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Single-particle structure along the boundary of the ''island of inversion'': Radioactive beam spectroscopy of ^{33}Si and ^{34}P

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Intermediate-energy Coulomb excitation has been used to study excited states in the radioactive $N=19$ nuclei ^{33}Si and ^{34}P, which are neutron-rich spherical nuclei located along the boundary of the ''island of inversion.'' The present results for the 1010 keV state in ^{33}Si and states up to 2.2 MeV excitation energy in ^{34}P can be understood in terms of $0\hbar\omega$ (nonintruder) configurations. This suggests that the energy differences between $0\hbar\omega$ and $2\hbar\omega$ configurations are large enough in ^{33}Si and ^{34}P that the low-lying $0\hbar\omega$ states are not significantly perturbed.

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The strongly deformed ground state shapes of several neutron-rich nuclei at or near the $N=20$ shell closure have provided an important challenge to the field of nuclear structure for more than 20 years. Only three $N=20$ isotones (^{30}Ne, ^{31}Na, and ^{32}Mg) appear to be deformed in their ground states, and the occurrence of deformed ground states in these three nuclei can be understood in the larger framework of shape coexistence which occurs all along the $N=20$ shell closure. One of the remarkable consequences of this shape coexistence is the sharp contrast between the $N=20$ isotones ^{34}Si, which is rigidly spherical in its ground state [1], and ^{32}Mg, in which the ground state is strongly deformed [2,3]. The low-lying behavior of ^{32}Mg is generally understood in terms of excitations of neutrons across the $N=20$ shell closure (called $2\hbar\omega$—or intruder—configurations), while the spherical shape of the ground state of ^{34}Si can be explained with sd-shell orbits ($0\hbar\omega$ configurations) [4–7].

In the present Rapid Communication, we report measurements of two spherical nuclei which are neighbors of ^{34}Si using the technique of intermediate-energy Coulomb excitation, which is described in Refs. [2,8,9]. In ^{33}Si, we have measured the electromagnetic matrix element $B(E2\uparrow)$ for exciting a state at 1010 keV. We reproduce the experimental matrix element with a shell model calculation in which only $0\hbar\omega$ configurations are used and which assumes that the ground state and the 1010 keV excited state of ^{33}Si are dominated by $d_{3/2}$ and $s_{1/2}$ single neutron hole configurations, respectively, coupled to the spherical ^{34}Si core. The γ rays observed in the measurement of ^{34}P provide evidence that members of the $\pi(d_{3/2})\nu(d_{3/2})^{-1}$ multiplet have strong $E2$ matrix elements connecting them to the ground state, which is dominated by the $\pi(s_{1/2})\nu(d_{3/2})^{-1}$ configuration. Once again, these data can be understood in terms of $0\hbar\omega$ configurations. While the energy gap between the $0\hbar\omega$ and $2\hbar\omega$ configurations has not been measured in $Z<16$ nuclei for either $N=19$ or 20, the present results suggest that the energy of the $2\hbar\omega$ configurations in ^{33}Si and ^{34}P is large enough so that the structure of the low-lying $0\hbar\omega$ states is not significantly perturbed.

The experiments were performed at the National Superconducting Cyclotron Laboratory (NSCL). 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 midacceptance target position of the A1200 fragment separator [10].

A 518 mg/cm^2 ^{197}Au foil was used as the secondary target. The secondary beams slowed significantly in this target, and the beam energies used in the analysis of the γ-ray cross sections were those of the secondary beams in the middle of the secondary ^{197}Au target. For ^{33}Si and ^{34}P, these energies were 40.8 and 44.4 MeV/nucleon, respectively. The secondary beams were stopped in a cylindrical fast/slow plastic phoswich detector located at zero degrees. Both energy loss in the phoswich detector and time of flight relative to the cyclotron RF signal were used for particle identification. The zero-degree detector subtended the scattering angles of 0° to 3.96° in the laboratory. In total, 1.02×10^9 ^{33}Si beam particles were detected in the zero-degree detector. For ^{34}P, the total number of detected particles was 1.06×10^8.

The γ rays were detected in coincidence with the zero-degree detector by the NSCL NaI(Tl) array [11]. The γ-ray spectrum measured in coincidence with beam particles identified as ^{33}Si and ^{34}P in the zero-degree detector are shown in Fig. 1. The upper panels show the background subtracted spectra in the laboratory frame. The lower panels show the corresponding spectra in the projectile frame (that is, with a Doppler correction). The 547 keV $7/2^+\rightarrow3/2^+_{\mathrm{g.s.}}$ γ ray in the ^{197}Au target nucleus appears strongly in both the laboratory-frame spectra.

