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# In-beam $\gamma$-ray spectroscopy of $^{38,40,42}$Si

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**Abstract.** Excited states in the nuclei $^{38,40,42}$Si have been studied using in-beam $\gamma$-ray spectroscopy following multi-nucleon removal reactions to investigate the systematics of excitation energies along the $Z$=14 isotopic chain. The most probable candidates for the transition from the yrast $4^+$ state were tentatively assigned among several $\gamma$ lines newly observed in the present study. The energy ratios between the $2^+_1$ and $4^+_1$ states were obtained to be 2.09(5), 2.56(5) and 2.93(5) for $^{38,40,42}$Si, respectively, indicating a rapid development of deformation in Si isotopes from $N$=24 to, at least, $N$=28.

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## 1 Introduction

One of the most predominant properties of nuclei is nuclear shell structure, and the resultant "magic number" (2, 8, 20, 28, ...) have been provided experimentally by systematic behaviors of physical properties, such as quadrupole transition strengths $B(E2)$ and excitation energies of the first $2^+$ state $E_x(2^+_1)$ [1]. However, it is now well established that magic numbers are not universal and develop in the region far from stability line. One of well-known examples is the case of the neutron-rich isotope $^{32}$Mg, where the low energy $E_x(2^+_1)$ and large $B(E2)$ indicate shell quenching despite of a conventional magic number $N$=20 [2, 3]. It is a fundamental and open question whether and how the changes of the major shell closures and magic numbers occur along the nuclear chart.

The $N$=28 isotope, $^{42}$Si, can be regarded as a magic nucleus in the traditional shell model, because a large energy gap exists at $N$=28 and $Z$=14 due to the $f_{7/2} - f_{5/2}$ and $d_{5/2} - d_{3/2}$ spin-orbit splitting, respectively. The disappearance of the spherical shell closure together with a large deformation, however, has been suggested for $^{42}$Si from the observation of a low energy $2^+_1$ state [4]. Several experiments have been performed so far [5–10], but no experimental data have been reported on higher-lying state, such as $4^+_1$ state, which may contribute valuable information on the nature of the collectivity and/or shell evolution.

## 2 Experiment

In order to investigate the $2^+_1$ and $4^+_1$ states, we performed in-beam $\gamma$-ray spectroscopy of $^{38,40,42}$Si with multi-nucleon removal reactions [11]. Experiment was carried out at the RI Beam Factory accelerator complex operated by the RIKEN Nishina Center and CNS, University of Tokyo. The $^{40}$S and $^{44}$S beams were produced by a projectile fragmentation reaction of a $^{48}$Ca primary beam with a typical intensity of around 70 pnA. The primary beam with the energy of 345 MeV/nucleon bombarded a 15 mm-thick rotating Be target located at the F0 focal plane of the in-flight RI beam separator BigRIPS [12]. The energy and intensity of the secondary $^{40}$S ($^{44}$S) beam were approximately 210 MeV/nucleon (210 MeV/nucleon) and around $4\times10^4$ particles per second (pps) ($6\times10^4$ pps), respectively. The secondary beams bombarded a reaction target of 2.54 g/cm$^2$-thick carbon located at the F8 focal plane in the ZeroDegree Spectrometer [13], which was employed to analyze the reaction products $^{38}$Si and $^{40,42}$Si produced by the multi-nucleon removal reaction of $^{40}$S and $^{44}$S, respectively. De-excitation $\gamma$-rays were detected by the DALI2 $\gamma$-ray spectrometer [14] in coincidence with each beam and scattered particles.

