Recent results from γ-ray spectroscopy studies of unstable nuclei performed at RIPS

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Abstract. In-beam γ-ray spectroscopy is one of the most fruitful experimental methods for the structure study of unstable nuclei performed at RIPS. The experiments become more elaborated following the development of experimental devices and techniques. This paper introduces several experiments recently performed at RIPS utilizing recently developed devices, such as the RF-deflector, liquid helium target, and DALI2 γ-detector array.

1. Introduction
γ-ray spectroscopy has revealed a variety of exotic phenomena of unstable nuclei, since the disappearance of the N=20 magicity in $^{32}$Mg has been demonstrated by the intermediate energy Coulomb excitation[1]. Considerable progress in experimental devices and techniques has been made and consequently, experimental capability has been enlarged, with which more sophisticated spectroscopic information in wider region of nuclei becomes available.

One of such devices is the RF-deflector[2], which has extended the field of the RI beam experiments toward heavier and more proton rich region by improving the isotope purity of the RI beams. Another major device is the cryogenic target, which offers a variety of probes of spectroscopy such as proton, deuteron, and alpha inelastic scattering, as well as the nucleon transfer reactions ($^{\alpha}$t) and ($^{\alpha}$,3He). The γ-ray detector array DALI2 (Detector Array for Low Intensity radiation 2)[3] has been developed for the use of more detailed spectroscopy. Compared with the former DALI array, DALI2 has better detection efficiency, higher angular (and thus energy) resolution, and wider angular coverage, which provides us the capability of the coincidence measurement and γ-ray angular distribution measurement. The present paper introduces two experiments recently performed at RIPS[4]: One is the Coulomb excitation experiments of proton rich $T_2 = -1$ nuclei, $^{46}$Cr, $^{50}$Fe, $^{54}$Ni[5], the other is the spectroscopy of $^{23}$F by using proton transfer reaction[6]. Both experiments have been realized by use of the recently developed devices mentioned above.

2. Coulomb excitation of $T_2 = -1$ nuclei
The reduced transition probabilities $B(E2)$ between ground and first $2^+$ states have been extensively studied both experimentally and theoretically as a measure of the nuclear collectivity. To further investigate this quantity, the comparison between contributions of the protons and neutrons to the quadrupole excitation is intriguing, which could be seen in the double ratio $(|M_n|/|M_p|)/(N/Z)$, where $M_p$ and $M_n$ are the proton and neutron $E2$ matrix elements.
Bernstein’s mirror nucleus method [7] could be employed to determine $M_p$ and $M_n$ separately, where $|M_p|$ is derived from $B(E2)$ of the nucleus of interest and $|M_n|$ is derived from $B(E2)$ of its mirror pair. To apply this method, $B(E2)$ for isospin doublet is needed. However, the experiments with neutron deficient nuclei is rather difficult because of the low isotope purity of neutron deficient RI beams produced by in-flight separators. Indeed, the systematics of $B(E2)$ for isospin $T_z = \pm 1$ even-even pairs were available only up to $A = 42$ mass system. In the present work, a newly developed RF deflector was used to cope with the difficulty of low purity and the Coulomb excitation experiments of $^{46}$Cr, $^{50}$Fe, and $^{54}$Ni were performed to study the collective aspects of f-shell nuclei[5].

The low isotope purity of the neutron deficient nuclei arises both from the reaction mechanism of the projectile-fragmentation-like reaction at the energy around 100$A$ MeV and from the limitation of the separation principle using magnetic rigidity by the help of an energy degrader. Therefore, drastic increase in the isotope purity requires an independent separation method. For this purpose a radio frequency (RF) deflector system [2] was constructed. The RF-deflector was used to further purify the secondary beams of contaminants arriving at the electrodes at the different phase are deflected by the electric field adjusted so that the nucleus of interest pass through the electrodes without deflection. Other frequency is applied to the transverse direction to the beam axis. The oscillation phase is adjusted so that the nucleus of interest pass through the electrodes without deflection. Other contaminants arriving at the electrodes at the different phase are deflected by the electric field and stopped at a slit placed downstream of the electrodes. In this way, the RF deflector works as a velocity filter. The RF-deflector was used to further purify the secondary beams of $^{46}$Cr, $^{50}$Fe, and $^{54}$Ni produced at RIPS by the projectile fragmentation of $^{58}$Ni. The isotope purities were improved by a factor of $\sim 10$ from 0.1% to 1.0% for $^{46}$Cr, from 0.05% to 0.5% for $^{50}$Fe, and from 0.02% to 0.2% for $^{54}$Ni. The secondary beams bombarded a lead target with a typical thickness of 200 mg/cm$^2$. Outgoing particles were detected by a $\Delta E-E$ silicon-detector telescope to select inelastic-scattering events. De-excitation $\gamma$-rays were measured by a subset of DALI2 [3] consisting of 116 NaI(Tl) scintillators with 11 layers.

