Spin-isospin responses studied with RI-beams

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Abstract. In light of availabilities of a variety of radioactive isotope (RI) beams and progress in physics of unstable nuclei, new possibilities in experimental studies of spin-isospin responses are foreseen. They include: 1) studies of spin-isospin responses of unstable nuclei, 2) studies of higher multipoles, in particular spin-dipole responses, 3) studies of higher tones, such as isovector monopole resonances, and 4) studies of many phonon states. In this article, we discuss how the study of spin-isospin responses will be proceeded, taking examples from experiments with the SHARAQ spectrometer at RI Beam Factory and with the Grand Raiden spectrometer at Research Center for Nuclear Physics, Osaka University.

1. Introduction
Charge exchange reactions at intermediate energies can extend studies of nuclear spin-isospin responses to higher excitation energies that are out of the reach of $\beta$-decay experiments[1, 2, 3]. Rich information on nuclear structure, correlations in nuclei[4], nuclear matter properties, and quantities needed to understand astrophysical phenomena[5] has been obtained through experimental studies of spin-isospin responses. In particular, experiments with light-ion induced reactions, such as $(p,n)$, $(d,^3\text{He})$, and $(^3\text{He},t)$ reactions, have been carried out intensively, with some emphases on Gamow-Teller (GT) transitions that are characterized by $\Delta n=0$, $\Delta L=0$, $\Delta S=1$, and $\Delta T=1$. Here $\Delta n$, $\Delta L$, $\Delta S$, and $\Delta T$ are changes of a principal quantum number, orbital and spin angular momenta, and isospin. The experimental data bring about reasonable understanding of GT transitions in stable nuclei.

On the other hand, availability of RI-beams has increased rapidly since 1990’s and has brought intense attention of nuclear scientists to physics of unstable nuclei. RI Beam Factory (RIBF) at RIKEN[6, 7, 8] is a new-generation RI-beam facility that can provide highly-intense RI beams by means of fragmentation reactions of heavy-ion beams and by in-beam fission of an uranium beam.

In light of availabilities of a variety of RI-beams and progress in physics of unstable nuclei, new possibilities in experimental studies of spin-isospin responses are foreseen. They include:

(i) Spin-isospin responses of unstable nuclei
(ii) Studies of higher multipoles ($\Delta L=1,2,...$)
(iii) Studies of higher tones ($\Delta n \geq 1$)
(iv) Studies of many phonon states

Case 1 is a straightforward extension of studies with the light-ion beams on stable targets, while cases 2–4 are not. In cases 2–4, RI-beam induced charge exchange reactions with unique...
capabilities which are missing in stable-beam induced reactions are used to reveal new aspects of spin-isospin responses in nuclei. The capabilities of RI-beam induced charge exchange reactions are based on

- A variety of selectivities in transferred quantum numbers, $\Delta S$, $\Delta T$, $\Delta T_z$, $\Delta L$ etc, and
- Kinematical conditions which can not be reached via the stable-beam induced reactions.

We have constructed the high-resolution SHARAQ spectrometer [9] and the dedicated beam-line [10] at RI Beam Factory to proceed studies of spin-isospin responses with RI-beams. The ion-optical system is designed to achieve a momentum resolution of $\Delta p/p = 1/14700$ and an angular resolution of $\Delta \theta \sim 1$ mrad for RI-beams with a momentum spread of $\pm 0.3\%$. The performances facilitate missing-mass spectroscopy experiments with RI-beams.

In this article, we discuss how the study of spin-isospin responses will be proceeded in light of the availability of RI-beams and/or of physics of unstable nuclei, putting emphasis on experiments with the SHARAQ spectrometer.

2. Spin-isospin responses of unstable nuclei

The $(p,n)$ reaction study of unstable nuclei was initiated in late 1990’s at RIKEN. In the first experiment with a $^{11}$Li beam, Teranishi and his collaborators succeeded in observing an isobaric analog state of the $^{11}$Li ground state in an invariant mass spectrum of neutrons and a heavy residue[11]. The invariant mass method were applied to $(p,n)$ reactions studies of other drip-line nuclei[12, 13].

The invariant mass method is attractive in that it enables a high excitation energy resolution even in experiment with a thick target. On the other hand, it has weak points that it is not sensitive to bound excited states and an experimental acceptance at high excitation energies can not be so large. The latter would prevent one from investigating giant resonances locating at excitation energies higher than 10 MeV. Thus a missing mass approach is definitely needed.

Recently, new neutron detection setups for the missing mass spectroscopy with an inverse-kinematics $(p,n)$ reaction have been developed by the Michigan State University group and by the Tokyo-RIKEN group. The Michigan group has applied the setup called LENDA[14] to extract Gamow-Teller strengths in $^{56}$Ni[15, 16] which is of astrophysical importance.

At RI Beam Factory, the $^{12}$Be$(p,n)^{12}$B experiment at 200 MeV/nucleon has been performed[17] with the newly-developed neutron detector array WINDS[18]. The GT transitions to the ground and excited states at around 10 MeV in $^{12}$B are clearly observed. The experimental technique established here will furnish excellent opportunities to investigate GT and higher multipole strengths in unstable nuclei.

