Abstract. A variety γ-spectroscopy experiments are successfully performed at RIPS, RIKEN. Among them, we report on the proton inelastic scattering on $^{60,62}$Cr. Large quadrupole deformation parameters were obtained showing the enhancement of the collectivity in these nuclei. The perspective in the γ-spectroscopy experiment at RIBF are discussed.

1. Introduction
γ spectroscopy technique has accomplished a variety of fruitful outcome in the structure study of unstable nuclei using fast RI beams. At RIKEN, systematic studies of the excitation energies of low-lying states and the transition probabilities have revealed various peculiar structures in the high isospin nuclei, such as rearrangement of shell structure.

These studies have thus far been performed mostly in the region with the mass number smaller than 40 at the present RI beam facility, RIPS [1]. The limitation on the mass region is mainly due to the difficulties in the production of the unstable nuclei with heavy mass and difficulties of the particle identification (PID) of these nuclei. In order to extend the structure study toward heavier region, a new experimental devices, TOF spectrometer, has been developed, which, together with the recently developed intense $^{70}$Zn and $^{86}$Kr beams, enables us to direct to heavier mass region up to around mass 70. Study of still heavier nucleus will be performed at the next generation facility, RI Beam Factory (RIBF). In this paper, the preliminary results of proton inelastic scattering on $^{60,62}$Cr performed at RIPS and the perspective in the γ-spectroscopy experiment at RIBF are discussed.

2. Proton inelastic scattering on $^{60,62}$Cr with γ-spectroscopy method at RIPS
The Cr isotopes are located in the middle of the proton $f_{7/2}$-shell and thus, would favor collective ground state structure. This preference of protons would be reinforced or suppressed by neutrons depending on the occupation in the neutron orbitals. An interesting question arises how static and dynamic deformation evolves in the Cr isotope chain when the neutron number changes across the neutron $pf$-shell. In the recent experimental studies, level structures of low-lying states have been determined for the neutron rich Cr isotopes up to $A=62$ by β-γ spectroscopy technique [2, 3, 4] and low energy heavy ion induced reactions [5, 6, 7, 8, 9]. As a clear measure of nuclear collectivity, excitation energies of the first $2^+$ states ($E_x(2^+)$) of even-even Cr isotopes are measured up to $^{62}$Cr$_{38}$. The $E_x(2^+)$ value takes a large value at $^{56}$Cr$_{32}$ and monotonically decreases as the neutron number increases toward $N = 38$ ($^{62}$Cr$_{38}$). This decrease was interpreted to mean that the collectivity of Cr is small at $^{56}$Cr reflecting the $N = 32$ sub-shell closure and becomes gradually more collective when the neutron number is increased along
58Cr, 60Cr and 62Cr. The electro-magnetic transition rates between the ground states and the first 2+ states were measured for 54, 56, 58Cr by intermediate energy Coulomb excitation [10]. The reduced transition probabilities (B(E2)) are anti-correlated with E_x(2+) supporting the sub-shell closure at N = 32. The behavior of E_x(2+) in Cr isotopes is contrary to the trend in Ni isotopes, whose E_x(2+) increases when approaching N = 40. The drop of the first 2+ energies are rather similar to that of Fe isotopes but the drop for Cr is much steeper suggesting larger collectivity of Cr isotopes near N = 40 as pointed out in Ref. [3]. The enhancement of the collectivity in Cr isotopes near N = 40 was studied by measuring the quadrupole deformation parameters from the proton inelastic scattering study [11].

The experiment was performed using the projectile fragment separator, RIPS [1] at RIKEN. Secondary beams were produced by the fragmentation of an intense 70Zn beam impinging on a 95 mg/cm² thick Be target at 63A MeV with the typical beam intensity of 150 pnA. PID of the incident beam was made event-by-event by measuring magnetic rigidity (Bρ), time-of-flight (TOF), and energy loss (ΔE) of each nucleus. The intensities of 60Cr and 62Cr were 40 and 34 count per second, respectively.

The secondary beams bombarded a liquid hydrogen target [12] with a thickness of 79 mg/cm² at F3 to induce proton inelastic scatterings. The energies of 60Cr and 62Cr at the middle of the secondary target were 38.7A MeV and 34.1A MeV, respectively. The levels populated by the secondary reactions were identified by the de-excitation γ-rays from the populated excited states and the PID of the reaction residues obtained with the time-of-flight spectrometer (TOF spectrometer).

De-excitation γ rays were measured by a granular array of 160 NaI(Tℓ) scintillators DALI2 [13] placed surrounding the secondary target. The full-energy-peak efficiency was calculated by a Monte Carlo simulation using the GEANT code [18] and was found to be 26% for a 646 keV γ ray emitted from a moving source with a velocity of β = 0.3.

