

The deformed 0^+ state in ^{34}Si

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Abstract. The energy of the lowest deformed 2-particle 2-hole (2p2h) 0^+ state in even-even $N = 20$ nuclei is a key observable directly related to the size of the neutron $N = 20$ shell closure. ^{34}Si , with 14 protons and 20 neutrons, lies at the boundary of the “island of inversion”, where the deformed 2p2h 0^+ state is the ground state in even- A nuclei. In ^{34}Si , the 2p2h 0^+ state is expected to be particularly low lying - in some theories it is even predicted to lie below the first 2^+ state. While there have been a number of attempts, using various techniques, no experiment to date has been able to firmly locate the ^{34}Si 2p2h 0^+ state although a number of candidates have been suggested. Here we present, for the first time, data obtained from a fusion-evaporation reaction $^{18}\text{O}(^{18}\text{O}, 2p)$ to produce ^{34}Si . Gammasphere and Microball were used to detect γ - γ coincidences and charged particles (two protons), respectively. The increased sensitivity of this experiment using γ - γ coincidences and a high charged-particle detection efficiency helped to exclude previously reported candidates and provided a stringent limit on the anticipated γ decay from the first 2^+ state to the 2p2h 0^+ state.

1. Introduction

Neutron-rich nuclei have attracted great experimental and theoretical interest since they have shown a significant difference in their shell structure as compared to the expected one obtained from studies of nuclei near the valley of β -stability. Such phenomena were first observed by Thibault *et al* [1] in mass-measurement experiments of neutron-rich Na isotopes, in which the additional binding energy observed for ^{31}Na was attributed to a deformed ground state. This deformation, which was later confirmed also for the Mg isotopes [2] and other nuclei with $Z \approx 11$ and $N \approx 20$, was not expected within a simple sd -shell model picture. To reproduce the ground state deformation at $N = 20$ it is required to involve particle-hole excitations across the $N = 20$ shell gap by involving pf -shell neutron configurations [3]. The region where these intruder states become the ground state is known as the “island of inversion” [4]. This dramatic change in the shell structure suggests a reduction of the $N = 20$ shell gap, which is governed by the spin-isospin and tensor components of the nucleon-nucleon interaction, as suggested by Otsuka

et al [5]. Just outside the “island of inversion”, where the expected orbital for the ground state is restored, these intruder states should exist as low-lying excited states. The location of these states for an increasing number of protons occupying the *sd* shell provides a way to study the evolution of the neutron *sd*-*pf* shell gap and the strength of the interaction.

Numerous experimental and theoretical studies were focused on determining these intruder states. In particular, ^{34}Si , the first even-even $N = 20$ nucleus outside the “island of inversion”, with just two more protons compared to the well deformed ^{32}Mg , has attracted much interest [6, 7, 8, 9, 10, 11, 12]. Its ground state has been found to be spherical [10], while the first 2^+ state is suggested to be of deformed $2\hbar\omega$ *pf*-shell nature [7]. The deformed 0^+ state, which in ^{32}Mg is the ground state, is expected to be a low lying excitation in $N = 20$, even- Z nuclei outside the island of inversion. Such a state has indeed been identified for ^{36}S [13], ^{38}Ar [14] and ^{40}Ca [15] and it is located at ~ 3.3 MeV for all three. The theoretical predictions by different models for the location of this state in ^{34}Si and ^{36}S nuclei seem to deviate. For example, the Monte Carlo Shell Model (MCSM) calculations [16], which perform fairly well in this region, predict that this state should come down gradually in energy as one removes protons from the $N = 20$ isotones to become the ground state in ^{32}Mg . For ^{34}Si , it is expected to lie ~ 1 MeV below the first 2^+ state [17]. Other calculations, however, suggest that this state should be higher in excitation energy [18] and in some cases it is predicted to lie above the first 2^+ state [10]. Identifying this state experimentally would provide a further test of the models in this region. This state has not been unambiguously observed despite numerous attempts with many different types of experiments, such as transfer [6], Coulomb excitation [7], neutron knockout [8], deep inelastic reactions [9] and β -decay measurements [10, 11]. Here we present the first results from a fusion-evaporation experiment aimed at studying ^{34}Si via the $^{18}\text{O}(^{18}\text{O}, 2p)$ fusion reaction. The complementarity of this approach comes from its higher sensitivity and the population of higher-spin states.

