EXPERIMENTAL STUDY OF SINGLE-PARTICLE STRUCTURE IN ^{33}Si AND ^{34}P

B.V. Pritychenko, T. Glasmacher, B.A. Brown, P.D. Cottle[a], R.W. Ibbotson, K.W. Kemper[a], H. Scheit

Recent measurements of ^{32}Mg and ^{34}Si [1-3] clearly indicate the region of large deformations near $N = 20$ and $Z \leq 14$. The strongly deformed ground state in ^{32}Mg is caused by excitations of neutrons across the $N = 20$ shell closure (called $2\hbar\omega$ - or intruder - configurations), while the spherical shape of ^{34}Si with the sd-shell orbits ($0\hbar\omega$ configurations) [4,5]. Recent calculations of Caurier *et al.* [6] predict that intruder configurations dominate ground states in ^{30}Ne, ^{31}Na, and ^{32}Mg, and they are nearly degenerate with the closed shell states in ^{31}Ne, ^{32}Na and ^{33}Mg. However the exact boundaries of the "island of deformed nuclei" are still not known experimentally.

In the present report, we present measurements of two spherical nuclei which are located near ^{34}Si by the technique of intermediate energy Coulomb excitation [7]. The experiments were performed at the National Superconducting Cyclotron Laboratory. The primary beam of 90 MeV/nucleon ^{40}Ar was produced with the laboratory's K1200 cyclotron. The secondary beams of 50.5 MeV/nucleon ^{33}Si and 54.5 MeV/nucleon ^{34}P were made via fragmentation of the primary beam in a ^{9}Be production target of thickness 564 mg/cm^2 located at the mid-acceptance target position of the A1200 fragment separator [8]. A 518 mg/cm^2 thick gold foil was used as the secondary target. The secondary beams with $\theta_{lab}^{max} \leq 3.96^\circ$ were stopped in a cylindrical fast/slow plastic phoswich detector. Both energy loss in the phoswich detector and time of flight relative to the cyclotron RF signal were used for particle identification. In total, 1.02×10^9 and 1.06×10^8 beam particles were detected in the phoswich for ^{33}Si and ^{34}P, respectively.

The γ-ray spectra were collected in coincidence with the phoswich detector by the NSCL NaI(Tl) array [9]. The projectile-frame spectrum for ^{33}Si shows two clear peaks at 1010±7 and 1924±5 keV, with the corresponding cross sections of 4.1±0.8 mb and 11.7±1.4 mb, respectively. The 1010 keV γ-ray is in agreement with the previous results for ^{33}Si [10,11], while the 1924±5 keV transition matches the energy of the $2_1^+ \rightarrow 0_{gs}^+$ transition in ^{32}Si, which would be the product of single-neutron stripping from ^{33}Si on the ^{197}Au target. Such reactions have been observed before [1] , and we conclude this is the explanation for the 1924 keV γ-ray in this spectrum. The spectrum also appears to have a sharp cutoff near 4300 keV with the excitation cross section of 11.6±2.2 mb. The 4.3 MeV transition may arise from excitation of the 4.3 MeV state of ^{33}Si with the corresponding $B(E2\uparrow)$ = 69.2±12.9 e^{2}fm^4 or from population of the 4230.8 keV 2_2^+ state in ^{32}Si via neutron stripping. The γ-ray spectra of ^{33}Si and ^{34}P are shown in Figure 1.

For ^{34}P, the projectile-frame spectrum includes two peaks at 422±7 and 627±9 keV, with the corresponding cross sections of 5.2±2.4 mb and 6.8±3.0 mb, respectively. A 429.1 keV γ-ray was observed in the β-decay of ^{34}Si [12]. The 627 keV γ-ray has not been observed in ^{34}P before, and there is no known γ-ray of this energy in ^{33}P, which would be the product of a neutron-stripping reaction. However, the energy difference between two states observed in the ^{34}S(t,^{3}He)^{34}P reaction [13] at 2225±10 and 1605±10 keV matches the measured energy of this γ-ray to within experimental uncertainty. We suggest that the 627 keV γ-ray observed here connects the the 2225±10 keV level with the 1605±10 keV level. This implies that the 2225 keV level is populated in the Coulomb excitation reaction. According to [12], the 627 keV γ-ray would be followed by the 1607.6 keV transition (36% of the time) or a cascade of the 1178.5 and 429.1 keV γ-rays (64% of the time). Neither the 1178.5 or 1607.6 keV γ-rays are apparent in the projectile-frame spectrum for ^{34}P. However, at these energies the detection efficiency is low enough and the background level high enough to obscure these γ-ray peaks at the intensities that would be expected.