Figure 1 shows the Doppler-shift-corrected $\gamma$-ray spectra measured with $^{46}$Cr, $^{50}$Fe, and $^{54}$Ni beams. $\gamma$-ray peaks corresponding to the transitions from the $2^+$ states to the ground states were clearly observed at 900±10 keV, 767±7 keV, and 1370±30 keV, which agree with the previously reported values, 892 keV, 765 keV, and 1396 keV, respectively. The angle-integrated cross sections were deduced to be 460±90 mb, 690±120 mb, and 300±80 mb. The respective $B(E2; 0^+_g.s. \to 2^+_1)$ values are calculated with DWBA analysis to be 930 ± 200 e$^2$fm$^4$, 1400 ± 300 e$^2$fm$^4$, and 590 ± 170 e$^2$fm$^4$. In the DWBA analysis, two optical parameter sets were used, which were obtained from the elastic scattering of $^{40}$Ar on $^{208}$Pb at 44 MeV/u [9] and $^{58}$Ni on $^{208}$Pb at 17 MeV/u [10]. The quoted $B(E2)$ values were the averages of the results with the two potential sets, and their differences were included in the error.

Obtaining the $B(E2)$ values of $^{46}$Cr, $^{50}$Fe, and $^{54}$Ni together with their mirror nuclei, $^{46}$Ti, $^{50}$Cr, and $^{54}$Fe, the systematics of $B(E2)$ for the $T_z = \pm 1$ even-even pairs up to $Z = 28$ is completed. Then, following the Bernstein’s mirror nucleus method [7], the $|M_p|$ and $|M_n|$ values were derived and the double ratio ($|M_n|/|M_p|)/(N/Z)$ is calculated as plotted in Fig. 2 for the $T_z = -1$ even-even nuclei in the $Z = 10−28$ region. The ratio exhibits systematic trend, which can be understood in the following way. For the nucleus with proton and neutron number close to but smaller than a magic number, more neutrons contribute to the excitation than protons and consequently, ($|M_n|/|M_p|)/(N/Z)$ becomes larger than 1. Contrarily, for the nucleus with proton and neutron numbers close to but larger than a magic number, ($|M_n|/|M_p|)/(N/Z)$ becomes smaller than 1. Finally, for the nucleus in the mid-shell region, the ratio is close to 1, since the proton and neutron collectivly and thus equally contribute to the excitation. The results obtained for both $^{46}$Cr and $^{50}$Fe are close to 1 and are consistent with the pictures of collective nuclei without neutron and proton shell closures. The ratio for $^{54}$Ni, which is also close to 1, may indicate the weakness of the $Z = 28$ shell closure.
Figure 1. Doppler-corrected $\gamma$-ray spectra obtained for the Coulomb excitation of $^{46}$Cr (a), $^{50}$Fe (b), and $^{54}$Ni (c). The solid curves are fits to the data, which contain the simulated line shapes for $\gamma$-rays (dashed curves) and exponential background contributions (dotted curves).

Figure 2. Double ratio (|$M_n$|/|$M_p$|)/(N/Z) for $T_z = -1$ even-even nuclei in the $Z = 10 - 28$ region. The open circles indicate the ratios extracted from the present results. The closed circles are obtained from the $B(E2)$ values in Ref. [11]. In Fig. 2, the ratios are compared with theoretical calculations. The dashed lines show the shell-model calculations. For the $sd$-shell region, the calculation using the USD interaction by Brown and Wildenthal [12] are shown, while for the $pf$-shell region, the results calculated by Honma et al. [13] using GXPF1 interaction with $c_p = 1.5$ and $e_n = 0.5$ are plotted. The dot-dashed line indicates the calculation by Sagawa et al. [14] using the deformed Hartree-Fock + BCS calculation with SIII interaction. The tendency of the systematic behavior is reproduced by these calculations. However, the shell-model calculations exhibit stronger single-particle natures compared with the experimental results in the vicinity of the shell closure at 20 and 28, suggesting the importance of collective aspects which should be taken into account. In this respect, better agreements are obtained by the deformed HF + BCS prediction. However, it
considerably underestimates the amplitude of the matrix elements: for example, the predicted $|M_p|$ values are smaller by a factor of about 20 for $^{38}\text{Ca}$ and $^{42}\text{Ti}$.

