Selectivity of the one-neutron knockout reaction on ^{45}Cl and the collapse of the $N = 28$ shell closure

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Abstract

Neutron hole states in the exotic $N = 27$ isotope ^{44}Cl have been populated using the intermediate energy single-neutron knockout reaction ^{9}Be(^{45}Cl,^{44}Cl)X. The momentum distribution of the residual ^{44}Cl nuclei after direct population of the ground state is consistent with removal of an $l = 1$ neutron. This observation and comparison with a shell model calculation imply that $p_{3/2}$ neutrons from above the $N = 28$ major shell closure play important roles in the ground states of both ^{44}Cl and ^{45}Cl. The present result is significant because ^{44}Cl is even closer to the valley of stability than ^{43}S, where a similar result was recently obtained using a g-factor measurement.

The neutron-rich nuclei in the vicinity of the $N = 28$ major shell closure have become a critical laboratory for developing the experimental and theoretical tools to gain a deep understanding of nuclear structure in exotic nuclei. The experimental advances demonstrated in studies of reactions that selectively populated single neutron and single neutron-hole states coupled to exotic ^{46}Ar [1–4] are paving the way for the determination of the role of the tensor force in the apparent narrowing of the gap at $N = 28$ between the $0f_{7/2}$ and $1p_{3/2}$ orbits. In the present work, we report on a study of the single neutron-knockout reaction from the $N = 28$ isotope ^{45}Cl at intermediate beam energies. Using this highly selective reaction, we were able to demonstrate that the $1p_{3/2}$ neutron orbit plays an important role in the ground states of both ^{45}Cl and its $N = 27$ neighbor ^{44}Cl, even though this orbit lies above the $N = 28$ shell closure. Gaudefroy *et al.* [5] recently reached a similar conclusion regarding the ground state of the $N = 27$ isotone ^{43}S using a g-factor measurement of an isomer in that nucleus. The present result demonstrates the intrusion of an orbit from above the $N = 28$ shell closure in a nucleus even closer to the valley of stability than ^{43}S.

The experiment was performed at the Coupled-Cyclotron Facility of the National Superconducting Cyclotron Laboratory at Michigan State University. A cocktail beam including 16 % ^{45}Cl was produced by fragmentation of a 140 MeV/nucleon ^{48}Ca primary beam incident on a 705 mg/cm^2 ^{9}Be fragmentation target. Components of the secondary beam were separated in the A1900 fragment separator [6] and delivered to a 376 mg/cm^2 thick ^{9}Be reaction target mounted at the target position of the S800 magnetic spectrograph [7]. A total of 2.59×10^7 ^{45}Cl beam particles were incident on the reaction target. The mid-target beam energy was 99.6 MeV/nucleon. Incoming beam particles were identified from their time-of-flight difference measured between scintillators mounted at the extended focal plane of the A1900 and at the object of the S800 analysis line, and projectile-like reaction products were identified by the time-of-flight to the focal plane of the S800 and energy loss in the S800 ion chamber.

An inclusive single neutron knockout cross section of $\sigma_{inc} = 128(11)$ mb to bound final states of ^{44}Cl was determined from the number of outgoing ^{44}Cl particles relative to the number of incoming ^{45}Cl beam particles and the particle density of the reaction target. The uncertainty in the inclusive cross section includes the stability of the composition of the incoming beam (8%), the correction for the momentum acceptance of the S800 (3%), and the software gates used to select the reaction of interest (1%).