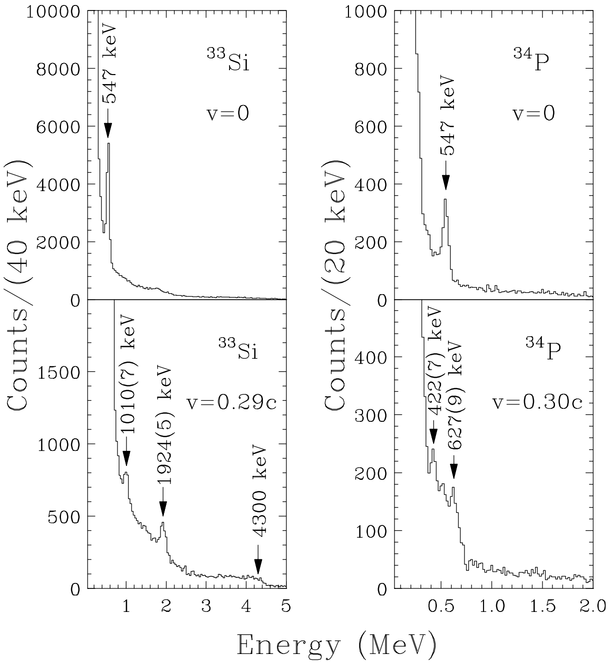

Figure 1: Photon spectra gated on ^{33}Si and ^{34}P beams. The upper panels show the laboratory-frame spectra, while the lower panels illustrate projectile-frame spectra (adjusted for Doppler shifts).

For ^{33}Si, Caurier *et al.* [6] predict the $E(2\hbar\omega) - E(0\hbar\omega)$ energy difference of 3.35 MeV, while Warburton *et al.* [4] predict 2.72 MeV. Caurier *et al.* do not provide a prediction for ^{34}P, but Warburton *et al.* give 3.78 MeV. Hence, the state at 1010 keV we are studying in ^{33}Si is quite likely to be a $0\hbar\omega$ state. The 429 keV state in ^{34}P is definetely a $0\hbar\omega$ state, while the states near 2.5 MeV are still likely to be dominated by $0\hbar\omega$ configurations. The ground states and first excited states of the $N = 19$ isotones ^{39}Ca, ^{37}Ar and ^{35}S have $J^\pi = 3/2^+$ and $J^\pi = 1/2^+$, respectively [10,11]. For ^{39}Ca and ^{37}Ar, ^{40}Ca, the ^{38}Ar(p,d) reactions indicate that the ground states are dominated by the $d_{3/2}$ neutron hole configuration, while the $J^\pi = 1/2^+$ states are primarily of a $s_{1/2}$ neutron hole nature [14]. Consequently, the spin and parity assigments for the ground and first excited states in ^{33}Si are $3/2^+$ and $1/2^+$, respectively. From these J^π assignments we can extract a $B(E2\uparrow)$ value by using the relativistic theory of Winther and Alder [15]. The result for $B(E2\uparrow)$ for this excitation is 16.5±3.2 e^{2}fm^4.

In ^{34}P, the ground state is known to have $J^\pi = 1^+$ from its β-decay to ^{34}S [16]. Given the $d_{5/2}$–$s_{1/2}$–$d_{3/2}$ ordering of spherical single particle orbits for both protons and neutrons in the neighborhood of this nucleus, the simplest interpretation of the ground state is as the 1^+ member of the $\pi(s_{1/2})\nu(d_{3/2})^{-1}$ multiplet and the 429 keV state is the 2^+ member of this multiplet. The log *ft* value measured for population of the 1608 keV level in the β-decay of ^{34}Si suggests both that this level has $J^\pi = 1^+$ and that $\pi(d_{3/2})\nu(d_{3/2})^{-1}$ is the proper choice for the configuration of this state. Therefore, the 2225 and 2309 keV states are other members of this multiplet. Thus, the spins of these two states would be limited to 0^+, 2^+ and 3^+. The direct population of the 2225 keV state by a photon with $E2$ multipolarity completely excludes $J^\pi = 0^+$ spin and parity assigment. Furthermore, it must have an appreciable $E2$ matrix element to the ground state to be populated, so the 627 keV de-excitation to the 1608 keV state almost certainly has an $M1$ multipolarity. Consequently the 2225 keV state has $J^\pi = 2^+$. If the yield of the 429 keV γ-ray results entirely from direct population of the 429 keV state in the Coulomb excitation reaction, then the $B(E2\uparrow)$ value for this state would be 20.2±9.6 e^{2}fm^4, which would be extraordinarily large for an $E2$