3. Spectroscopy of $^{23}\text{F}$

Structure of neutron-rich nuclei has so far been investigated mostly with an emphasis on their neutron structure. However, the proton wave functions are also anticipated to have a peculiar structure in neutron-rich nuclei and are important for understanding these nuclei. In the present study, proton single particle states in a neutron-rich fluorine $^{23}\text{F}$ were studied by a one-proton transfer $(\alpha,t)$ reaction using an in-beam $\gamma$-ray spectroscopy technique.

For the study of single-particle states, stripping reactions such as $(d,n)$ or $(d,p)$ reactions have been used in traditional low energy beam experiments. However, these reactions are not directly applicable to the experiments using high energy secondary beams produced by the projectile fragmentation reactions, because the matching conditions are not satisfied with this energy region and thus the cross sections are very small. In contrast, the $(\alpha,t)$ reaction has reasonably large cross section (of the order of mb) even in this energy region. This is because the nucleons in an $\alpha$ particle have large Fermi momenta reflecting their large binding energies and therefore, the matching conditions are satisfied even with the high bombarding energies. Taking this advantage of $(\alpha,t)$ reaction, the present study measured the $^{22}\text{O}(\alpha,t)$ reaction in inverse kinematics with the in-beam $\gamma$-spectroscopy method, namely, $^4\text{He}(^{22}\text{O},^{23}\text{F}\gamma)$, to study proton single particle states of $^{23}\text{F}$ selectively and efficiently. To further confirm the nature of the excited states, the $^4\text{He}(^{23}\text{F},^{23}\text{F}\gamma)$ and $^4\text{He}(^{24}\text{F},^{23}\text{F}\gamma)$ reactions were also measured. Comparison among population strengths of these three reactions provides the information on the excitation mode of the levels. Three reactions were efficiently observed by using a cocktail beam comprised of $^{22}\text{O}$, $^{23}\text{F}$ and $^{24}\text{F}$, which enabled us to measure the three reactions simultaneously.

The cocktail beam was produced by projectile fragmentation reactions of $63A$ MeV $^{40}\text{Ar}$ beam impinging on a $^9\text{Be}$ target of $180\ \text{mg/cm}^2$ thickness. The averaged intensities and energies of components in the cocktail beam were $2 \times 10^3$ cps and $35\ A$ MeV for $^{22}\text{O}$, $6 \times 10^2$ cps and $40\ A$ MeV for $^{23}\text{F}$, and $2.5 \times 10^2$ cps and $45\ A$ MeV for $^{24}\text{F}$. The yields of $\gamma$-rays obtained in the three reactions are shown in Figure 3.

**Figure 3.** $\gamma$-ray spectra obtained in the three reactions: (a) proton transfer reaction $^4\text{He}(^{22}\text{O},^{23}\text{F}\gamma)$, (b) inelastic scattering $^4\text{He}(^{23}\text{F},^{23}\text{F}\gamma)$, and (c) neutron-knockout reaction $^4\text{He}(^{24}\text{F},^{23}\text{F}\gamma)$.
Figure 4. Tentative level scheme and $\gamma$-decay scheme of $^{23}$F. Levels with underlined energies show levels newly observed in the present experiment. The bars shown at the right side of excitation energies indicate the relative cross sections to populate these states.

32 A MeV for $^{23}$F, and $3 \times 10^2$ cps and 36 A MeV for $^{24}$F. The secondary beam bombarded a liquid helium target[15] with a thickness of 100 mg/cm$^2$, which was developed at CNS, University of Tokyo. Reaction products were detected by a $\Delta E$-$E$ telescope located behind the target and were identified using time-of-flight (TOF), energy loss ($\Delta E$), and energy ($E$) information. Scattering angles of the reaction products were measured by parallel-plate avalanche counters (PPACs) [8]. Final state channels were identified by measuring the de-excitation $\gamma$-rays from the excited states fed by the reactions, for which the DALI2 NaI(Tl) detector array[3] was used.

The $\gamma$-ray spectra obtained from the three reactions, $^4\text{He}(^{22}\text{O},^{23}\text{F})\gamma$, $^4\text{He}(^{23}\text{F},^{23}\text{F})\gamma$, and $^4\text{He}(^{24}\text{F},^{23}\text{F})\gamma$ are shown in Fig. 3, where a number of peaks were seen. The level scheme of $^{23}$F was preliminarily established as shown in the Fig. 4 by examining the $\gamma$-$\gamma$ coincidence relation. In the obtained level scheme, eight new excited states were found at $3385 \pm 10$ keV, $3887 \pm 19$ keV, $4619 \pm 17$ keV, $4756 \pm 3$ keV, $5508 \pm 38$ keV, $5549 \pm 23$ keV, $5563 \pm 27$ keV, and $6872 \pm 36$ keV for the first time, which are shown with underlines. The quoted errors show statistical error determined in the fit to the simulated response functions of the $\gamma$-ray detectors. Other six excited states agree with the observations by Orr et al. [16] and Belleguic et al. [17].

