In-beam γ spectroscopy of ^{34}Si with deuteron inelastic scattering using reverse kinematics

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Excited states of ^{34}Si were studied in the ^{2}H(^{34}Si,^{34}Siγ) reaction using a radioactive ^{34}Si beam at 38.4*A* MeV and a liquid deuterium target. Deexcitation γ rays were measured using a NaI(Tl)-scintillator array in coincidence with scattered ^{34}Si particles. From γ-γ coincidence analyses, the γ lines at 1.193, 1.715, and 2.696 MeV, which were reported previously but unplaced in the level diagram, were found to be associated with the 3.326-MeV γ line corresponding to the transition from the first 2^+ state to the ground state. This excludes the 1.193-MeV line as a candidate for the transition from the 2^+ state to the second 0^+ state, as suggested by Nummela *et al.* [Phys. Rev. C **63**, 044316 (2001)].

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The disappearance of magicity in nuclei at $N=20$ and $Z=10$–12 has attracted much attention, because it is related to the weakening of the gap between the sd and pf neutron shells [1,2]. Recent experimental data on masses, level structures, and transition probabilities for ^{32}Mg and ^{31}Na reveal strong deformations of the ground states [3,4], which cannot be explained by sd shell models. However, in ^{34}Si, which has just two more protons than ^{32}Mg, the high excitation energy of 3.326 MeV for the first 2^+ (2_1^+) state [5] suggests the $(sd)^{12}$ neutron shell closure and a spherical ground (0_1^+) state. This sharp contrast between the ground state configurations of ^{32}Mg and ^{34}Si was theoretically interpreted using a picture of shape coexistence [1,5–9]. A spherical 0^+ state with the sd neutron shell closure and a deformed 0^+ state with the $2p$-$2h$ intruder configuration are expected. Due to differences in the amount of weakening of the gap between the sd and pf neutron shells, the ground states of ^{32}Mg and ^{34}Si correspond to the deformed and spherical 0^+ states, respectively. These models predict a low-lying deformed second 0^+ (0_2^+) state in ^{34}Si and a low-lying spherical second 0^+ state in ^{32}Mg. However, the second 0^+ states in ^{32}Mg and ^{34}Si have not been found experimentally. The small $B(E2;\, 0_1^+\rightarrow 2_1^+)$ value of $85\pm 33\ e^2\ \mathrm{fm}^4$ in ^{34}Si measured by Ibbotson *et al.* [10], which is even smaller than the value predicted in the pure sd-shell configuration, supports the prediction that the 2_1^+ state at 3.326 MeV is well deformed [10,9,8], suggesting the existence of the 0_2^+ state.

Recently, Nummela *et al.* observed new γ lines at 0.591, 1.053, 1.193, 1.715, and 2.696 MeV following the ^{34}Al β decay [11] in addition to the four known transitions in ^{34}Si [5]. The γ lines at 0.591 and 1.053 MeV were assigned to be the transitions from a new state at 4.970 MeV to the known state at 4.379 MeV, and from the 4.379 MeV to 3.326 MeV states in ^{34}Si, respectively [11], as shown in Fig. 1. The other three γ lines were not placed in the level diagram. Nummela *et al.* suggested that the γ line at 1.193 MeV is the only candidate for the $2_1^+\rightarrow 0_2^+$ transition [11]. Enders *et al.* also observed these unplaced γ lines in the ^{9}Be(^{35}Si,^{34}Siγ) reaction [12], indicating that they belong to ^{34}Si.

To clarify the nature of these unplaced γ lines and to examine the suggestion by Nummela *et al.* regarding the 0_2^+ state, deuteron inelastic scattering of ^{34}Si in inverse kinematics was studied. A thick liquid deuterium target facilitated the measurement of γ lines with high statistics, in contrast to experiments using a compound target such as CD_2. This enables us to analyze γ-γ coincidence events, and to obtain evidence of the three unplaced γ lines associated with the 3.326-MeV γ line corresponding to the transition from 2_1^+ to 0_1^+.

