Measurement of
the Isovector Spin Monopole Resonance
via the $^{208}$Pb, $^{90}$Zr($t$, $^3$He) Reactions at 300 MeV/u

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Abstract. The isovector spin monopole resonances (IVSMR) of the $^{208}$Pb and $^{90}$Zr($t$, $^3$He) reactions at 300 MeV/u. The experiment was performed at the RIBF by using the newly-constructed magnetic spectrometer SHARAQ. The double differential cross sections for the $^{208}$Pb and $^{90}$Zr($t$, $^3$He) reactions were obtained at the excitation energy of $0 \leq E_x \leq 70$ MeV and the scattering angles of $0 \leq \theta \leq 3\degree$. The monopole component was obtained as a difference between the zero-degree and backward-angle spectra. The signatures for the IVSMR were discovered at excitation energies of 12 MeV in $^{208}$Pb and 20 MeV in $^{90}$Zr, respectively, and they show good correspondences to the theoretical predictions.

1. Introduction

The isovector spin monopole resonance (IVSMR) has been an important topic of interest in the study of spin-isospin responses in nuclei [1–4]. The operator for the IVSM mode is defined as $O_{\mu} = \sum_i \sigma_{\mu}(i)\tau_{\pm}(i)$, which induces the changes of the orbital angular momentum $\Delta L = 0$, the spin angular momentum $\Delta S = 1$ and the isospin $\Delta T = 1$. The Gamow-Teller (GT) transition also has the same changes, but the GT transition is $\partial \omega$ while the IVSM is $2\omega$. An interesting feature of the $r^2$ dependence of the transition operator is that model independent sum rule of IVSM is sensitive to the difference of the proton and neutron distributions. The sum rule is written as, $S_+ - S_- = 3[Z(r^4)_p - N(r^4)_n]$, where $S_-$ ($S_+$) is the total IVSM strength for the
\( \beta^- (\beta^+) \) direction. Therefore, if the sum-rule value is experimentally obtained, it would give a constraint to the equation of state of neutron matter similar to that given by the neutron skin thickness. In spite of the importance of the IVSMR, it has not been clearly identified, especially for the \( \beta^+ \) type.

The \((t, ^3\text{He})\) reaction at 300 MeV/u is an effective probe to observe the IVSMR \((\beta^+)\) for three reasons. Firstly, at the incident energy of 300 MeV, the spin-isospin excitation can be selectively and reliably extracted, because the isovector spin-flip excitation is about 15 times more populated than that of non-spin-flip type [5].

The second point is the surface sensitivity of triton and \(^3\text{He}\) particles [1, 3, 6]. The transition density of IVSM has a radial node and its volume integral is zero. This makes the cross section small for the nucleonic reactions such as \((p, n)\) or \((n, p)\), because they penetrate deeply into the target nuclei and probe the entire volume part of transition density. Actually, an existing spectrum of the \((n, p)\) reaction [7] did not show evidence for the IVSMR \((\beta^+)\). On the other hand, the composite particles, such as triton or \(^3\text{He}\), are strongly absorbed by a large imaginary part of the optical potential and therefore they are sensitive only to the surface region of target nuclei. Thus they may have significant cross sections for IVSMR compared to the nucleonic probes.

Thirdly, excitations other than IVSM, especially the GT transition, are hindered in the \( \beta^+ \) channel due to the Pauli-blocking effect. Furthermore, in heavy nuclei such as \(^{208}\text{Pb}\), the spin dipole excitations are also hindered owing to a large neutron excess as shown in Fig. 4. Hence one may obtain a clear signature of IVSMR in the \( \beta^+ \) channel.

For these reasons, the \(^{208}\text{Pb}\) and \(^{90}\text{Zr}(t, ^3\text{He})\) measurements at 300 MeV/u was performed at RI Beam Factory at RIKEN, which is the only facility where the triton beams above 200 MeV/u are readily available. It should be noted that this is the first physics experiment performed with the newly-constructed SHARAQ spectrometer [8].

2. Experiment
A schematic picture of the experimental setup is shown in Fig. 2. A primary \( \alpha \) beam was accelerated up to 320 MeV/u and was fragmented by a \(^9\text{Be}\) production target (thickness: \( d = 4 \text{ cm} \)) installed at the starting point (F0) of the BigRIPS separator [9]. The produced tritons of 300 MeV/u were transported along the high-resolution beam line to the secondary target installed at the pivot of the SHARAQ spectrometer. The SHARAQ facility was not operated in the high-resolution dispersive mode but in the achromatic mode because of the requirement for the large statistics. In order to improve the resolution of the excitation energy
and the scattering angle, the emittance of the secondary beam was reduced by a momentum slit $(|Δp/p| < 0.06\%)$ at F1 and an angular collimator $(|Δθ| < 15\text{ mrad})$ at F2. They corresponded to a beam-energy spread of 2 MeV (FWHM) and an angular spread of 7 mrad (FWHM) at the secondary target position. The beam intensities were typically 300 particle nA for the primary beam and $1 \times 10^7$ cps for the secondary tritons. The purity of the triton beam was better than 99%. This is because no other particle has the same momentum-to-charge ratio $(p/Q = 2.4 \text{ GeV/c})$ at the energy due to kinematic restrictions.

