Overview of activities of the NUSPEQ group in CNS

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Varieties in the properties of nuclei far from stability give rich information on the nuclear structure in a wide area of the nuclear chart. Experiments using radioactive isotope (RI) beams in the last few decades have shown exotic phenomena such as neutron halos, soft collective excitations, and changes of magic numbers. We are realizing that the nuclear structure should be studied as a function of the proton and neutron numbers (Z and A) as well as of the excitation energies (E_x).

Based on this consideration, the NUSPEQ[a)] group in CNS started the in-beam spectroscopy of exotic nuclei with direct reactions of RI beams at several tens of MeV per nucleon in FY2000. In FY2003, we extended the studies to approach high-spin states by using fusion reactions of RI beams at a few MeV per nucleon. Major parts of the studies before FY2006 were performed at the RIPS facility.

The firstly developed equipment was a liquid helium target,[1)] which enables measurements of α-induced reactions on exotic nuclei. An array of position-sensitive Ge detectors, GRAPE, was developed for measuring in-flight γ decay with high resolution.[2)] For total-energy measurements of projectile-like ejectiles, an array of NaI(Tl) detectors was also developed.

By using the developed equipments combined with invariant mass and/or in-beam γ-ray spectroscopies, the following studies were performed: (1) (α, α') reactions for studying isoscalar responses of ^{14}O[3)] and cluster states in ^{12}Be.[4)] (2) shell evolution in neutron-rich fluorine[5)] and boron[6)] by using proton-transfer reactions (α,t), and (3) electric quadrupole excitation of neutron-rich nuclei by Coulomb excitations.[7)] As a by-product of the experiment using the ^{12}Be beam, the isomeric 0^+ state was discovered by analyzing cascade γ-ray decays in flight, and its lifetime was measured, which shows the disappearance of $N = 8$ magicity.[8)]

For high-spin study, we developed a low-energy ^{46}Ar beam by using a set of energy degraders.[9)] By using the ^{46}Ar beam and the GRAPE array, a fusion reaction ^{9}Be(^{46}Ar, 5n)^{50}Ti was measured to study high-spin states of ^{50}Ti.[10)] The superdeformation in ^{40}Ar was also found for the first time by using the ^{26}Mg(^{18}O, 2p2n)^{40}Ar reaction at the JAEA tandem facility.[11)]

In FY2005, CNS started the SHARAQ[b)] project[12)] in order to extend research opportunities in the RIBF and completed the construction of the spectrometer at the end of FY2008. The NUSPEQ group a played major role in the developments and research activities. The basic idea of the SHARAQ project is to use the RI beams as probes for the direct reactions, in which a variety of isospin (T), internal energy (mass excess), and spin (S) different from those of stable beams exist. We focused on the exothermic charge-exchange reaction of RI beams, in which the internal energy of the beam particle is used for exciting the target nucleus with a very small momentum transfer.

In the SHARAQ project, we developed tracking detectors for the high-resolution beamline[13)] and the focal plane of the SHARAQ spectrometer. We also contributed to the development of the DAQ system including SHARAQ.[14)]

The first result from the SHARAQ project was the isovector spin-monopole resonances in ^{90}Zr and ^{208}Pb by using the (t, ^{3}He) reaction at 300 A MeV.[15)] The recent highlight is the possible candidate of the tetra-neutron resonance immediately above the 4n threshold obtained by using the ^{4}He(^{8}He, ^{8}Be) reaction at 190 A MeV[16)] (Fig. 1).

Another program in the SHARAQ project is the direct measurement of the mass. In order to obtain very good timing information, we developed diamond detectors having $\sim$ 10 ps resolution.[17)] The masses of nuclei around ^{54}Ca were simultaneously measured and determined with 160, 250, and 990 keV resolution for $^{55, 56, 57}$Ca to clearly demonstrate $N = 34$ magicity in the Ca isotopes.[18)]

Parallel to the SHARAQ project, the NUSPEQ group joined the SEASTAR and the EURICA collaboration. Isomer spectroscopy of heavy neutron-rich nuclei was performed, several results of which have already been published.[19)]