The projectile-frame spectrum for ^{33}Si shows two clear peaks at 1010 ± 7 and 1924 ± 5 keV. The spectrum also ap-

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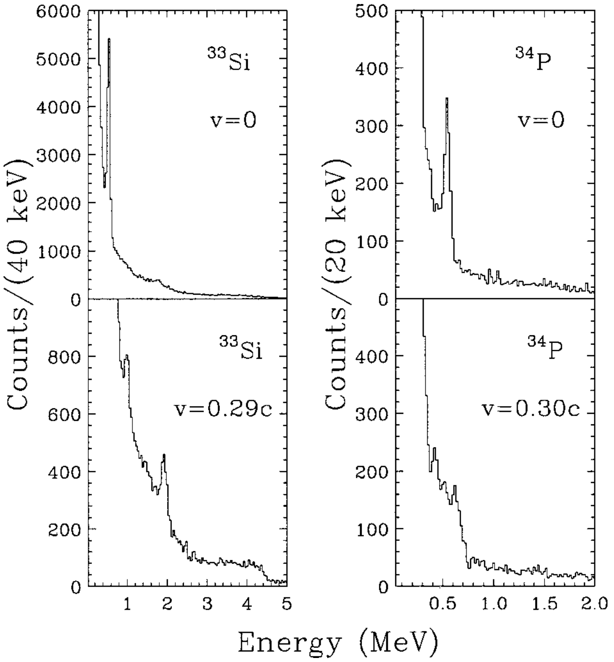

FIG. 1. Photon spectra gated on ^{33}Si and ^{34}P beams. The upper panels show the laboratory-frame spectra, while the lower panels illustrate projectile-frame spectra (adjusted for Doppler shifts).

pears to have a sharp cutoff near 4300 keV, and this may indicate another transition at this energy. The 1010 keV γ ray was first observed in ^{33}Si during a study of neutron-rich products from heavy-ion collisions by Fornal *et al.* [12]. They identified this γ ray with a state at 1.06±0.02 MeV seen by Fifield *et al.* [13] in the ^{36}S(^{11}B,^{14}N)^{33}Si reaction. This γ ray is produced in the present experiment (that is, with the projectile scattering angle integrated over the laboratory angular range of 0° to 3.96° corresponding to less than 4.62° in the center of mass) with a cross section of 4.1±0.8 mb. The 1924 keV γ ray is close to the energy of the $2_1^+ \rightarrow 0_{\mathrm{g.s.}}^+$ 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 that this is the explanation for the 1924 keV γ ray in this spectrum. The cross section for production of this γ-ray is 11.7±1.4 mb. The γ-ray yield around 4.3 MeV, for which the cross section is 11.6±2.2 mb, may arise from excitation of the 4.3 MeV state of ^{33}Si seen in the ^{36}S(^{11}B,^{14}N)^{33}Si reaction or from population of the 4230.8 keV 2_2^+ state in ^{32}Si via neutron stripping. Assuming Coulomb excitation to the 4.3 MeV state, the measured excitation cross section corresponds to $B(E2\uparrow)=69\pm13\ e^2\ \mathrm{fm}^4$, which is consistent with the shell model prediction discussed below.

For ^{34}P, the projectile-frame spectrum includes two peaks at 422±7 and 627±9 keV. A 429.1 keV γ ray was observed by Nathan and Alburger [14] in the β decay of ^{34}Si. They identified this transition as the ground state decay of a state seen in the ^{34}S(t,^{3}He)^{34}P reaction [15] at 423±10 keV. In the present experiment, this γ ray is produced with a cross section of 5.2±2.4 mb.

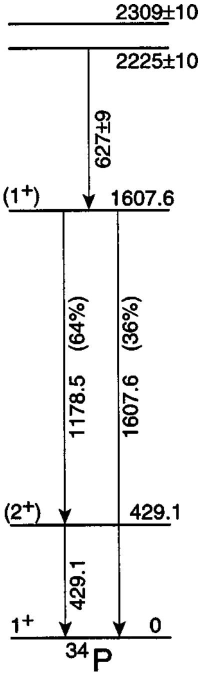

FIG. 2. Level scheme of ^{34}P relevant to the present study. All four excited states were previously identified in [15]. The excitation energies of the levels below 2 MeV and the branching ratio for the 1607.6 keV state are taken from [14].