3. Higher multipoles: search for collective spin-dipole $0^-$ resonances

Study of spin-isospin responses with higher multipoarities, $\Delta L \geq 1$, is another interesting subject. Spin-dipole (SD) states excited with $\Delta L = 1$, $\Delta S = 1$, and $\Delta J = 0^-, 1^-, 2^-$, attract recent theoretical attention due to its strong relevances to tensor-force effects. For example, self-consistent HF+RPA calculations in Ref. [19] predict that the tensor correlations cause hardening of the collective $0^-$ resonance, resulting in a shift of the strength toward higher excitation energy. It is also predicted that the effect is sensitive to the magnitude of tensor strength. Thus experimental data of the SD $0^-$ distribution enables us to quantitatively examine the tensor correlation effects in nuclei.

In spite of its interesting properties described above, experimental information on $0^-$ states is limited. This is because, as a recent polarization transfer experiment for the $^{208}$Pb$(p,n)$ reaction shows[20], $0^-$ states are populated only weakly compared with $1^-$ and $2^-$ states and they are strongly fragmented over a wide range of excitation energy. A well-suited experimental tool to probe the $0^-$ states is definitely desired.
Dozono and his collaborators propose a new experiment with the parity-transfer \((^{16}\text{O},^{16}\text{F}(0^-))\) reaction\(^{21}\). The parity-transfer reaction uses \(0^+ \rightarrow 0^-\) transition in the projectile to probe \(0^-\) states in a target nucleus. This reaction has a unique sensitivity to unnatural parity states, which is an advantage of the parity-transfer reaction over other reactions used so far. The first experiment for a \(^{12}\text{C}\) target is planned with the SHARAQ spectrometer in 2014.

4. Higher tones: isovector monopole resonances

It is well known that an isoscalar giant monopole resonance (ISGMR) is an oscillation mode of (isoscalar) density and can be related to the incompressibility of nuclear matter\(^{22}\). Microscopically, on the other hand, ISGMR comprises coherent particle-hole excitations with \(\Delta n = 1, \Delta L = \Delta S = 0\).

Isovector analogies of ISGMR are an isovector monopole resonance (IVGMR) and an isovector spin monopole resonance (IVSGMR). By the analogy, IVGMR (IVSGMR) is considered to be an oscillation mode of isovector (isovector spin) density (see Fig. 1) and can be related to (spin-) isospin properties of nuclear matter. IVGMR and IVSGMR are regarded as higher tones \((\Delta n = 1)\) of an isobaric analogue resonance and a giant Gamow-Teller resonance with \(\Delta n = 0\).

![Figure 1. Isoscalar and isovector monopole resonances.](image)

Although IVGMR and IVSGMR were observed in several previous experiments\(^{23, 24}\), our knowledge on the resonances were still poor when compared with that on IAS and GT resonances. The first series of experiments with the SHARAQ spectrometer were performed to extract new information of IVSGMR and IVGMR.

4.1. \((t,^3\text{He})\) reaction

The \((t,^3\text{He})\) reaction is the most established RI-beam induced charge exchange reaction. It has been used to investigate \(\beta^+\) strengths in nuclei at 115 MeV/nucleon\(^{25}\) and at lower energies. Effectiveness of the reaction in investigating isovector spin-flip strengths in nuclei should be more emphasized at the RIBF energy of \(\sim 300\) MeV/nucleon, because \(\sigma\tau\)-modes are most strongly populated and nuclear distortion effects are the weakest at the energies.

The first \((t,^3\text{He})\) experiment with the SHARAQ spectrometer was performed to search for \(\beta^+\)-type IVSGMR in \(^{90}\text{Zr}\) and \(^{208}\text{Pb}\)\(^{26}\). A 300-MeV/nucleon triton beam with an intensity of \(10^7\) sec\(^{-1}\) was produced by the projectile fragmentation of a primary 320-MeV/nucleon \(^4\text{He}\) beam on a 4-cm thick beryllium target and was irradiated onto the secondary targets. The scattered \(^3\text{He}\) ions were momentum-analyzed by the SHARAQ spectrometer.

Red histograms in the upper panels of Fig. 2 show the monopole \((\Delta L = 0)\) cross section for the \(^{208}\text{Pb}, ^{90}\text{Zr}(t,^3\text{He})\) reactions. The monopole cross section is deduced by the multipole
decomposition analysis. Yellow histograms overlaid on the \((t, {}^3\text{He})\) cross section present cross section for the \((p, n)\) reaction. Since a nucleon can penetrate more deeply in the target nucleus than a triton, strong cancellation of the transition amplitude takes place in the case of IVSGMR. Thus the \((p, n)\) cross section is considered to be dominated by GT strengths. Thus, enhancement of the \((t, {}^3\text{He})\) cross section over \((p, n)\) observed in Fig. 2 is considered to be a clear signature of IVSGMR. The monopole strength is compared with HF-RPA calculations in the lower panels of Fig. 2. The theoretical calculations reasonably reproduce the experimental data.