The TOF spectrometer, which is schematically shown in Fig. 1, provided the PID information from TOF-ΔE (atomic number, Z) and TOF-E (mass number, A). The scattered particles were transported by the Superconducting Triplet Quadrupole magnet (STQ) [14] to focus on the detectors located at about 5 m downstream of the target. TOF of the scattered particles were measured between two plastic scintillators placed after the target at the entrance of STQ and at the focal point of STQ. The TOF of ions with E ~34A MeV is ~53 ns. After the plastic scintillator at the focus of STQ, a Si telescope, consisting of 100 μm Si detectors and two layers of 320 μm Si detectors, was mounted to measure the energy loss and total energy of the scattering particles. The atomic number, Z and mass number, A are obtained from TOF-ΔE and TOF-E with resolutions (FWHM) of 1.6% and 1.0%, respectively. From the ion optics simulation using the COSY Infinity code [16], the angular acceptance is found to be 100% for particles with a scattered angle smaller than two degrees, while it gradually decreases to about 30% for particle with the scattering angle 4.5 degrees [17]. In the case of 1H(62Cr,62Crγ) experiment, the overall acceptance of the TOF spectrometer is 95%, where the spatial, angular and momentum spreads

![Figure 1. Schematic view of the TOF spectrometer.](image-url)
of the beam are taken into account.

Figure 2. Doppler corrected γ-ray spectrum for the proton inelastic scattering on $^{60}$Cr (upper panel) and $^{62}$Cr (lower panel).

Figure 2 shows Doppler corrected energy spectra of γ rays measured in coincidence with inelastically scattered $^{60}$Cr (upper panel) and $^{62}$Cr (lower panel). In the spectra, prominent peaks are seen, which correspond to the $2^+_1 \rightarrow 0^+_{gs}$ transitions with the energies of 646 keV and 446 keV observed in the previous study \cite{3}. From the γ-ray yields, the cross sections of the inelastic proton scatterings to the $2^+_1$ states were obtained to be $52 \pm 14$ mb and $58 \pm 10$ mb for $^{60}$Cr and $^{62}$Cr, respectively, where cascade decay contributions from higher excited states were eliminated, which were determined from a γ-γ coincidence analysis. The quadrupole deformation parameters $\beta_2$’s were extracted by a coupled-channel calculation using the ECIS97 code \cite{19} to be $0.37 \pm 0.05$ and $0.38 \pm 0.03$ for $^{60}$Cr and $^{62}$Cr, respectively. In the calculation, the global phenomenological optical parameter set CH89 \cite{20} was used. In order to estimate the uncertainty due to the choice of the optical parameters, calculation with another optical parameter set proposed in Ref. \cite{21} by F.D. Becchetti et al. was also performed. The obtained deformation parameter agrees with the latter value within 2%, which is taken into account as a systematic error.

In order to evaluate the collectivity of $^{60}$Cr and $^{62}$Cr, the obtained $\beta_2$ values are compared with the $\beta_2$ values of neighboring Cr isotopes obtained from $B(E2)$ \cite{10, 23, 24}, as shown in the lower panel of Fig. 3. The two $\beta_2$ values deduced from the different observables are not the same, but give similar measure of nuclear collectivity: $\beta_2$ obtained from $B(E2)$ represents the (static or dynamic) deformation of protons, while $\beta_2$ obtained from the proton inelastic scattering represents the deformation of both protons and neutrons. These two quantities are the same under the assumption that protons and neutrons have the same collectivity. The $\beta_2$ values of $^{60}$Cr and $^{62}$Cr are clearly larger than those of lighter Cr isotopes showing enhanced collectivity in $^{60}$Cr and $^{62}$Cr. This finding is consistent with the decreasing trend of the $E_x(2^+)$ energies as shown in the upper panel of Fig. 3. In Fig. 3, shell model calculations within $pf$-shell \cite{22} and $pfgd$-shell \cite{3} are also shown. The $pf$-shell calculation fails to reproduce the observed $\beta_2$ values of $^{60,62}$Cr, which is consistent with the discussion based on the $E_x(2^+)$ values \cite{3}, that $pf$-space is not sufficient to describe $^{60}$Cr and $^{62}$Cr. By adding $g$- and $d$- shells in the calculation, the results are improved, namely, $E_x(2^+)$’s are decreased and $\beta_2$’s are increased.
However, the improvement of the calculation is not sufficient yet and the observed values show even larger collectivity.

Figure 3. $E_x(2^+)$ energies (upper panel) and $\beta_2$ values (lower panel) of Cr isotopes. The $\beta_2$ values of Cr with $A \leq 58$ are calculated from $B(E2)$ [10, 23, 24], while those of $^{60}$Cr and $^{62}$Cr are from proton inelastic scattering cross section obtained in this work. Dashed line and dot dashed line are shell model calculations of $E_x(2^+)$ and $\beta_2$ with the $pf$-shell [22] and $pfgd$-shell [3].