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 single-neutron stripping reaction. However, the energy difference between two states observed in the ^{34}S(t,^{3}He)^{34}P reaction [15] at 2225±10 and 1605 ±10 keV matches the measured energy of this γ ray to within the experimental uncertainty. The energy of the latter state was determined with more precision by Nathan and Alburger to be 1607.6 keV via the observation of a γ ray of that energy decaying to the ground state and another γ ray of energy 1178.5 keV decaying to the 429.1 keV state. We suggest that the 627 keV γ ray observed here, which was produced with a cross section of 6.8±3.0 mb, connects the 2225±10 keV level with the 1607.6 keV level. This in turn implies that the 2225 keV level is populated in the Coulomb excitation reaction being reported here. The deexcitation scheme we are suggesting is illustrated in Fig. 2. According to Nathan and Alburger, 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). Of course, the 429.1 keV γ ray appears clearly in the ^{34}P γ ray spectrum. In fact, the measured cross section of 5.2±2.4 mb for production of the 429.1 keV γ ray can be explained by the hypothesis that the 429.1 keV state is not directly populated in the Coulomb excitation reaction at all, but is populated only via feeding from the 1607.6 keV state. Of course, 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. Therefore, the lack of visible γ-ray peaks at 1178 and 1608 keV is consistent with the feeding pattern proposed above.

The extraordinary contrast in the ground state shapes of

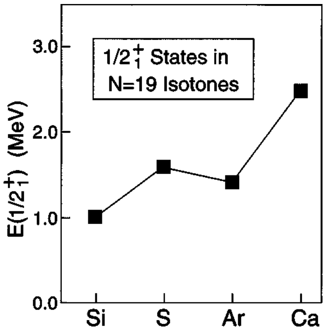

FIG. 3. Energies of the $1/2_1^+$ states in the $N=19$ isotones. Data are taken from [17–19] and the present work.

spherical ^{34}Si and deformed ^{32}Mg is caused by the competition between configurations in which all 20 neutrons remain in the closed sd shell ($0\hbar\omega$ configurations) and configurations in which two neutrons are promoted across the $N=20$ gap ($2\hbar\omega$ configurations). In ^{34}Si—and heavier $N=20$ isotones—the spherical $0\hbar\omega$ configuration has a lower energy. In three $N=20$ isotones—^{32}Mg, ^{31}Na, and ^{30}Ne—the deformed $2\hbar\omega$ configuration becomes the ground state. That is, the two configurations become ''inverted,'' and the group of deformed nuclei at and near the $N=20$ shell closure is called the ''island of inversion.'' The difference between the energies of the $0\hbar\omega$ and $2\hbar\omega$ configurations is not known experimentally in either ^{32}Mg or ^{34}Si, or in any of the other $N=19$, 20, and 21 isotones with $Z<16$. In ^{34}Si, the theoretical calculations presented in Refs. [4,6] predict that the $2\hbar\omega$ configuration is 1.8 MeV higher than the $0\hbar\omega$ configuration. The authors of Refs. [4,6] also predict that the $2\hbar\omega$ configuration is approximately 1 MeV lower than the $0\hbar\omega$ configuration in ^{32}Mg. Of more immediate relevance to the present study are the $E(2\hbar\omega)-E(0\hbar\omega)$ energy differences predicted for ^{33}Si and ^{34}P. For ^{33}Si, Caurier *et al.* [6] predict 3.35 MeV, while Warburton, Becker, and Brown [4] predict 2.72 MeV. Caurier *et al.* do not provide a prediction for ^{34}P, but Warburton, Becker, and Brown 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 almost certainly a $0\hbar\omega$ state, while the states near 2.5 MeV are still likely to be dominated by $0\hbar\omega$ configurations although they are closer to the $2\hbar\omega$ threshold.

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 [16]. For ^{39}Ca and ^{37}Ar, the ^{40}Ca(p,d) and ^{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 [17,18]. There are no ^{36}S(p,d) data available for ^{35}S; however, ^{34}S(d,p) results support the same interpretation of the ground state and first excited state in ^{35}S [19]. Clearly, the systematics favor a $J^\pi=3/2^+$ assignment for the ground state of ^{33}Si and a $J^\pi=1/2^+$ assignment for the 1010 keV state observed in the present study of ^{33}Si. The energies of the $J^\pi=1/2^+$ states in ^{39}Ca, ^{37}Ar, and ^{35}S are shown along with the 1010 keV state in ^{33}Si in Fig. 3. A simple interpretation of these results is that the separation between the $d_{3/2}$ and $s_{1/2}$ neutron orbits is decreasing as Z decreases. However, wave functions for these states obtained with standard sd-shell calculations with the USD interaction [20,21] show that a significant fraction of the $s_{1/2}$ spectroscopic strength gets fragmented into states at higher energy. When this fragmentation is taken into account the spacing between the $s_{1/2}$ and $d_{3/2}$ single-particle energies is actually rather constant with values of 2.47, 2.87, 2.18, and 1.92 MeV for $Z=20$, 18, 16, and 14, respectively.

