‘Magic’ nucleus ^{42}Si

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Nuclear shell structures – the order and separation of the quantum states of the individual protons and neutrons – provide one of our most important guides for understanding the stability of atomic nuclei. It has long been recognized^{1,2} that nuclei with “magic numbers” of protons and/or neutrons (corresponding to closed shells) are particularly stable. Whether the major shell closures and magic numbers change in very neutron-rich nuclei is a fundamental and presently open question^{3,4}. A unique opportunity to study these shell effects is offered by the neutron-rich ^{42}Si nucleus, which has 28 neutrons, a magic number in stable nuclei, and 14 protons. This nucleus has a 12-neutron excess over the heaviest stable silicon nuclide and has only one neutron less than the heaviest silicon nuclide observed so far⁵. We report new measurements of ^{42}Si and two neighboring nuclei

using a novel experimental technique, one- and two-nucleon knockout from beams of exotic nuclei^{6,7}. We present strong evidence for a well-developed proton subshell closure at $Z=14$, the near degeneracy of the $s_{1/2}$ and $d_{3/2}$ proton orbits in the vicinity of ^{42}Si , and a nearly spherical shape for ^{42}Si .

The nuclide ^{42}Si has become the focus of particular interest in discussions of nuclear shell structure at the neutron drip line, the locus of the heaviest nuclides in which all the neutrons are bound to the nucleus. The nuclide ^{42}Si is only one neutron lighter than the heaviest silicon nucleus yet observed⁵ and is close to the drip line, as illustrated in Fig. 1. The $N=28$ (28 neutron) major shell closure is the lightest neutron shell closure caused by the spin-orbit force, which is responsible for all major shell closures in heavier nuclei^{1,2}. However, the increasing experimental difficulty of reaching the neutron drip line with increasing proton number, means that this $N=28$ case is the only such spin-orbit shell closure that can currently be examined at the neutron drip line. In fact, it has been predicted⁸⁻¹⁴ that this shell closure should be less well developed, or even collapse altogether, in ^{42}Si , resulting in a strongly deformed shape for this nucleus. Two recent experimental results – one a measurement¹⁵ of the β -decay half-life of ^{42}Si and the other the determination that ^{43}Si is particle-bound⁵ - have been cited in support of this view. On the other hand, ^{42}Si , with 14 protons, is expected to have a good proton subshell closure and, if the $N=28$ major shell closure is also maintained, then ^{42}Si should have a distinctive spectroscopy characteristic of a rigidly spherical shape, like the $N=28$ isotone ^{48}Ca or the $N=20$ nuclide ^{34}Si ¹⁶. Shell model calculations¹⁷ predict a situation between these two extremes: a weakly deformed shape for ^{42}Si in which the $N=28$ shell gap is narrower than in ^{48}Ca but in which the $Z=14$ subshell closure prevents strong deformation.

In the present study, the nuclides ^{43}P and ^{42}Si were produced using one- and two-proton knockout reactions (respectively) with a beam of the exotic nucleus ^{44}S . In

addition, a ^{46}Ar beam was used to perform spectroscopy of ^{44}S via the two-proton knockout reaction. The experiment was performed with the Coupled Cyclotron Facility (CCF) at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. The A1900 fragment separator¹⁸ was used to produce the exotic beams (which had kinetic energies of 98.6 MeV/nucleon and 98.1 MeV/nucleon for ^{44}S and ^{46}Ar , respectively), the S800 spectrograph¹⁹ to detect and identify the residues of the knockout reactions, and the SeGA array of segmented germanium detectors²⁰ to detect γ -rays from the residues. The knockout reactions took place in a beryllium target of thickness 375 mg/cm².