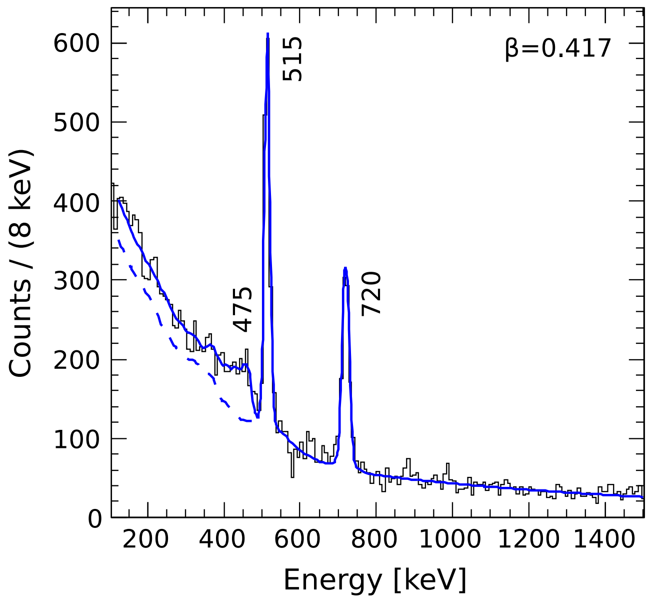

FIG. 1: Spectrum of gamma rays measured in coincidence with recoiling ^{44}Cl particles. The solid curve is the Geant4 fit described in the text. The dashed curve is the fit without the 475 keV gamma ray.

Gamma rays emitted by excited reaction products were detected by the Segmented Germanium Array (SeGA) [8] of 32-fold segmented high purity germanium detectors. The Doppler-reconstructed energy spectrum of gamma rays from outgoing ^{44}Cl particles is shown in Fig. 1. Measured laboratory-frame gamma-ray energies were Doppler corrected using a velocity of $\beta = 0.417$. Geant4 [9] simulations of the response of SeGA to gamma rays were used to extract total gamma-ray yields from the measured spectrum. The measured spectrum was fitted with a linear combination of the simulated responses of the observed gamma rays and an exponential function, included to account for the empirically-observed prompt component of the background. The resulting fit is shown as a solid curve in Fig. 1.

In addition to the dominant gamma rays at 515 keV and 720 keV, the fitting process revealed a broad peak at 475 keV. The dashed line in Fig. 1 corresponds to the best fit without the contribution of this transition. We attribute the significant broadening of the photopeak of the 475 keV gamma ray to the lifetime of the state it de-excites. The best fit, shown in Fig. 1, is obtained with a mean lifetime of $1.5^{+5.0}_{-1.0}$ ns. The lower limit on the error range is based on a χ^2 analysis of the photopeak and Compton edge of the 475 keV gamma ray. Using a χ^2 test, we can rule out mean lifetimes below 500 ps at the 5% level and those below 420 ps at the 1% level. Above the best-fit lifetime, χ^2 does not increase rapidly enough to establish an upper limit. However, the yield of the 475 keV gamma ray from the fit increases with increasing lifetime. The upper limit on lifetime corresponds to the balance of the inclusive cross section not accounted for by knockout to the ground and excited states observed.

The momentum distribution of the recoiling ^{44}Cl nuclei was analyzed for the direct population of its ground state using the method described in Ref. [10]. The ground-state momentum distribution shown in panel (c) of Fig. 2 was obtained by subtracting the scaled distribution, measured in coincidence gamma rays with energies between 110 and 5000 keV, shown in panel (b) of the figure from the inclusive momentum distribution in panel (a). The integrated ground-state distribution corresponds to a cross section of 12(3) mb. In the figure, these experimental results are compared with eikonal-model calculations produced using the method described in Ref. [11] to reveal the orbital angular momentum l of the single particle state from which the neutron is removed in the incident ^{45}Cl to populate the final ^{44}Cl state. These theoretical distributions have been transformed to the laboratory frame and folded with the measured momentum distribution of the incoming ^{45}Cl beam. They assume neutron removal from single-particle states with orbital angular momentum $l = 1$ (dashed) and $l = 3$ (dotted) and separation energy 6.2 MeV. The measured inclusive and gamma-gated distributions exhibit low-momentum tails below 18.4 GeV/c typically observed in knockout measurements [1, 10, 12–15]. This phenomenon is not well understood and is not accounted for by the eikonal-model calculations. In panel (c), the theoretical distributions have been scaled to fit the integrated measured distribution above 18.4 GeV/c. In panel (a) of Fig. 2, the solid curve is a linear combination of the theoretical $l = 1$ and $l = 3$ distributions giving the best fit to the inclusive momentum distribution above 18.4 GeV/c. The fit to the inclusive distribution yields a total measured cross section for $l = 1$ neutron removal of 16.6(14) mb.