## 3 Experimental Results

The Doppler-shift corrected $\gamma$-ray energy spectra obtained for $^{38}$Si, $^{40}$Si and $^{42}$Si are shown in Fig. 1. As shown in Fig. 1 (c), the $2^+_1 \rightarrow 0^+_{g.s.}$ transition in $^{42}$Si, previously observed at 770(19) keV [4], is measured here at 742(8) keV with high statistics, while three weaker $\gamma$-ray transitions with energies of 1431(11), 2032(9) and 2357(15) keV are reported for the first time. Using $\gamma$-$\gamma$ coincidences and $\gamma$-ray relative intensities, the 1431-keV line was deduced to fully feed the $2^+_1$ state from a higher-lying excited state at 2173 keV. On the other hand, yield of the 2357-keV transition in $\gamma$-$\gamma$ coincidence spectrum indicated that it does not, or at least does not fully, populate the $2^+_1$ state at 742 keV. The present study indicates no direct evidence for firm spin assignments. However, the 1431-keV $\gamma$ line was tentatively assigned as the $4^+_1 \rightarrow 2^+_1$ transition in $^{42}$Si based on the fact that yrast states are preferentially populated for isotopes in this mass region via multi-nucleon removal reactions [15–17] and it directly feeds the $2^+_1$ state, as mentioned above. Similar analytical techniques were applied $^{38}$Si and $^{40}$Si. The 1168(22)- and 1539(16)-keV $\gamma$ lines, as shown in Fig. 1 (a) and (b), were obtained as the most probable candidates for the $4^+_1 \rightarrow 2^+_1$ transitions in $^{38}$Si and $^{40}$Si, respectively.

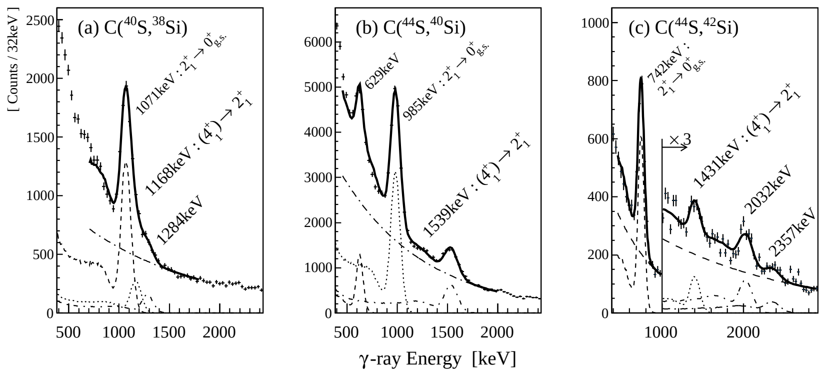


**Figure 1.** Doppler-shift corrected $\gamma$-ray energy spectra obtained in coincidence with (a) C($^{40}$S,$^{38}$Si), (b) C($^{44}$S,$^{40}$Si) and (c) C($^{44}$S,$^{42}$Si) reactions.

## 4 Discussion and Summary

The isotopic dependence of the excitation energy of $2^+_1$ and $4^+_1$ states are shown for $^{34-42}$Si together with their ratio $R_{4/2}$ in Fig. 2, where the systematic properties of Ca isotopes are also given for the comparison. In the Ca isotopic chain, the relatively high energy $2^+_1$ state clearly demonstrates the persistence of the conventional neutron magic number at $N$=28 as well as $N$=20. The depressed $R_{4/2}$ ratios at the both neutron magic numbers are much smaller than 2, showing the spherical nature of $^{40}$Ca and $^{48}$Ca, and supporting the above perception from the $2^+_1$ state. In contrast, Si isotopes, with a lack of six protons from Ca isotopes, show different behaviors. The continuous decrease of $E_x(2^+_1)$ indicates the enhancement of nuclear collectivity from $N$=20 to $N$=28. The lowest energy $2^+_1$ state, 742 keV observed in $^{42}$Si, suggests the disappearance of its magic nature and the deviation from the conventional shell model scheme. As for the $4^+_1$ state, the $R_{4/2}$ ratios for $^{36}$Si and $^{38}$Si are close to the vibrational limit (2.00), whereas it increases to 2.56(5) at $^{40}$Si, indicating a deviation from the spherical shape at $N$=26. In the case of the $N$=28 isotope $^{42}$Si, the $R_{4/2}$ ratio further increases to 2.93(5) despite the neutron magic number $N$=28, indicating a well-deformed ground state property of $^{42}$Si. These results on Si isotopes are in good agreement with the prediction of the shell model calculations using SDPF-MU [18, 19] and SDPF-U-MIX [20, 21] effective interaction, which are denoted by solid and dashed line in Fig. 2, respectively.