2. Experimental Details

The ^{34}Si nucleus was populated utilizing the $^{18}\text{O}(^{18}\text{O}, 2p)$ fusion-evaporation reaction at an incident beam energy of 25 MeV. This beam energy was chosen based on a test experiment performed at the 88-inch Cyclotron at Lawrence Berkeley National Laboratory (LBNL). The beam was delivered by the Argonne Tandem-Linac Accelerator System (ATLAS) with an average beam current of 30 pA for five days. The target was $259 \mu\text{g}/\text{cm}^2$ of ^{18}O on a $22 \text{mg}/\text{cm}^2$ Ta backing, prepared with the method described in Ref. [19].

The evaporated protons were detected using the CsI(Tl) 4π -multidetector device Microball [20], while the de-exciting γ rays were detected using Gammasphere [21] consisting of 101 high-purity Ge detectors. The acquisition trigger was set to accept events with γ -ray multiplicity ≥ 2 . The fusion-evaporation products were stopped in the “thick” Ta backing and most γ rays were emitted at rest, allowing for an optimum γ -ray energy resolution of the order of 2-3 keV (FWHM) for 1 MeV γ rays.

The data were sorted in a γ - γ matrix requiring the detection of two protons in Microball and prompt time peaks in both Gammasphere and Microball. Off-prompt events were used to determine the background contributions and the random peaks entering the energy spectrum. Background levels were high due to the unlikely evaporation of two protons compared to neutrons from the neutron-rich compound nucleus ^{36}S . This contamination is understood since the proton gates defined from the Microball spectra, particularly those for the backward detectors where the proton energy is lower, are not 100% “clean” resulting in a neutron or a γ ray, for instance, that reacts with the CsI crystals to be misidentified as a proton. Although the percentage of misidentified protons is very low (1 - 2%), a channel with many orders of magnitude higher production rate will appear in the γ -ray spectrum as a dominant one. For example, in the two proton gated spectra shown in Fig. 1, the much more favored ^{34}P ($1p1n$ - exit channel) is dominant. Furthermore, high neutron yields entering the Ge detectors generate characteristic

broad, triangular-shaped peaks corresponding to inelastic neutron excitation of the various Ge isotopes in the crystal. However, due to the high resolving power of Gammasphere and the use of the Microball particle detector, an extensive γ -coincident investigation of the ^{34}Si level scheme was possible.

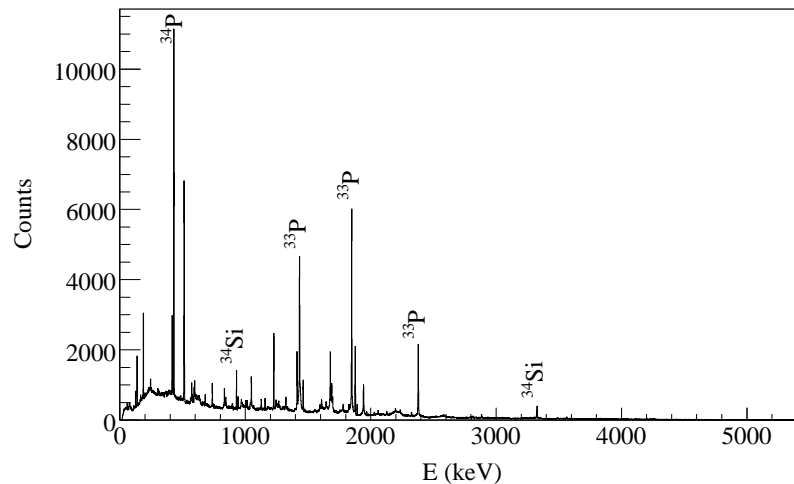


Figure 1. γ -ray energy spectrum in coincidence with two protons.

3. Results

γ -coincidence spectra are given in Fig. 2 for the 929 keV (left) and 3326 keV (right) gates. The level scheme obtained from the present experiment is provided in Fig. 3. Two new levels at 6233 and 4920 keV and six new γ rays were observed for the first time. The four new γ rays (1264, 1594, 1314 and 665 keV) associated with the decay of these two newly observed levels are also shown in the level scheme. The 1191 keV γ ray is found in coincidence with the 3326 keV 2^+ to 0^+ transition, in agreement with Ref. [9], confirming that this could not be the 2^+ to 0_2^+ transition as suggested by Ref. [11]. Two of the six newly observed γ rays (991 and 1380 keV) are not placed in the level scheme. These transitions are found in coincidence with the 929 keV gate; they are, however, Doppler broadened, indicating that these γ rays are emitted as soon as the compound nucleus is formed, before stopping in the Ta backing. The 1053, 1480, 1716 and 2696 keV γ rays previously reported to be from ^{34}Si were not observed in the present experiment. However, it is worth noting that the 1716 keV transition matches the energy difference between the newly observed level at 6233 keV and the 4517 keV level. The 665 keV transition observed in the present experiment could be the same as the 670 keV transition reported in Ref. [22], where this γ ray was assigned to the de-excitation of the 0_2^+ level to the first 2_1^+ state. This scenario is, however, excluded by the present work since this γ ray is seen in coincidence with the 929 and 4255 keV gates and it also matches the energy difference between the newly observed 4920 and the known 4255 keV state. All γ -ray energies reported in the level scheme are accurate to within 1 keV and the widths of the arrows are roughly proportional to the intensities of the γ rays. The γ -ray intensities shown in the level scheme suggest that in this reaction the ^{34}Si nuclei are preferably populated at lower excitation energies. This is understood if one considers the relatively low beam energy used in this reaction and the energy required for the subsequent emission of two protons from the neutron-rich compound nucleus ^{36}S .