In the simplest picture of the $N = 27$ and 28 isotopes ^{44}Cl and ^{45}Cl, the valence neutrons are located in the $0f_{7/2}$ orbit (having $l = 3$). Hence, we would at first expect to see the experimental momentum distribution of the ground state reproduced by a calculation that assumes knockout from an $l = 3$ orbit. However, the population of the ground state in ^{44}Cl proceeds by knockout of an $l = 1$ neutron - presumably from the $p_{3/2}$ orbit.

While the ground state spin in ^{45}Cl has not been measured, we can appeal to a shell

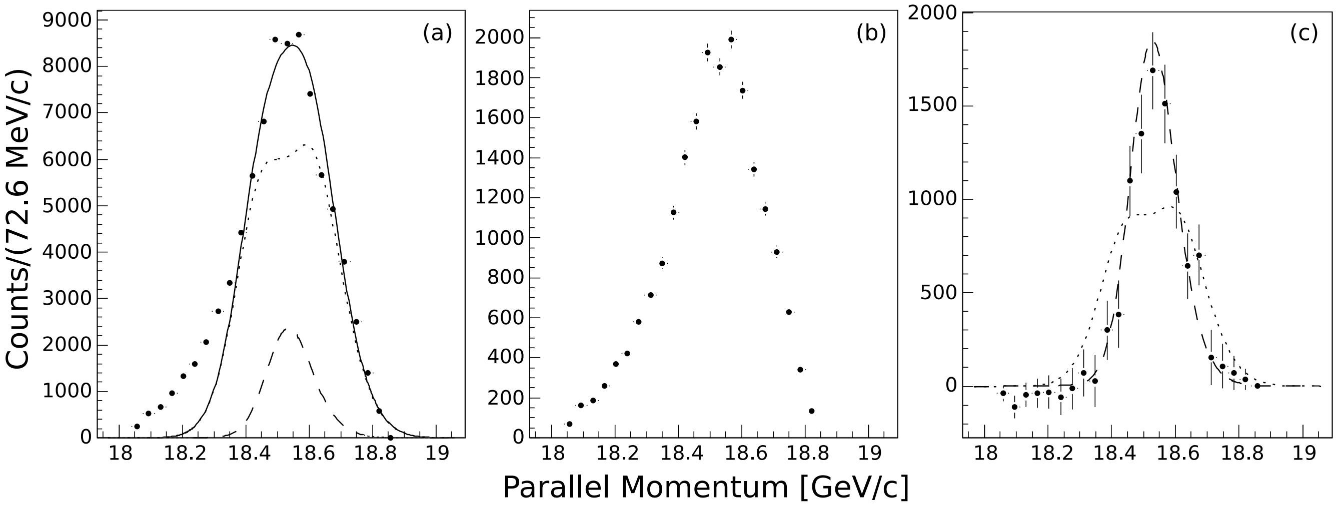

FIG. 2: (a) Inclusive, (b) gamma-gated, and (c) ground-state parallel momentum distributions of ^{44}Cl particles produced in one-neutron knockout from ^{45}Cl. The dashed (dotted) curves are theoretical distributions for $l = 1$ ($l = 3$) neutron removal. The solid curve in panel (a) is the fit described in the text.