Given these J^π assignments for the ground and 1010 keV states in ^{33}Si, we can extract a $B(E2\uparrow)$ value from the cross section observed for the 1010 keV γ ray ($M1$ excitations are strongly retarded in the present reaction). To do this, we use the relativistic theory of Winther and Alder [22] as described in [8]. The result for $B(E2\uparrow)$ for this excitation is $16.5\pm3.2\ e^2\ \mathrm{fm}^4$.

In ^{34}P, the ground state is known to have $J^\pi=1^+$ from its β decay to ^{34}S [23]. 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. Thus, it is reasonable to propose that the state at 429 keV is the 2^+ member of this multiplet.

The large energy gap between the 429 keV state and the next state at 1608 keV suggests that the latter state is a member of either the $\pi(s_{1/2})\nu(s_{1/2})^{-1}$ multiplet or the $\pi(d_{3/2})\nu(d_{3/2})^{-1}$ multiplet [15]. However, 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. This configuration would be populated from the ground state of ^{34}Si via the $\nu(d_{3/2})\rightarrow\pi(d_{3/2})$ transition [14]. We expect that the states reported in Ref. [15] at 2225 and 2309 keV are other members of this multiplet. Therefore, the spins of these two states would be limited to 0^+, 2^+, and 3^+. If the 2225 keV state is populated directly in the present Coulomb excitation reaction by a photon with $E2$ multipolarity, then it cannot have $J^\pi=0^+$. Furthermore, it must have an appreciable $E2$ matrix element to the ground state to be populated, so the 627 keV deexcitation to the 1608 keV state almost certainly has an $M1$ multipolarity (if it were $E2$, it would likely be overwhelmed by the much higher energy ground state decay). From this line of reasoning, we can suggest that 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 $20.2\pm9.6\ e^2\ \mathrm{fm}^4$, which would be extraordinarily large for an $E2$ matrix element connecting members of a two-particle multiplet. However, as noted above, 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 $26\pm12\ e^2\ \mathrm{fm}^4$ 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 (that is, they are limited to $0\hbar\omega$ configurations) with the USD interaction [21]. 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 $B(E2\uparrow)=19.1\ e^2\,\text{fm}^4$ for this state, which reproduces our experimental result of $16.5\pm3.2\ e^2\ \text{fm}^4$. Of course, a measurement of the $^{34}\text{Si}(p,d)^{33}\text{Si}$ reaction would provide a more definitive test of the interpretation of the ground state and 1010 keV state as $d_{3/2}$ and $s_{1/2}$ single neutron states (respectively). Studies of direct reactions such as this one are now possible at the new generation of radioactive beam facilities coming on line. The USD prediction for the spectroscopic factors and energies of the lowest two $1/2^+$ states are $S=1.46$ for a state at 0.85 MeV and $S=0.42$ for a state at 4.93 MeV. The same shell model calculation predicts a $5/2^+$ state at 4.38 MeV with a $B(E2\uparrow)=22.3\ e^2\ \text{fm}^4$ as well as a $3/2^+$ state at 4.42 MeV with a $B(E2\uparrow)=26.6\ e^2\ \text{fm}^4$. This predicted transition strength is consistent with the experimentally observed photon yield around 4.3 MeV, which corresponds to a total strength of $B(E2\uparrow)=69\pm13\ e^2\ \text{fm}^4$.

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 $0.3\ e^2\ \text{fm}^4$, 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 $B(E2\uparrow)=9.6\ e^2\ \text{fm}^4$ for this state. This calculation highlights the relatively strong $E2$ 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). The effect of the $\pi s_{1/2}\rightarrow\pi d_{3/2}$ transition seems to provide the most reasonable explanation for the excitation of the 2225 keV state in the present measurement of ^{34}P. An investigation of this nucleus with higher γ-ray resolving power and γ-γ coincidences will be required to answer the questions raised in our interpretation of the present ^{34}P γ-ray spectrum.

In summary, this Rapid Communication demonstrates that low-lying states in these nuclei right at the boundary of the ''island of inversion'' can be understood in the framework of $0\hbar\omega$ excitations. While the energy differences between the $0\hbar\omega$ and $2\hbar\omega$ configurations have not been measured experimentally in these neutron-rich $N=19$ isotones, the present results provide evidence that this gap remains large enough for $Z\geqslant14$ that the $0\hbar\omega$ states are not significantly perturbed.

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