The extreme sensitivity in this experiment can be illustrated in the following way: the exotic ^{44}S and ^{46}Ar beams were produced via fragmentation reactions with a stable ^{48}Ca “primary” beam. The primary beam current was 15 particle nanoamperes, or 3.4×10^{14} particles per hour. From this, 1.5×10^6 particles of the ^{44}S exotic beam were produced per hour. Of the three residual nuclides studied here, the one with the smallest yield was ^{42}Si , which gave 1.6 counts per hour. The particle spectrum used to identify ^{42}Si is shown in Fig. 2.

The γ -ray energy spectrum obtained in coincidence with the ^{43}P residues, following one-proton removal from ^{44}S , is shown in Fig. 3. The spectrum is shown in the rest frame of the residues; that is, the γ -ray energies are Doppler corrected from the laboratory frame. A single strong γ -ray transition appears in this ^{43}P γ -ray spectrum at 184(3) keV, the first γ -ray observed in this nucleus. The single-nucleon knockout reaction preferentially populates states that have a structure of a single nucleon hole in the beam nucleus⁶. The measured cross sections for populating the two states of ^{43}P observed here – the ground state and the excited state deexcited by the 184 keV γ -ray – are large, so an interpretation of these two states as $d_{3/2}$ and $s_{1/2}$ single-proton states is justified. Their sum is 7.6(11) mb. This cross section can be compared to theoretical

cross sections calculated for pure $d_{3/2}$ and $s_{1/2}$ single-proton states using the prescription described in Refs. 21 and 22. These theoretical cross sections are 7.7 and 6.1 mb, respectively. An examination of the measured cross section using γ -ray coincidences shows that the excited state accounts for $75 \pm 15\%$ of the cross section. Furthermore, the 184 keV γ -ray likely connects the two states, setting the energy splitting of the two orbits.

We performed a shell model calculation of the wavefunctions of the ground state and lowest excited state in ^{43}P that provides strong evidence for the identification of the excited state with the $d_{3/2}$ proton orbit and the ground state with the $s_{1/2}$ orbit. The calculations were carried out in the model space of $(0d_{5/2}, 1s_{1/2}, 0d_{3/2})$ for protons and $(0f_{7/2}, 1p_{3/2}, 0f_{5/2}, 1p_{1/2})$ for neutrons with an effective interaction used in Ref. 23. The computer code OXBASH²⁴ was used to perform the shell model calculations. The one-proton knockout cross sections were calculated from the wavefunctions using the approach described in references 21 and 22. According to the calculation, the state corresponding to the $d_{3/2}$ proton orbit should have 72% of the total cross section in the present one-proton knockout reaction. The share of the cross section measured for the excited state, $75 \pm 15\%$, provides a strong argument for the identification of the excited state with the $d_{3/2}$ proton orbit and the ground state with the $s_{1/2}$ orbit. The near-degeneracy of these two proton orbits seen in the data (with a splitting of 184 keV) is also seen in the shell model calculation with a splitting of 1 keV. This theoretical result is consistent with the observed splitting because shell-model calculations of this type are generally accurate to within 100-200 keV at best. The shell model fit of Duflo and Zuker²⁵ also predicted this near-degeneracy with a splitting of 100 keV.

A previous study of proton hole states populated in the potassium nuclides using the $^X\text{Ca}(d, ^3\text{He})$ reaction at low energy²⁶ provides some perspective for the ^{43}P result. The relative energies of the $d_{3/2}$, $s_{1/2}$ and $d_{5/2}$ proton orbits extracted¹⁶ from these data are