model calculation for guidance on its spin and structure. The shell-model configuration-interaction calculations were carried out in the model space of the sd shell for protons and the pf shell for neutrons with the SDPF-NR Hamiltonian [16], as was done for the study of the odd-A K, Cl and P isotopes in Ref. [2]. This calculation gives $J^{\pi} = 1/2^{+}$ (with a $1s_{1/2}$ unpaired proton) for the ground state of ^{45}Cl. The calculation yields neutron spectroscopic factors for the ^{45}Cl ground state of 6.63, 0.23, 1.03 and 0.10 for the $0f_{7/2}$, $0f_{5/2}$, $1p_{3/2}$ and $1p_{1/2}$ orbitals, respectively. In addition, the calculation predicts that the ground state for ^{44}Cl has $J^{\pi} = 2^{-}$, and this spin value alone makes it clear why the population of this state results from $l = 1$ neutron knockout instead of the $l = 3$ $0f_{7/2}$ neutron knockout: With the unpaired proton in the ground state of ^{45}Cl being $1s_{1/2}$, an $l = 3$ knockout cannot populate the $J = 2$ ground state of ^{44}Cl. Instead, the only way to populate this state is via the knockout of a $l = 1$ $1p_{3/2}$ neutron from the ^{45}Cl ground state, which in turn can only occur because of the significant $1p_{3/2}^{2}$ component in the ground state of the latter nucleus. In the framework of the calculation, this large $1p_{3/2}$ neutron occupation is responsible for the large cross section for the $l = 1$ knockout to the ground state of ^{44}Cl. In short, the selectivity of the neutron knockout reaction gives us an opportunity to probe the ground states of these nuclei for components involving such neutron intruder orbits from above the $N = 28$ shell closure.

The theoretical cross section for single nucleon knockout to a final state identified by nJ^{π} is given by [17]

$$\sigma_{\rm th}(nJ^{\pi}) = \left(\frac{A}{A-1}\right)^{N} C^2S\ \sigma_{\rm sp}(l, B_n), \tag{1}$$

where $\sigma_{\rm sp}(nJ^{\pi})$ is the single-particle cross section from eikonal-model calculations, C^2S is the shell-model spectroscopic factor, N is the oscillator quantum number of the removed nucleon, l is the angular momentum of its orbital, and $B_n = S_n + E_x$ is the energy required to remove the nucleon and populate the final state of the residue with excitation energy E_x. The ground-state spectroscopic factor from the shell model is 0.32, and the single particle cross section is 18.68 mb, giving a theoretical cross section for the ground state of $\sigma_{th} = 5.98$ mb, roughly half of the measured cross section. The total theoretical cross section for $l = 1$ neutron removal below the neutron separation energy $S_n = 4.0(3)$ MeV is 17.9 mb, consisting of 16.9 mb from the $p_{3/2}$ orbital and 1.0 mb from the $p_{1/2}$ orbital. This is much closer to the measured total $l = 1$ cross section.

However, it has been demonstrated in both $(e, e'p)$ with stable nuclei and in single-nucleon knockout measurements away from stabililty that measured knockout cross sections are suppressed relative to shell-model predictions. The systematic dependence of this reduction on the difference in proton and neutron separation energies is discussed in detail in Ref. [18]. On the basis of systematics, a suppression factor of 0.72(2) is expected for one-neutron removal from ^{45}Cl. Hence, we would expect the measured cross sections to be roughly 30% smaller than the theoretical predictions. We conclude, based on the measured ground state and total $l = 1$ cross sections, that the $l = 1$ strength is concentrated at lower energy than is predicted by the shell model calculations. These results indicate the need for a lowering of the $p_{3/2}$ single particle energy approaching ^{42}Si. A lowering of the $p_{3/2}$ single particle energy by 0.5 MeV (1.0 MeV) increases the ground-state spectroscopic factor from 0.32 to 0.495 (0.669). The consequences of such a change for other spectroscopic data including energy levels must be explored to confirm this.