The experiment was carried out at the RIKEN accelerator research facility. A radioactive ^{34}Si beam was produced in a 2-mm-thick beryllium target by the fragmentation of a ^{40}Ar beam at 95*A* MeV from the RIKEN ring cyclotron. The beam was separated by the RIKEN projectile-fragment separator (RIPS) [13]. An aluminum energy degrader with a thickness of 444 mg/cm^2 and a wedge angle of 2.2 mrad was placed at the dispersive focus $F1$. A typical intensity and resultant purity of the ^{34}Si beam were 2×10^4 cps and 99%, respectively. The major contaminating particles were ^{31}Mg. The beam particles were identified event by event using the

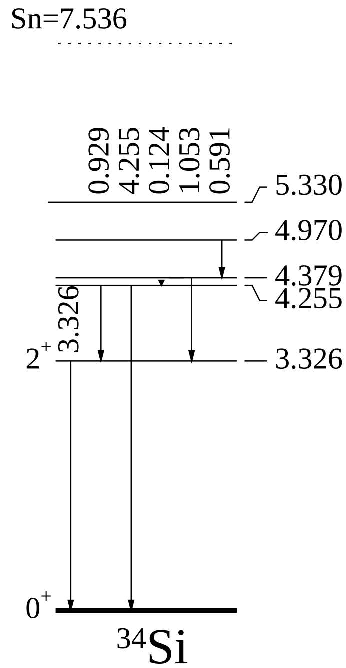

FIG. 1. Level diagram of ^{34}Si. The levels and excitation energies, given in MeV, are quoted from the previous experiments [17,5,11]. The arrows indicate the γ transitions observed in the previous β-decay study [11].

time-of-flight (TOF) measurement performed by two 0.3-mm-thick plastic scintillators placed 5.31 m apart from each other. The beam spot size and incident angle at the final achromatic focus $F3$ were, respectively, 5 mm and 7 mrad in the horizontal direction, and 3 mm and 11 mrad in the vertical direction at 1σ, which were measured by two parallel plate avalanche counters (PPAC) placed 120 and 90 cm upstream of $F3$.

A liquid deuterium target [14] was placed at $F3$. The target has two windows of aromatic polyamide foils with a thickness of 50 μm and a diameter of 24 mm. The target thickness was 150 ± 5 mg/cm^2 in the central part, decreasing to 97 ± 8 mg/cm^2 at the edges of the windows. The positional dependence of the thickness was determined under the assumption of spherically shaped windows. The average beam energy in the center of the target was $38.4A$ MeV.

The reaction products were detected by four silicon counter telescopes arranged in a 2×2 matrix, placed 1.357 m downstream of the target. Each telescope consisted of four ion-implanted silicon detectors with a thickness of 500 μm and an active area of 50×50 mm^2. The ^{34}Si beam stopped at the second detector in each telescope. The third and fourth detectors were used to identify and reject low-Z particles punching though the two detectors. Particle identification was performed using the ΔE-E method. The information on TOF between the target and telescopes, which was obtained by the timing signals from the two plastic scintillators and a PPAC placed in front of the telescopes, was incorporated in the particle identification process. The mass resolution of the reaction products was 0.5 amu at 1σ.

Deexcitation γ rays were detected in coincidence with reaction products by an array of 68 NaI(Tl) scintillators

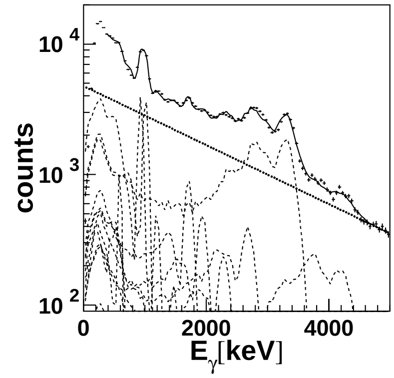

FIG. 2. Doppler-corrected γ energy spectrum measured in coincidence with ^{34}Si. The solid curve represents the best fit by simulated line shapes (dashed curves) and an exponential background (dotted curve).