The secondary targets used were $^{208}\text{Pb}$ ($d = 0.35 \text{ mm}$) and $^{90}\text{Zr}$ ($d = 0.46 \text{ mm}$) foils for the IVSMR measurements and a CH$_2$ ($d = 0.5 \text{ mm}$) foil for calibrations. The $^3\text{He}$ particles in the reaction products were momentum analyzed by the SHARAQ spectrometer and counted by cathode-readout drift chambers [10] installed in the final focal plane of the SHARAQ spectrometer, and finally identified by the energy-loss in the focal plane scintillators. The differential cross sections were measured at an excitation energy of $0 ≤ E_x ≤ 70 \text{ MeV}$ and scattering angles of $0° ≤ θ ≤ 3°$.

The blank-target run was also performed for the background estimation. The distribution of the background component had no structures and the count rate was negligibly small (less than 0.1%) compared to $^{208}\text{Pb}$ and $^{90}\text{Zr}$ runs.

Figure 3 shows the measured CH$_2(t,^3\text{He})$ spectra. The left panel shows the XY spectrum measured in the focal plane of the SHARAQ spectrometer. $X_{FP}$ and $Y_{FP}$ are proportional to the momentum and the vertical scattering angle of the $^3\text{He}$ particles, respectively. Two main loci can be identified in the figure; these are attributed to the $^1\text{H}(t,^3\text{He})n$ and $^{12}\text{C}(t,^3\text{He})^{12}\text{B}$ [g.s.] reactions. A kinematic correlation due to the recoil of target protons is observed for the $^1\text{H}(t,^3\text{He})$ reaction. A projection of this picture is shown in the right panel. From the distance between the two observed peaks, the dispersion of the SHARAQ spectrometer is determined to be 6.10 m, which is close to the design value of 5.86 m [8]. The energy resolution obtained
Figure 3. The obtained image at the SHARAQ focal plane for the polyethylene target [left] and its projection [right].

from the $^{12}$C($t$, $^3$He)$^{12}$B [g.s.] peak is about 2 MeV (FWHM), which is consistent with the beam-energy spread.

3. Results
The obtained $^{208}$Pb($t$, $^3$He) spectra are shown in the top panel of Fig. 4. Two peaks are observed at $E_x = 5$ MeV and 15 MeV. Since the angular distribution for the monopole transition has its maximum at 0 degrees, we extracted the monopole component by subtracting the $0.5^\circ - 1.0^\circ$ spectrum from that of $0^\circ - 0.5^\circ$ as a preliminary analysis. The obtained difference spectrum is shown in the bottom panel of Fig. 4. A significant amount of the monopole component is observed at $E_x = 12$ MeV with a width of $\Gamma = 9$ MeV, which would be attributed to the IVSMR. The broken line and the dot-broken line represent the Tamm-Dancoff approximation (TDA) calculations using the effective interaction SGII and SIII, respectively [1]. The calculations are normalized so that they fit to the experimental data. It is found that both calculations reproduce the overall shape. A monopole component is discovered also in the $^{90}$Zr($t$, $^3$He) spectrum at $E_x = 20$ MeV with a width of $\Gamma = 11$ MeV as shown in Fig. 5, and the TDA predictions show a similar agreement as in the $^{208}$Pb case.

In the future analysis, the monopole cross sections will be precisely extracted via the multipole decomposition technique [5], which will allow us to discuss the detailed structure of the IVSMR.

[1] Hamamoto I and Sagawa H 2000 Phys. Rev. C 62 024319
[2] Auerbach N and Klein A 1984 Phys. Rev. C 30 1032
[3] Prout D L et al. 2000 Phys. Rev. C 63 014603
[4] Zegers R G T et al. 2003 Phys. Rev. Lett. 90 202501
[5] Ichimura M, Sakai H and Wakasa T 2006 Prog. Part. Nucl. Phys. 56 446
[6] Auerbach N, Osterfeld F and Udagawa T 1989 Phys. Lett. B 219 184
[7] Moinester M A et al. 1989 Phys. Lett. B 230 41
[8] Uesaka T et al. 2008 Nucl. Instr. Meth. B 266 4218
[9] Kubo T 2003 Nucl. Instr. Meth. B 204 97, and Kubo T et al. 2007 IEEE Trans. Appl., Supercond. 17 1069
[10] Michimasa S et al. 2009 RIKEN Accel. Prog. Rep. 42 177
Figure 4. (preliminary) The double differential cross section spectra for the $^{208}\text{Pb}(t,^3\text{He})$ reaction [top] and their difference spectrum [bottom]. A monopole component was discovered at $E_x = 12$ MeV with a width of $\Gamma = 9$ MeV. Theoretical calculations are taken from Ref. [1].

Figure 5. (preliminary) Same as Fig. 4 but for the $^{90}\text{Zr}(t,^3\text{He})$ reaction. A monopole component was discovered at $E_x = 20$ MeV with a width of $\Gamma = 11$ MeV. (The peak at $-1.5$ MeV on the top panel is due to hydrogen contaminants in the $^{90}\text{Zr}$ foil. The dip around 4 MeV on the bottom panel is due to $L \geq 1$ components.)