3. $\gamma$-spectroscopy at BigRIPS

The RI Beam Factory (RIBF) is a next generation facility for radioactive isotope beams, which will extend the capability of the RI beam experiments toward more neutron rich and heavier region. A high-power heavy-ion booster system consisting of three ring cyclotrons will be newly constructed to provide intense heavy-ion primary beams, such as, $^{48}$Ca, $^{86}$Kr, $^{136}$Xe or $^{238}$U with the typical energy 350$A$ MeV. The primary beams will be converted to RI beams using an in-flight fragment separator, BigRIPS. It is designed to achieve efficient collection of fragments produced not only by projectile fragmentation reactions but also by in-flight fissions. As a result of the success of the RI beam experiments performed so far at RIPS and other RI beam facilities all over the world, a variety of experiments are proposed. Among them, the importance of the study of bound states would be increased, since the locations of neutron or proton drip lines become farther from the stability line as the objective nuclei becomes heavier. For these studies $\gamma$-spectroscopy is one of the most promising experimental techniques.

The experimental apparatus or methods developed in the present facility can basically be applied to the experiments to be performed at the new facility, but several modifications should be made to optimization to the experiments with higher energy beams. For the $\gamma$-ray detection, present $\gamma$-ray detectors, such as NaI array, DALI2 [13], or Ge array GRAPE [26] will be used with a small modification to maximize the detection efficiencies and energy resolutions. When the beam energy becomes higher, the emitted $\gamma$-rays are more largely affected by the Doppler shift. Therefore, more precise determination of the $\gamma$-emission angle are required, which will be realized by increasing the distance between the target position and the detector. The $\gamma$-ray emitted from higher energy beam will be more boosted toward forward angle and thus the total efficiency will be increased by the reinforcement of the detectors at forward angle.
For the PID of reaction residues, several devices are considered. The ZeroDegree spectrometer provides a high resolution and relatively large acceptance, which is indispensable for the PID of heavy mass nuclei or high resolution momentum analysis of the ejectiles to extract nuclear structure information in secondary reactions such as nucleon knockout reactions. Figure 4 schematically shows the layout of BigRIPS and the ZeroDegree spectrometer. The eighth focal plane (F8) is the target position of the ZeroDegree spectrometer, where a secondary target and γ-ray detectors will be placed. The reaction residues will be transported to the focal plane of the ZeroDegree spectrometer (F11) through two dipole magnets. The ZeroDegree spectrometer has several operation modes and in the case of the highest resolution mode, first order resolving power of 4000 will be obtained. γ-spectroscopy with heavy mass nuclei would be made with the ZeroDegree setup. One of the examples is the neutron rich N ∼ 82 or N ∼ 126 nuclei, which are relevant to the second and third peaks of the r-process abundances. The neutron rich nuclei around Zr or Dy regions are also of great interest, since exotic deformation modes are theoretically predicted.

Another option for PID is to use TOF as in the RIPS experiment discussed above. Because the TOF spectrometer does not use dipole magnets, nuclear species with various charge to mass ratio (A/Z) are accepted, so that many reaction residues produced by secondary reactions can be studied simultaneously. This is advantageous in the BigRIPS experiment, where cocktail beams with many nuclear species will mostly be used. The importance of the large “A/Z acceptance” is emphasized in the proton target experiment, because in the case of proton induced reactions, many reaction channels such as inelastic scattering, on or a few nucleon knockout channel, or charge exchange reactions, have comparable cross sections and all these reaction channel can be observed simultaneously. Its resolution is not as good as the resolution available with ZeroDegree, though mass number smaller than 100 can be reasonably well resolved. Therefore, for the experiment with nuclei lighter than mass number about 100, the TOF spectrometer would be appropriate. The beam line between F8 and F12 will be used as the TOF spectrometer. The secondary target and the γ-detectors will be placed at F8, the same place as the ZeroDegree target position. The scattered particles will be transported to F12, where TOF, ΔE, and E...
detectors will be placed. With the TOF spectrometer setup, proton inelastic scattering on the nuclei $^{78}$Ni or $^{54}$Ca are promising.

The commissioning of RIBF will start at the end of 2006 and experiments will start in 2007.

4. summary
At the present RI beam facility RIPS, effort to perform the $\gamma$-ray experiment on more neutron rich and heavier nuclei are being made. One of such experiments is the proton inelastic scatterings on $^{60}$Cr and $^{62}$Cr. The obtained $\beta_2$ values are larger than those of the lighter Cr isotopes, $^{54,56,58}$Cr, which is consistent with their small $E_x(2^+)$ values. This is the indication of the enhancement of collectivity in the Cr isotopes near the $N \sim 40$ region.

The $\gamma$-spectroscopy experiment will be extended toward more neutron rich and heavier region at the next generation RI beam facility, RIBF. At RIBF, various experiments using $\gamma$-spectroscopy technique are planned, which will start soon in 2007.

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