(DALI) [3] surrounding the target from 40 to 138 deg with respect to the beam axis. Each scintillator crystal had a rectangular shape with a size of $6\times6\times12$ cm^3. Typical energy resolution was measured to be 9% [full width at half maximum (FWHM)] for 0.661-MeV γ rays from a ^{137}Cs source. The detection efficiency was measured by ^{137}Cs, ^{60}Co, ^{22}Na, and ^{88}Y calibrated sources, and agreed with results of Monte Carlo simulations using GEANT3 [15] within error. Based on the full-energy peak efficiency thus obtained for each detector, total detection efficiency was calculated by considering the Doppler shift. It was, for example, 4.9% for a 3.326-MeV photon emitted from a source moving with a velocity of $0.28c$. Lead shields with a thickness of 5 cm surrounded the NaI(Tl) array for background reduction. Further background reduction was achieved by selecting prompt γ-ray emissions measuring TOF between the target and the NaI(Tl) crystals in off-line analyses. Remaining background events were measured using an empty target formed by vaporizing the liquid deuterium, and revealed that this contribution was found to be negligibly small. Due to the high γ-detection efficiency together with the low background level, γ-γ coincidence data could be taken as will be discussed.

The Doppler-corrected γ-ray energy spectrum measured in coincidence when both beam particles and reaction products were identified as ^{34}Si is shown in Fig. 2. Peaks were observed at 0.58, 1.00, 1.18, 1.73, 1.93, 2.30, 2.68, 3.33, and 4.26 MeV. They correspond to the known γ lines at 0.591, 0.929 (and 1.010), 1.193, 1.715, 1.941, 2.289, 2.696, 3.326, and 4.255 MeV, respectively [11,16]. An additional peak at 1.48 MeV was also observed with the 2.5σ confidence level, which had not been reported in the previous studies [5,11].

As shown in Fig. 1, the lines at 0.591, 0.929, and 3.326 MeV are due to the γ transitions in ^{34}Si [11]. The line at 4.255 MeV was also attributed to the transition in ^{34}Si [11], but a considerable amount of contamination from the 4.320-MeV γ line in ^{33}Si and the very intense 4.231-MeV γ line in ^{32}Si were mixed in because of the limited mass resolution (0.5 amu at 1σ) for the reaction products. The 1.010, 1.941, and 2.289 MeV lines are of ^{33}Si, ^{32}Si, and ^{32}Si, respectively [17,16]. As mentioned before, the γ lines at 1.193, 1.715,

TABLE I. Energies and relative intensities of γ rays from the present experiment, together with the results of the β decay study by Nummela *et al.* [11] and those of the ^{9}Be(^{35}Si, ^{34}Si) reaction study by Enders *et al.* [12]. Relative intensity was normalized against the intensity of the 3.326-MeV line. All energies are given in MeV (g.s. represents ground state).

Energy (MeV)	Relative intensity Present	Ref. [11]	Ref. [12]		Transition From	To
0.124		51.9±4.3		^{34}Si	4.379	4.255
0.591	4.1±0.5	7.7±0.8	26±6	^{34}Si	4.970	4.379
0.930	26.2±0.7	103.9±9.7	61±7	^{34}Si	4.255	3.326
1.010	29.8±0.8	2.7±0.4		^{33}Si	1.010	g.s.
1.053		3.9±0.6	7±4	^{34}Si	4.379	3.326
1.193	4.9±0.7	6.4±0.8	15±4	^{34}Si	4.519 [b]	3.326 [b]
1.435		13.9±1.4		^{33}Si	1.435	g.s.
1.480	2.0±0.8			^{34}Si	a	
1.715	15.8±0.9	2.4±0.4	22±7	^{34}Si	5.041 [b]	3.326 [b]
1.941	11.0±1.0			^{32}Si	1.941	g.s.
2.289	7.0±1.2			^{32}Si	4.231	1.941
2.696	14.7±1.3	4.8±1.0	9±4	^{34}Si	6.022 [b]	3.326 [b]
3.326	100.0	100.0	100±6	^{34}Si	3.326	g.s.
4.255	14.0±0.8[†]	24.0±3.8	13±2	^{34}Si	4.255	g.s.