shown in Fig. 4, as are the $Z=8$ and $Z=20$ major proton shell closures and the $Z=14$ and 16 subshell closures. The energy gap between the $d_{3/2}$ and $s_{1/2}$ proton orbits decreases dramatically from more than 2 MeV in the $N=20$ nuclide ^{39}K , where this gap forms the $Z=16$ subshell closure, to approximately 300 keV in the $N=28$ nuclide ^{47}K , collapsing the $Z=16$ closure. Such shifts are observed throughout the Periodic Table, as demonstrated recently by Schiffer *et al.*²⁷ in the tin nuclides and the $N=82$ isotones. The separation between the $d_{5/2}$ and $s_{1/2}$ proton orbits remains large – averaging 5 MeV – throughout the K nuclides. The large energy gap between the $d_{5/2}$ proton orbit and the two higher-lying orbits forms a strong $Z=14$ subshell closure which is more robust than the $Z=16$ closure. The present result shows that the $d_{3/2}$ and $s_{1/2}$ proton orbits maintain their near-degeneracy in ^{43}P . It is remarkable that the energy difference between the $d_{3/2}$ and $s_{1/2}$ proton orbits remains so stable along the $N=28$ isotones from ^{47}K to ^{43}P (as illustrated in Fig. 4) while it changes so dramatically along the potassium isotopic chain.

While the ^{43}P result provides strong evidence for the near-degeneracy of the $d_{3/2}$ and $s_{1/2}$ proton orbits, the cross sections for the two-proton knockout reactions $^{44}\text{S} \rightarrow ^{42}\text{Si}$ and $^{46}\text{Ar} \rightarrow ^{44}\text{S}$ provide evidence that the $Z=14$ subshell closure that exists at ^{48}Ca persists near the neutron drip line in the vicinity of ^{42}Si . The inclusive cross sections for these reactions - 0.23(2) mb for $^{46}\text{Ar} \rightarrow ^{44}\text{S}$ and 0.12(2) mb for $^{44}\text{S} \rightarrow ^{42}\text{Si}$ - are significantly smaller than those for the other two-proton knockout reactions measured to date⁷ (1.50(10) mb for $^{28}\text{Mg} \rightarrow ^{26}\text{Ne}$; 0.76(10) mb for $^{34}\text{Si} \rightarrow ^{32}\text{Mg}$; and 0.49(5) mb for $^{30}\text{Mg} \rightarrow ^{28}\text{Ne}$). The cross section for the two-proton knockout reaction depends in part on the number of valence protons in the projectile nucleus – the smaller the number of valence protons, the smaller the cross section is expected to be⁷. If the $Z=14$ subshell closure persists to ^{42}Si , then the number of valence protons is small in ^{46}Ar (four) and even smaller in ^{44}S (two). Therefore, the decrease in cross section from the $^{46}\text{Ar} \rightarrow ^{44}\text{S}$ reaction to the $^{44}\text{S} \rightarrow ^{42}\text{Si}$ reaction is qualitative evidence for the persistence of the $Z=14$ shell closure at $N=28$.

We can provide a quantitative basis for this two-proton knockout discussion using a calculation that combines the shell model calculations described above – which include the $Z=14$ subshell closure - with eikonal reaction theory. The present calculation scheme²⁸ is more complete than that given in Ref. 7. We calculate only the dominant stripping contribution to the two-nucleon removal cross section. Since the two-proton knockout reactions are from deeply-bound single-particle states, contributions from diffraction dissociation processes, are assumed to be small. The shell model calculations for the two-proton amplitudes were obtained with a truncated space of $(0f_{7/2}, 1p_{3/2})$ for neutrons (in order to keep feasible matrix dimensions for OXBASH²⁴), but comparison with the full-space results for ^{46}Ar and ^{44}S showed that this truncation is adequate. In this calculation, the ground state of ^{42}Si is dominated (about 70%) by the closed-shell configuration of $(0d_{5/2})^6$ for protons and $(0f_{7/2})^8$ for neutrons and is therefore not well-deformed, although it is not as spherical as ^{34}Si and ^{48}Ca .