Figure 2. Monopole cross sections of the \(^{90}\text{Zr}({}^3\text{He})\) reaction (red), together with those of the \((n, p)\) reactions (yellow). Reprinted from Ref. [26]. Copyright (2012) by the American Physical Society.

In 2010, two experiments were carried out to reveal different aspects of IVGMR and IVSGMR. One was the \(^7\text{Li,}{}^{90}\text{Zr}(^{10}\text{C,}^{10}\text{B}(0^+;\text{IAS}))\) experiment to search for IVGMR[27]. The \((^{10}\text{C,}^{10}\text{B}(0^+;\text{IAS}))\) reaction with a unique selectivity to isovector (\(\Delta T = 1\)) non-spin-flip (\(\Delta S = 0\)) modes was employed in the experiment. In the Doppler-corrected gamma-ray spectrum, the 1.022-MeV peak that is a signature of \(\Delta S = 0\) transitions is clearly observed[27]. The other was the \(^{90}\text{Zr}(^{12}\text{N,}^{12}\text{C})\) experiment aiming at populating IVSGMR with a small momentum transfer. In the experiment, the RI-beam induced \((^{12}\text{N,}^{12}\text{C})\) reaction with a large positive \(Q\) value (\(Q = +17\) MeV), which we call the exothermic charge exchange reaction, was used to populate the high-lying \(\beta^-\)-IVSGMR in a recoilless manner. Since IVSGMR is strongly excited when an accompanied momentum transfer is small, prominent strength is expected to be observed by the exothermic reaction. Preliminary results show that the cross section ratio of IVSMR to GT is largely enhanced in the \((^{12}\text{N,}^{12}\text{C})\) compared to the \((p, n)\) reaction[28].

5. Many phonon states: search for double GT resonances and spectroscopy of unstable nuclei

Double charge exchange (DCX) reactions can be unique spectroscopic tools through which we can transfer quantum numbers by an amount of two to a target nucleus. Their obvious applications are population of multi-phonon excitation in nuclei and spectroscopy of unstable nuclei.

Among possible multi-phonon excitations, double Gamow-Teller resonances (DGTR)[29] are of particular interest, partly because of its relevance to double beta decay processes and partly because of the fact that it is remained to be discovered. Attempts to find DGTR via the heavy
double charge exchange reactions were made at GANIL/MSU and at RCNP by using the \((^{18}\text{O},^{18}\text{Ne})\)[30] and \((^{11}\text{B},^{11}\text{Li})\)[31] reactions, respectively, but no clear evidence was found so far.

Another application of double charge exchange reaction is a spectroscopic study of light unstable nuclei. Through DCX, we can easily access to neutron/proton-rich nuclei even with stable-beam induced reactions. Prior to RI-beam experiments, we carried out an experimental program with DCX reactions at Research Center for Nuclear Physics, Osaka University, aiming at establishing DCX reactions as spectroscopic tools. In the first experiment, the \((\beta^+)^2\)-type DCX \(^{12}\text{C}(^{18}\text{O},^{18}\text{Ne})\) reaction at 80 MeV/nucleon were used to investigate structure of the neutron-rich \(^{12}\text{Be}\) nucleus[32]. In the missing mass spectrum, three peaks corresponding to the ground and excited states of \(^{12}\text{Be}\) were clearly observed.

In 2012, an experiment to search for tetraneutron states via the DCX \(^4\text{He}(^{8}\text{He},^{8}\text{Be})\) reaction has been conducted with the SHARAQ spectrometer[33]. The exothermicity of the \((^{8}\text{He},^{8}\text{Be})\) reaction is advantageous in populating the fragile tetraneutron states from the \(^4\text{He}\) target. The experiment at SHARAQ is expected to present decisive information on the nature of tetraneutron states. Another RI-beam induced \((\beta^-)^2\)-type DCX reaction, the \((^{10}\text{C},^{10}\text{Be})\) reaction, which accompanies momentum transfer as small as 10–30 MeV/c at around 0-degrees will be an innovative probe to DGTR in future.

### 6. Summary

Possibilities of new experimental studies of spin-isospin responses are discussed. In studies of spin-isospin responses of unstable nuclei, the missing mass spectroscopy with an inverse-kinematics \((p,n)\) reaction will play a central role in future experiments. New neutron detection setups, LENDA at MSU and WINDS at Tokyo-RIKEN will be widely used to investigate GT and SD strengths in unstable nuclei. One of the main topic in studies of higher multipoles should be detailed study of the \(0^-\) strength. The parity-transfer \((^{16}\text{O},^{16}\text{F}(0^-))\) reaction will serve as a unique probe to \(0^-\). It has been shown that the RI-beam induced charge exchange reactions, \((t,^{3}\text{He})\), \((^{10}\text{C},^{10}\text{B}(0^+))\), \((^{12}\text{N},^{12}\text{C})\), are quite useful in observing IVSGMR and IVGMR in nuclei. Use of DCX reaction will be the next step to proceed.

### Acknowledgements

The present work was partly supported by the Grant-in-Aid for Scientific Research (Nos. 17002003 and 19204024) by the Ministry of Education, Culture, Sports, Science and Technology of Japan. The authors also thank the JSPS Core-to-Core program.

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