The shell model calculation also provides electromagnetic matrix elements for the transitions from the states we observe in the present experiment. The calculation predicts that the $J^{\pi} = 4^{-}$ state at 620 keV is an isomer, deexciting via an $E2$ transition to the ground state and via an $M1$ transition to the 515 keV state. In the experiment, the isomer is at 475 keV and is the first excited state, so we conclude that this state corresponds to the 620 keV state in the calculation. If we take the ground state to have $J^\pi = 2^-$ and the 475 keV state to have $J^\pi = 4^-$ as their corresponding states do in the calculation, then the only channel for the 475 keV state decay is via an $E2$ transition to the ground state. From the present measurement of the isomer's lifetime, we conclude that the reduced matrix element for this transition is $B(E2; 4^- \rightarrow 2^-) = 22^{+45}_{-17}\ e^2\text{fm}^4$. The shell model calculation predicts 49 $e^2\text{fm}^4$, which is consistent with the experimental result.

The population of the ground state in ^{44}Cl via $l = 1$ knockout from ^{45}Cl is a symptom of the breakdown of the $N = 28$ major shell closure in neutron-rich nuclei. Piekarewicz [19] calculated that this gap, defined to be the energy difference between the $0f_{7/2}$ and $1p_{3/2}$ neutron orbits, is approximately 2 MeV narrower at $Z = 14$ (Si) than it is at $Z = 20$ (Ca). This phenomenon, which is associated with the nearby neutron dripline, was first highlighted by a measurement of the $B(E2; 0^+_{gs} \rightarrow 2^+_1)$ value in ^{44}S [20], which has one proton less than ^{45}Cl. Recent measurements of ^{42}Si and ^{43}P have examined the effects that the narrowing of the $N = 28$ gap has on these nuclei [15, 21–23]. Most recently, Gaudefroy *et al.* [5] deduced from a g-factor measurement of an isomer in ^{43}S that the ground state of that nucleus has $J^\pi = 3/2^-$ and arises from the intrusion of the $p_{3/2}$ neutron orbit from above the $N = 28$ major shell closure. We have reached a similar conclusion here for the ^{44}Cl ground state; however,^{44}Cl is closer to the valley of stability than ^{43}S is.

In summary, we have used the one-neutron knockout reaction on the $N = 28$ isotope ^{45}Cl to study the ground state of ^{44}Cl for the first time. The knockout reaction to the ground state proceeded via $l = 1$ neutron removal, implying the knockout of a neutron from the $1p_{3/2}$ orbit, which is located above the $N = 28$ shell closure. This measurement indicates that the collapse of the N=28 major shell closure in neutron-rich isotopes observed [5] in ^{43}S persists in ^{44}Cl, a slightly more stable isotone.

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[1] A. Gade, D. Bazin, C. A. Bertulani, B. A. Brown, C. M. Campbell, J. A. Church, D. C. Dinca, J. Enders, T. Glasmacher, P. G. Hansen, et al., Phys. Rev. C **71**, 051301(R) (2005).

[2] A. Gade, B. A. Brown, D. Bazin, C. M. Campbell, J. A. Church, D. C. Dinca, J. Enders, T. Glasmacher, M. Horoi, Z. Hu, et al., Phys. Rev. C **74**, 034322 (2006).

[3] L. Gaudefroy, O. Sorlin, D. Beaumel, Y. Blumenfeld, Z. Dombradi, S. Fortier, S. Franchoo, M. Gelin, J. Gibelin, S. Grevy, et al., Phys. Rev. Lett. **97**, 092501 (2006).

[4] L. Gaudefroy, O. Sorlin, F. Nowacki, D. Beaumel, Y. Blumenfeld, Z. Dombradi, S. Fortier, S. Franchoo, S. Grevy, F. Hammache, et al., Phys. Rev. C **78**, 034307 (2008).

[5] L. Gaudefroy, J. M. Daugas, M. Hass, S. Grévy, C. Stodel, J. C. Thomas, L. Perrot, M. Girod, B. Rossé, J. C. Angélique, et al., Phys. Rev. Lett. **102**, 092501 (2009).

[6] D. J. Morrissey, B. M. Sherrill, M. Steiner, A. Stolz, and I. Wiedenhöver, Nucl. Instrum. Methods Phys. Res. B **204**, 90 (2003).

[7] D. Bazin, J. A. Caggiano, B. M. Sherrill, J. Yurkon, and A. Zeller, Nucl. Instrum. Methods Phys. Res. B **204**, 629 (2003).