[a]Unplaced yet.
[b]Tentatively assigned by the present experiment.

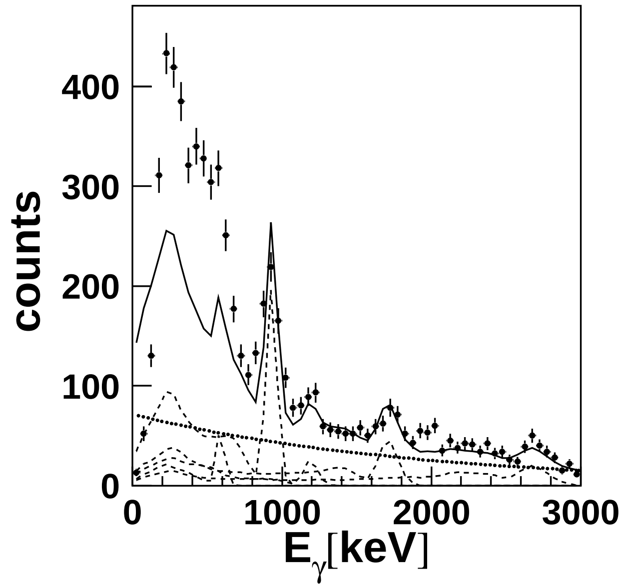

FIG. 3. Doppler-corrected γ energy spectrum measured in coincidence with ^{34}Si scattered particles and 3.326-MeV γ rays. The solid curve shows the fit to the data above 0.75 MeV by simulated line shapes and an exponential background represented by the dashed and dotted curves, respectively (see details in the text).

and 2.696 MeV were not placed in the β-decay study by Nummela *et al.* [11]. Though the γ line at 1.48 MeV is close in energy to the transition in ^{33}Si (1.435 MeV) tentatively assigned by Fornal *et al.* [18], the line appeared more likely to be due to ^{34}Si as indicated by mass identification, and because the measured energy is slightly higher than 1.435 MeV.

The dashed curves in Fig. 2 shows detector responses for the γ lines at 0.591, 0.929, 1.010, 1.193, 1.480, 1.715, 1.941, 2.289, 2.696, 3.328, and 4.255 MeV, obtained by Monte Carlo simulations based on GEANT3 [15]. Detector response to the γ line at 0.511 MeV in the laboratory frame produced by the positron annihilation was also plotted. The simulations included intrinsic energy resolutions, positions, and sizes of the NaI(Tl) detectors, and took the Doppler effect into account. These simulated responses were normalized using a χ^2 minimization procedure to best fit the observed γ-ray spectrum. The background was assumed to be a single exponential, which probably originated from neutrons and γ rays from the target. As shown in Fig. 2, the experimental spectrum is well reproduced by the fit. Energies, intensities, and transitions were listed in Table I, together with those measured by Nummela *et al.* [11] and Enders *et al.* [12].