4. Summary

The ^{34}Si nucleus, which lies just outside the “island of inversion”, has been studied in a fusion-evaporation experiment for the first time. Its level scheme has been extended through the

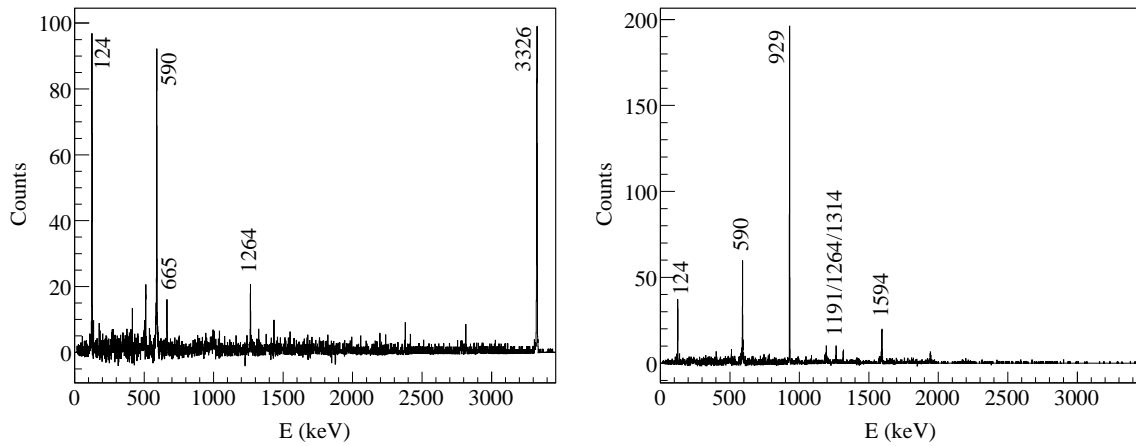


Figure 2. γ -ray energy spectra gated on the 929 keV (left) and 3326 keV (right) transitions.

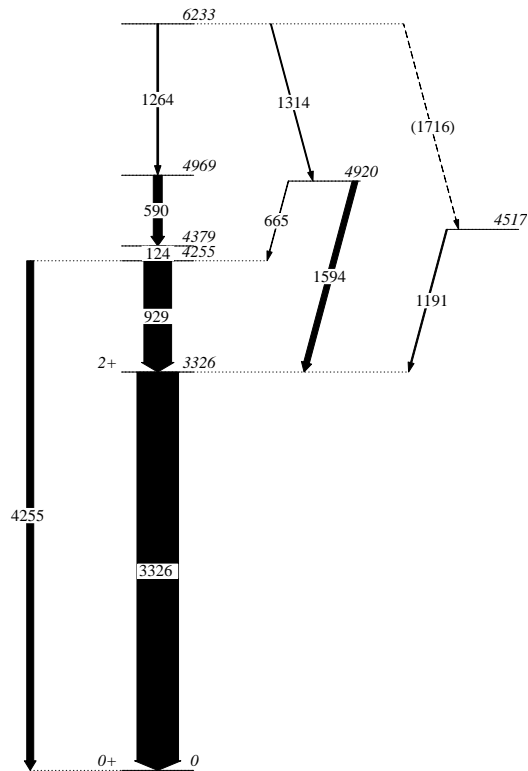


Figure 3. The level scheme of ^{34}Si obtained in the present work. The dashed line indicates a tentative placement of the γ rays in the level scheme. The widths of the arrows are roughly proportional to the intensities of the γ rays.

identification of two new states and six new γ rays, while it has also been possible to place some of the previously observed γ rays. Despite the increased sensitivity of this experiment, no state below the first 2^+ state has been observed, extending thus the exclusion region for the location and transition strength of the deformed 0^+ state.

Acknowledgments

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