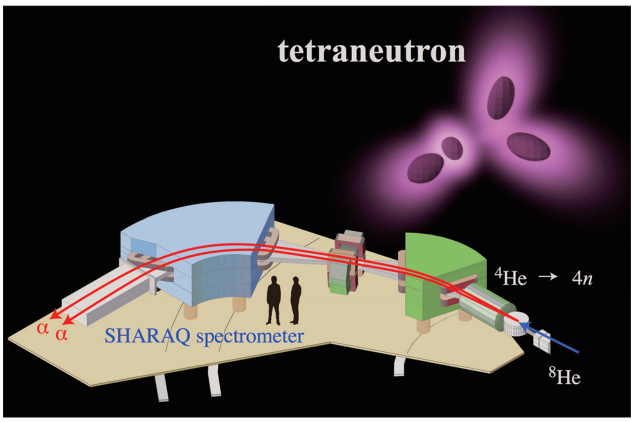

Fig. 1. Schematic image of the tetra-neutron experiment.

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a) **NU**clear **SP**ectroscopy for **E**xtreme **Q**uantum system

b) **S**pectroscopy with **H**igh-resolution **A**nalyzer of **R**adio**A**ctive **Q**uantum beam

In FY2015, we have initiated the OEDO[c] project, which aims at the deceleration of intense RI beams provided in the RIBF. Low-energy RI beams open opportunities for studying exotic nuclei by using nucleon/pair/cluster transfer, Coulomb excitation, incomplete fusion, and so on. The OEDO system consists of a mono-energetic degrader at a momentum-dispersive focus, two sets of quadrupole triplets, and an RF deflector. The RF deflector works as an optical matching element for the time-of-flight dispersion after the compression of energy spread after the degrader. The system was constructed by the end of FY2016.

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References

1) H. Ryuto et al., Nucl. Instrum. Methods Phys. Res. A **555**, 1 (2005).
2) M. Kurokawa et al., IEEE Trans. Nucl. Sci. **50** 1309 (2003); S. Shimoura, Nucl. Instrum. Methods Phys. Res. A **525**, 188 (2004).
3) H. Baba et al., Nucl. Phys. A **788**, 188c (2007).
4) A. Saito et al., Nucl. Phys. A **738**, 337 (2004); A. Saito et al., Mod. Phys. Lett. A **25**, 1858 (2010).
5) S. Michimasa et al., Phys. Lett. B **638**, 146 (2006).
6) S. Ota et al., Phys. Lett. B **666**, 311 (2008).
7) H. Iwasaki et al., Phys. Lett. B **620**, 118 (2005); H. Iwasaki et al., Phys. Rev. C **78**, 021304 (2008).
8) S. Shimoura et al., Phys. Lett. B **560**, 31 (2003); S. Shimoura et al., Phys. Lett. B **654**, 87 (2007).
9) E. Ideguchi, Prog. Theor. Exp. Phys. **2012**, 03C005 (2012).
10) M. Niikura et al., Eur. Phys. J. A **42**, 471 (2009).
11) E. Ideguchi et al., Phys. Lett. B **686**, 18 (2012).
12) T. Uesaka et al., Nucl. Instrum. Methods Phys. Res. B **266**, 4218 (2008); T. Uesaka et al., Prog. Theor. Exp. Phys. **2012**, 03C007 (2012); S. Michimasa et al., Nucl. Instrum. Methods Phys. Res. B **317**, 305 (2013).
13) H. Miya et al., Nucl. Instrum. Methods Phys. Res. B **317**, 701 (2013).
14) H. Baba et al., Nucl. Instrum. Methods Phys. Res. A **616**, 65 (2010).
15) K. Miki et al., Phys. Rev. Lett **108**, 262503 (2012).
16) K. Kisamori et al., Phys. Rev. Lett. **116**, 052501 (2016).
17) S. Michimasa et al., Nucl. Instrum. Methods Phys. Res. B **317**, 710 (2013).
18) M. Kobayashi, PhD Thesis (University of Tokyo), Mar. 2017.
19) R. Yokoyama et al., Phys. Rev. C **95**, 034313 (2017); E. Ideguchi et al., Phys. Lett. B **686**, 18 (2010); E. Ideguchi et al., Phys. Rev. C **94**, 064322 (2016).

[c] **O**ptimized **E**nergy **D**egrading **O**ptics for RI beam