Events of γ-γ coincidence were analyzed to locate the unplaced γ lines at 1.193, 1.715, and 2.696 MeV. Figure 3 shows a Doppler-corrected energy spectrum of γ rays associated with the $2_1^+ \rightarrow 0_1^+$ transition in ^{34}Si. The lines at 0.591, 0.929, 1.193, 1.715, and 2.696 MeV can be clearly identified. The dashed curves in Fig. 3 indicate the contributions ofthese transitions calculated from the detector response shown in Fig. 2 by taking the full-energy-peak efficiency for the 3.326-MeV γ line into account. Normalization of the exponential background was made independently. A smaller scale factor for the background reflects a lower background for the γ-γ coincidence. The shape and magnitude of the experimental spectra were found to be consistent with the simulated ones for $E_\gamma > 0.75$ MeV. This indicates that the transitions by the γ lines at 1.193, 1.715, and 2.696 MeV feed finally the 2_1^+ state in ^{34}Si with almost 100% probability. This implies that these three γ lines are directly connected to the 3.326-MeV state. An additional peak at around 2 MeV could be explained by a small amount of contamination from ^{32}Si, and may correspond to the $2^+ \rightarrow 0^+$ transition in ^{32}Si at the energy of 1.941 MeV measured in coincidence with the 3.278-, 3.347-, or 3.471-MeV γ rays feeding the 2^+ state in the 3.1–3.5 MeV coincidence gate [16]. This was confirmed by clear observation of the 1.93-MeV line in a Doppler-corrected γ spectrum obtained for ^{32}Si reaction products with a similar γ energy gate as in this experiment.

A low-lying intruder 0_2^+ state in ^{34}Si was predicted by Baumann *et al.* to lie just above the 2_1^+ state in ^{34}Si [5]. However, Heyde and Wood predicted that the 0_2^+ state lies between the 2_1^+ state and the 0_1^+ state [6]. Recent theoretical studies [7,9,8,10] have supported the prediction by Heyde and Wood [6]. From experimental observation of the ^{34}Al β decay, Nummela *et al.* concluded that the γ line at 1.193 MeV was the only candidate for the transition from the 2_1^+ state to the deformed 0_2^+ state [11]. However, the present result excludes this possibility, because this line is found to be connected to the $2^+ \rightarrow 0^+$ transition. In the empirical shell model calculation by Ibbotson *et al.* [10] which allowed for the $2p$-$2h$ neutron excitation and accounted for the observed small $B(E2;\ 0_1^+ \rightarrow 2_1^+)$ value mentioned before, the existence of the 0_2^+ state was expected at 2.02 MeV. The model evaluated the γ-ray branch for the $2_1^+ \to 0_2^+$ transition with only 2.4% of the $2_1^+ \to 0_1^+$ strength, which could explain why the 1.3-MeV γ line for the $2_1^+ \to 0_2^+$ decay was not observed in their experiment. No γ line at around 1.3 MeV was observed in any of the four experiments, the β decay [11], Coulomb excitation reaction [10], ^{9}Be(^{35}Si,^{34}Si) reaction [12], or present (d,d') reaction, within their statistics. As mentioned before, the peak observed at 1.48 ± 0.04 MeV in the current work is likely to be from ^{34}Si. Since this peak is not apparent in the γ spectrum associated with the $2_1^+ \to 0_1^+$ (note that 0_1^+ instead of 0_2^+) transition as shown in Fig. 3 at 1.3σ level, it is possible that the 1.48-MeV line corresponds to the $2_1^+ \to 0_2^+$ transition, although this has not been observed in previous experiments [10–12]. Further studies are therefore needed to examine the possible locations of the second 0^+ state in ^{34}Si.

In summary, the ^{2}H(^{34}Si,^{34}Si*) reaction has been studied at 38.4*A* MeV using a liquid deuterium target. The high statistics of the present result due to the use of the liquid deuterium target enabled us to perform γ-γ coincidence. Deexcitation γ rays were measured in coincidence with scattered ^{34}Si particles. All of the previously reported γ lines above 0.5 MeV [11,12] were observed. The γ lines at 1.193, 1.715, and 2.696 MeV, which were found in the study of ^{34}Al β decay [11], but not placed in the ^{34}Si level scheme, were newly found to be in coincidence with the $2_1^+ \to 0_1^+$ transition with almost 100% correlation. This indicates that the possible existence of the second 0^+ state at 2.133 MeV, as suggested by Nummela *et al.* [11] is unlikely.

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