[18] T. Niwase et al., arXiv:1904.11589.