In summary, the excited $4^+_1$ states in $^{38,40,42}$Si were tentatively assigned in the present study of in-beam $\gamma$-ray spectroscopy following multi-nucleon removal reactions [11]. The results on $^{42}$Si demonstrate the magicity loss together with a well-deformed ground state structure, which have been suggested in previous work [4], while the $R_{4/2}$ systematics indicate a rapid development of deformation from the $N$=24 isotope $^{38}$Si to the $N$=28 isotope $^{42}$Si.

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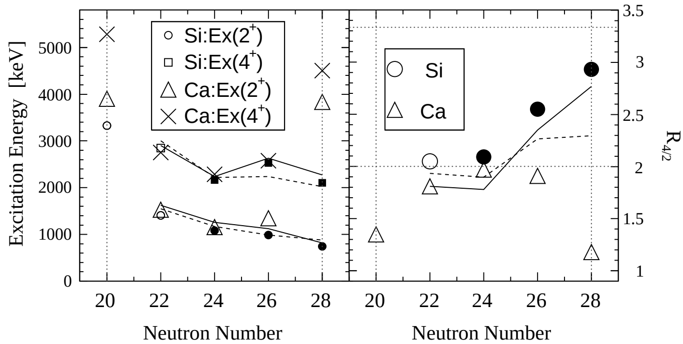


**Figure 2.** The energy of $2_1^+$- and $4_1^+$ state (left panel), and its ratio (right panel) of Si isotopes are compared with Ca isotopes. Filled symbols are results obtained from the present study. Solid and dashed lines show the prediction of the shell model calculations using SDPF-MU and SDPF-U-MIX interaction for Si isotopes, respectively. The horizontal lines at $R_{4/2}$=2.00 (3.33) in right panel indicates the vibrational (rotational) limit. The vertical lines at the neutron magic number in both panels are intended to guide the eye.

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## References

[1] S. RAMAN *et al.*, Atomic Data and Nuclear Data Tables **78**, 1-128 (2001)
[2] C. Detraz *et al.*, Phys. Rev. C **19**, 164 (1979)
[3] T. Motobayashi *et al.*, Phys. Lett. B **346**, 9 (1995)
[4] B. Bastin *et al.*, Phys. Rev. Lett. **99**, 022503 (2007)
[5] R.W. Ibbotson *et al.*, Phys. Rev. Lett. **80**, 2081 (1998)
[6] S. Grévy *et al.*, Phys. Lett. B **594**, 252 (2004)
[7] C.M. Campbell *et al.*, Phys. Rev. Lett. **97**, 112501 (2006)
[8] J. Fridmann *et al.*, Phys. Rev. C **74**, 034313 (2006)
[9] B. Jurado *et al.*, Phys. Lett. B **649**, 43 (2007)
[10] C.M. Campbell *et al.*, Phys. Lett. B **652**, 169 (2007)
[11] S. Takeuchi *et al.*, Phys. Rev. Lett. **109**, 182501 (2012)
[12] T. Kubo, Nucl. Instrum. Methods Phys. Res. Sect. B **204**, 97 (2003)
[13] Y. Mizoi *et al.*, RIKEN Accel. Prog. Rep. **38**, 297 (2005)
[14] S. Takeuchi *et al.*, RIKEN Accel. Prog. Rep. **36**, 148 (2003)
[15] M. Belleguic *et al.*, Phys. Scr. **T88**, 122 (2000)
[16] K. Yoneda *et al.*, Phys. Lett. B **499**, 233 (2001)
[17] P. Fallon *et al.*, Phys. Rev. C **74**, 041302 (2010)
[18] T. Otsuka *et al.*, Nucl. Phys. A **805**, 127c (2008)
[19] Y. Utsuno *et al.*, Phys. Rev. C **86**, 051301 (2012)
[20] F. Nowack *et al.*, Phys. Rev. C **79**, 014310 (2009)
[21] F. Rotau *et al.*, Phys. Rev. Lett. **109**, 092503 (2012)