matrix element connecting members of a two-particle multiplet. However, the yield of the 429 keV γ-ray can be explained entirely by feeding from the decay of the 2225 keV state through the 1608 keV state by emission of the 627 and 1178 keV γ-rays. To explain the cross section observed for the 627 keV γ-ray, a $B(E2\uparrow)$ value of 26±12 e^2fm^4 would be required for populating the 2225 keV state. We adopt this $B(E2\uparrow)$ result for the 2225 keV state and conclude that we have no evidence for direct $E2$ excitation of the 429 keV state.

Our experimental results on the 1010 keV state in ^{33}Si can be quantitatively understood in the framework of standard sd-shell calculations ($0\hbar\omega$ configurations) with the USD interaction [17]. These calculations predict that the ground state is dominated by the $d_{3/2}$ neutron hole, and that a state dominated by the $s_{1/2}$ neutron hole configuration occurs at 848 keV, which is not far from the experimentally observed energy of 1010 keV. The calculations also predict $B(E2\uparrow)$ = 19.1 e^2fm^4 for this state, which reproduces our experimental result of 16.5±3.2 e^2fm^4. The sd-shell calculations also provide quantitative support for our interpretation of the present ^{34}P experimental results. The $B(E2\uparrow)$ value predicted for excitation of the 429 keV state is 0.3 e^2fm^4, which reflects the relationship between the ground and 429 keV states as members of the $\pi(s_{1/2})\nu(d_{3/2})^{-1}$ multiplet. However, the model predicts a $J^{\pi} = 2^{+}$ state in which the structure is primarily $\pi(d_{3/2})\nu(d_{3/2})^{-1}$ at 2217 keV and also predicts $B(E2\uparrow)$ = 9.6 e^2fm^4 for this state. The relatively strong calculated $E2$ matrix element between the $s_{1/2}$ proton orbit (present in the ground state) and the $d_{3/2}$ proton orbit (present in the 2225 keV state) provides the most reasonable explanation for the excitation of the 2225 keV state in the present measurement of ^{34}P.

This work was supported by the National Science Foundation through grants PHY-9528844, PHY-9523974, PHY-9605207 and the State of Florida.

a. Department of Physics, Florida State University, Tallahassee, Florida 32306

References

1. T. Motobayashi et al., Phys. Lett. B **346**, 9 (1995).
2. B.V. Pritychenko et al., Phys. Lett. B **461**, 322 (1999).
3. R.W. Ibbotson et al., Phys. Rev. Lett. **80**, 2081 (1998).
4. E.K. Warburton, J.A. Becker and B.A. Brown, Phys. Rev. C **41**, 1147 (1990).
5. A. Poves and J. Retamosa, Nucl. Phys. A **571**, 221 (1994).
6. E. Caurier et al., Phys. Rev. C **58**, 2033 (1998).
7. T. Glasmacher, Ann. Rev. Nucl. Part. Sci., **48**, 1 (1998).
8. B.M. Sherrill et al., Nucl. Inst. and Meth. B **56**, 1106 (1991).
9. H. Scheit et al., Nucl. Inst. and Meth. A **422**, 124 (1999).
10. Table of Isotopes, edited by R. B. Firestone and V. S. Shirley (John Wiley and Sons, Inc.,1996) Vol.I.
11. P.M. Endt, Nucl. Phys. A **521**, 1 (1990).
12. A.M. Nathan and D.E. Alburger, Phys. Rev. C **15**, 1448 (1977).
13. F. Ajzenberg-Selove et al., Phys. Rev. C **15**, 1 (1977).
14. M. Matoba et al., Phys. Rev. C **48**, 95 (1993).
15. A. Winther and K. Alder, Nucl. Phys. A **319**, 518 (1979).
16. D.R. Goosman et al., Phys. Rev. C **8**, 1324 (1973).
17. B.A. Brown and B.H. Wildenthal, Ann. Rev. Part. Nucl. Sci. **38**, 29 (1988). The sd-shell energies obtained with the USD interaction are given on www.nscl.msu.edu/~brown/sde.htm.