The $\gamma$-ray spectra obtained from the three reactions, $^4\text{He}(^{22}\text{O},^{23}\text{F})\gamma$, $^4\text{He}(^{23}\text{F},^{23}\text{F})\gamma$, and $^4\text{He}(^{24}\text{F},^{23}\text{F})\gamma$ exhibit remarkably different structure among each other. Relative cross sections to each excited states are shown by the bar graph at the right side of the excitation energies in Fig. 3. Remarkable feature is that the the 4.061-MeV state is strongly populated only by the proton transfer reaction. The difference of population strengths among three reactions reflects the properties of the excited state. The transfer reaction mainly populates proton single-particle states; The $\alpha$ inelastic scattering makes core excitations and possibly populates single-particle states through non spin-flip excitation; and the neutron-knockout reaction populates neutron-hole states. This strongly suggests that the 4.061-MeV state is a single-proton state.

The angular distribution of the differential cross section to the 4.061-MeV state was compared with the DWBA calculation and was consistent with the result assuming $\Delta \ell = 2$. Therefore,
the 4.061-MeV state is preliminarily assigned to have $J^\pi = 3/2^+$ or $5/2^+$. The previous works [16, 18, 19] reported that the ground state in $^{23}$F has $5/2^+$. Therefore, the state at 4.061 MeV is considered reasonably to have $3/2^+$ as a proton single-particle state in the $d_{3/2}$.

4. Summary
The $B(E2)$ values for $^{46}$Cr, $^{50}$Fe, and $^{54}$Ni were measured by intermediate-energy Coulomb excitation. The RF deflector enabled us the efficient measurements for these proton-rich nuclei. The present study completes the systematics of experimental $B(E2)$ values for the isospin $T_z = \pm 1$ even-even pair nuclei up to $Z = 28$. Using the $B(E2)$ values of their mirror nuclei, the double ratios, $(|M_n|/|M_p|)/(N/Z)$, have been extracted up to $A = 54$ system. The present result suggests the necessity of more elaborate treatment of the nuclear collectivity in this mass region.

The proton single particle state in neutron-rich $^{23}$F was studied by in-beam $\gamma$-ray spectroscopy technique using the proton transfer reaction $^4$He$(^{22}$O, $^{23}$F). The $\gamma$-ray spectrum was compared to the one from the $\alpha$ inelastic scattering on $^{23}$F and the neutron-knockout reaction from $^{24}$F. The level scheme and $\gamma$-decay scheme in $^{23}$F were deduced by analyzing the coincidence relation of the de-excitation $\gamma$-rays. From this study, we reconfirmed the previous results and found eight new excited states. Furthermore the 4.061-MeV state was found to have the single-particle nature and reasonably considered to have $J^\pi = 3/2^+$.

References
[1] T. Motobayashi et al., Phys. Lett. B 346 (1995) 9.
[2] K. Yamada et al., Nucl. Phys. A 746, (2004) 156c.
[3] S. Takeuchi et al., RIKEN Accel. Prog. Rep. 36, (2003) 148.
[4] T. Kubo et al., Nucl.Instrum. Methods Phys. Res. B 70, (1992) 309.
[5] N. Yamada et al., The Fourth International Conference on Exotic Nuclei and Atomic Masses.
[6] S. Michimasa et al., The Fourth International Conference on Exotic Nuclei and Atomic Masses.
[7] A. M. Bernstein et al., Phys. Rev. Lett. 42, (1979) 425.
[8] H. Kumagai et al., Nucl. Instrum. Methods Phys. Res. A 470, (2001) 562.
[9] N. Alamanos et al., Phys. Lett. 137B, (1984) 37.
[10] M. Beckerman et al., Phys. Rev. C 36, (1987) 657.
[11] S. Raman et al., At. Data and Nucl. Data Tables 78, (2001) 1.
[12] B. A. Brown et al., Phys. Rev. C 26, (1982) 2247.
[13] M. Honma et al., Private communication: Phys. Rev. C 69, (2004) 034335.
[14] H. Sagawa et al., Private communication: to be submitted.
[15] H. Akiyoshi et al., RIKEN Accel. Prog. Rep. 34, 193 (2001).
[16] N.A. Orr et al., Nucl Phys. A491, 457 (1989).
[17] M. Belleuic et al, Nucl. Phys. A682, 136c (2001).
[18] D.R. Goosman et al., Phys. Rev. C 10, 756 (1974).
[19] E. Sauvan et al., Phys. Rev. C 69, 044603 (2004).