[8] W. F. Mueller, J. A. Church, T. Glasmacher, D. Gutknecht, G. Hackman, P. G. Hansen, Z. Hu, K. L. Miller, and P. Quirin, Nucl. Instrum. Methods Phys. Res. A **466**, 492 (2001).

[9] S. Agostinelli, J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. Arce, M. Asai, D. Axen, S. Banerjee, G. Barrand, et al. (GEANT4 Collaboration), Nucl. Instrum. Methods Phys. Res. A **506**, 250 (2003).

[10] A. Gade, D. Bazin, B. A. Brown, C. M. Campbell, J. A. Church, D. C. Dinca, J. Enders, T. Glasmacher, P. G. Hansen, Z. Hu, et al., Phys. Rev. C **69**, 034311 (2004).

[11] P. G. Hansen and J. A. Tostevin, Annu. Rev. Nucl. Part. Sci. **53**, 219 (2003).

[12] J. Enders, A. Bauer, D. Bazin, A. Bonaccorso, B. A. Brown, T. Glasmacher, P. G. Hansen, V. Maddalena, K. L. Miller, A. Navin, et al., Phys. Rev. C **65**, 034318 (2002).

[13] J. R. Terry, B. A. Brown, C. M. Campbell, J. M. Cook, A. D. Davies, D.-C. Dinca, A. Gade, T. Glasmacher, P. G. Hansen, B. M. Sherrill, et al., Phys. Rev. C **77**, 014316 (2008).

[14] C. A. Diget, P. Adrich, D. Bazin, M. D. Bowen, B. A. Brown, C. M. Campbell, J. M. Cook, A. Gade, T. Glasmacher, K. Hosier, et al., Phys. Rev. C **77**, 064309 (2008).

[15] L. A. Riley, P. Adrich, T. R. Baugher, D. Bazin, B. A. Brown, J. M. Cook, P. D. Cottle, C. A.

Diget, A. Gade, D. A. Garland, et al., Phys. Rev. C **78**, 011303(R) (2008).

[16] S. Nummela, P. Baumann, E. Caurier, P. Dessagne, A. Jokinen, A. Knipper, G. L. Scornet, C. Miehe, F. Nowacki, M. Oinonen, et al., Phys. Rev. C **63**, 044316 (2001).

[17] B. A. Brown, P. G. Hansen, B. M. Sherrill, and J. A. Tostevin, Phys. Rev. C **65**, 061601(R) (2002).

[18] A. Gade, P. Adrich, D. Bazin, M. D. Bowen, B. A. Brown, C. M. Campbell, J. M. Cook, T. Glasmacher, P. G. Hansen, K. Hosier, et al., Phys. Rev. C **77**, 044306 (2008).

[19] J. Piekarewicz, J. Phys. G **34**, 467 (2007).

[20] T. Glasmacher, B. A. Brown, M. J. Chromik, P. D. Cottle, M. Fauerbach, R. W. Ibbotson, K. W. Kemper, D. J. Morrissey, H. Scheit, D. W. Sklenicka, et al., Phys. Lett. B **395**, 163 (1997).

[21] J. Fridmann, I. Wiedenhöver, A. Gade, L. T. Baby, D. Bazin, B. A. Brown, C. M. Campbell, J. M. Cook, P. D. Cottle, E. Diffenderfer, et al., Nature **435**, 922 (2005).

[22] J. Fridmann, I. Wiedenhöver, A. Gade, L. T. Baby, D. Bazin, B. A. Brown, C. M. Campbell, J. M. Cook, P. D. Cottle, E. Diffenderfer, et al., Phys. Rev. C **74**, 034313 (2006).

[23] B. Bastin, S. Grévy, D. Sohler, O. Sorlin, Z. Dombrádi, N. L. Achouri, J. C. Angélique, F. Azaiez, D. Baiborodin, R. Borcea, et al., Phys. Rev. Lett. **99**, 022503 (2007).