The calculation yields inclusive two-proton knockout cross sections of 0.36 mb and 0.17 mb for the $^{46}\text{Ar} \rightarrow ^{44}\text{S}$ and $^{44}\text{S} \rightarrow ^{42}\text{Si}$ reactions, respectively. These calculations, which include the $Z=14$ subshell closure, reproduce the small magnitudes of the measured cross sections (relative to those previously measured⁷) with reduction factors similar to those of the single-proton knockout reactions and also the decrease in cross section from the $^{46}\text{Ar} \rightarrow ^{44}\text{S}$ reaction to the $^{44}\text{S} \rightarrow ^{42}\text{Si}$ reaction. A further schematic calculation in which the $Z=14$ subshell closure is removed *ad hoc* yields cross sections which are much larger than the data, confirming that the small observed cross sections imply the persistence of the closure near ^{42}Si .

As pointed out in Ref. 17, the persistence of the strong $Z=14$ subshell closure in ^{42}Si will prevent strong deformation and will result in a nearly spherical shape. The present results suggest that the short lifetime of ^{42}Si , reported in Ref. 15, and the

existence of ^{43}Si , reported in Ref. 5, must now be explained without the strong deformation assumed by the authors of those reports.

In summary, we have measured cross sections for the intermediate energy two-proton knockout reactions $^{46}\text{Ar} \rightarrow ^{44}\text{S}$ and $^{44}\text{S} \rightarrow ^{42}\text{Si}$ and the one-proton knockout reaction $^{44}\text{S} \rightarrow ^{43}\text{P}$, observing the first γ -ray in ^{43}P . Our results for the knockout reaction cross sections and the identification of the γ -ray in ^{43}P provide strong evidence for a well-developed proton subshell closure at $Z=14$, the near degeneracy of the $s_{1/2}$ and $d_{3/2}$ proton orbits in neutron-rich nuclei at $N=28$ and a nearly spherical shape for ^{42}Si .

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Fig. 1 A chart showing all particle-bound nuclides of the elements having $Z=8-20$. The stable nuclides are shaded. The nuclei studied here – ^{42}Si , ^{43}P and ^{44}S – are circled.

Fig. 2 Particle spectrum used to identify the two proton-knockout product ^{42}Si . Plotted are the energy loss in a plastic scintillator at the S800 spectrograph focal plane on the y-axis and time-of-flight through the spectrograph on the x-axis. The energy-loss signal groups ions of the same Z together, while the time-of-flight in conjunction with the magnetic rigidity selection of the spectrograph distinguishes ions according to their mass/charge ratio.

Fig. 3 The γ -ray energy spectrum in coincidence with ^{43}P residues. The γ -rays are Doppler-corrected so that the spectrum appears as in the rest frame of the residues.

Fig. 4 Relative energies of the $d_{5/2}$, $s_{1/2}$ and $d_{3/2}$ proton orbits in the K nuclides as extracted in Ref. 14 from the data of Ref. 23 (open shapes), and the relative energies of the $s_{1/2}$ and $d_{3/2}$ proton orbits in ^{43}P as determined in the present work (filled shapes).

																				N=20		N=28																						
																				↓		↓																						
Z=20→																				³⁵ Ca	³⁶ Ca	³⁷ Ca	³⁸ Ca	³⁹ Ca	⁴⁰ Ca	⁴¹ Ca	⁴² Ca	⁴³ Ca	⁴⁴ Ca	⁴⁵ Ca	⁴⁶ Ca	⁴⁷ Ca	⁴⁸ Ca	⁴⁹ Ca	⁵⁰ Ca	⁵¹ Ca	⁵² Ca	⁵³ Ca	⁵⁴ Ca	⁵⁵ Ca	⁵⁶ Ca			
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																					²² Al	²³ Al	²⁴ Al	²⁵ Al	²⁶ Al	²⁷ Al	²⁸ Al	²⁹ Al	³⁰ Al	³¹ Al	³² Al	³³ Al	³⁴ Al	³⁵ Al	³⁶ Al	³⁷ Al	³⁸ Al	³⁹ Al	⁴⁰ Al	⁴¹ Al				
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																				¹⁶ O	¹⁷ O	¹⁸ O	¹⁹ O	²⁰ O	²¹ O	²² O	²³ O	²⁴ O