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# Gamma-ray spectroscopy of one-proton knockout from $^{45}$Cl

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The role of proton shell effects in the structure of the $N = 28$ isotones $^{45}$Cl and $^{44}$S has been studied via one-proton knockout from $^{45}$Cl. We compare measured $\gamma$-ray intensties, inclusive and partial knockout cross sections, and the inclusive momentum distribution of outgoing $^{44}$S particles with shell-model and reaction-theory predictions. The strong population in this reaction of the recently identified $4_1^+$ state in $^{44}$S, identified through its subsequent gamma-ray decay energy, makes a compelling case for a $J^\pi = 3/2^+$ ground state in $^{45}$Cl.

The neutron-rich exotic isotones near $^{42}$Si have attracted considerable attention because of the novel role that neutron shell structure — and the narrowing or collapse of the $N = 28$ major shell closure — plays in causing deformation in these nuclei [1–17]. However, proton shell structure must also be involved [18–20]. Interest in the evolution of single-proton energies in the $N = 20-28$ Ca isotopes dates back to at least 1964, when Bansal and French [21] argued that the large gap that exists between the $d_{3/2}$ and $s_{1/2}$ proton orbits at $N = 20$ narrows with the addition of neutrons and finally disappears at $N = 28$ because of the interaction of protons in these orbits with the neutrons in the $f_{7/2}$ orbit.

Here we examine the role of proton shell structure in the $N = 28$ isotones via a measurement of the intermediate-energy one-proton knockout reaction from $^{45}$Cl at 99.6 MeV/nucleon. Recent two-proton and one-proton knockout measurements [17, 22] leading to $^{44}$S have solidified its level scheme. The intensities with which this reaction populates excited states in $^{44}$S, especially the $4^+$ state at 2447 keV [17], allows us to construct a strong argument that the ground-state spin of $^{45}$Cl is 3/2 and not the previous and tentative assignment of 1/2 proposed from systematics and comparison with shell-model calculations.

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 [23] and delivered to a 376 mg/cm$^2$ thick $^9$Be reaction target mounted at the target position of the S800 magnetic spectrograph [24]. A total of $2.59 \times 10^7$ $^{45}$Cl beam particles were delivered to the reaction target with a mid-target beam energy of 99.6 MeV/nucleon. Incoming $^{45}$Cl particles were identified using time-of-flight measured between scintillators mounted at the extended focal plane of the A1900 and at the object position of the S800 analysis line, and outgoing $^{44}$S particles were identified by the time-of-flight to the focal plane of the S800 and energy loss in the S800 ionization chamber.

The inclusive cross section of 13(1) mb for the one-proton knockout reaction from $^{45}$Cl was determined from the number of incoming $^{45}$Cl particles, the number of outgoing $^{44}$S particles, and the number 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%).

The measured inclusive momentum distribution of the $^{44}$S reaction products is compared with eikonal-model calculations in Fig. 1. The model calculations were produced using the method described in Ref. [25]. The solid curve in Fig. 1 is a linear combination of theoretical distributions assuming proton removal from single-particle states with orbital angular momentum $l = 0$ (dotted) and $l = 2$ (dashed) and a separation energy of 16.5 MeV. The relative $l = 0$ (20%) and $l = 2$ (80%) contributions are based on the shell-model calculations described below. The theoretical distributions have been transformed to the laboratory frame and folded with the measured momentum distribution of the incoming $^{45}$Cl beam. The measured distribution exhibits a low-momentum tail below 18.3 GeV/c typically observed in knockout measurements [12, 15, 26–29]. This phenomenon, discussed in detail in Ref. [12], is not accounted for by the eikonal-model calculations. The measured distribution has been corrected for the simulated acceptance of the S800 spectrograph. This correction affects only the low-momentum tail of the distribution and amounts to 2% of the total inclusive cross section.

Gamma rays emitted by excited reaction products were detected with the Segmented Germanium Array

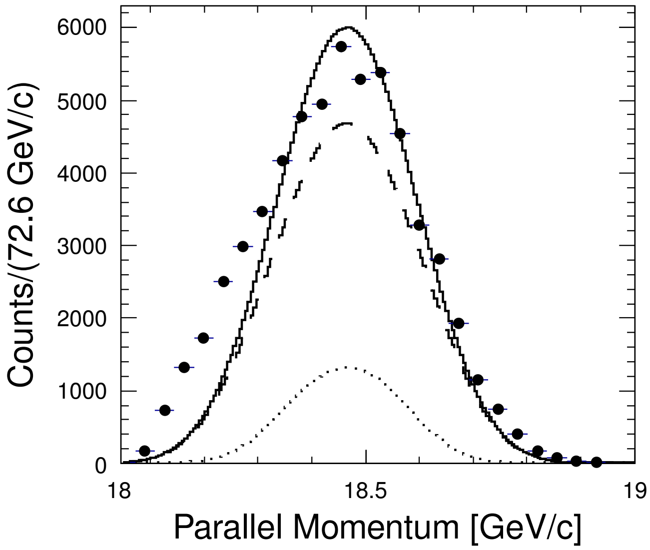


FIG. 1: Measured inclusive parallel momentum distribution of $^{44}$S particles produced in one-proton knockout from $^{45}$Cl. The dashed (dotted) curves are theoretical distributions for $l = 2$ ($l = 0$) proton removal. The solid curve is the linear combination of these theoretical distributions described in the text.

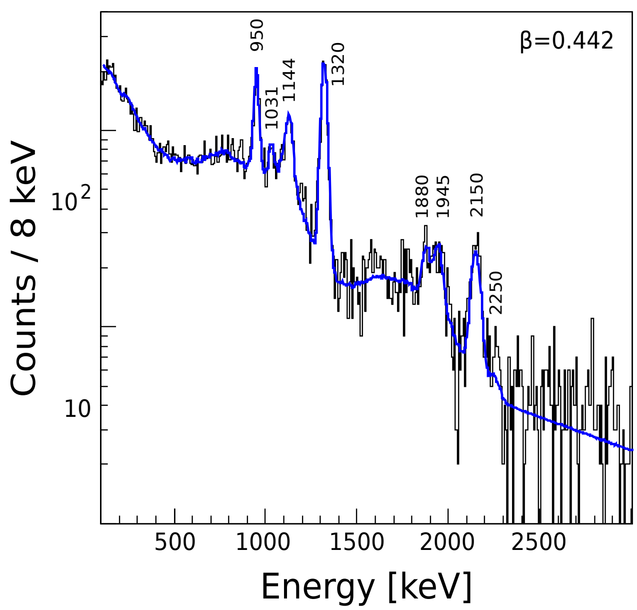


FIG. 2: (Color online) Doppler-corrected spectrum of $\gamma$ rays measured in coincidence with $^{44}$S particles. The solid curve is the GEANT4 fit described in the text.

(SeGA) [30] of 32-fold segmented high purity germanium detectors. The projectile-frame energy spectrum of $\gamma$-ray transitions detected in coincidence with $^{44}$S particles in the focal plane of the S800 is shown in Fig. 2. A source velocity of $\beta = 0.442$ was used in the Doppler correction of measured laboratory-frame $\gamma$-ray energies. The solid curve in Fig. 2 is a linear combination of GEANT4 [31] simulations of the response of SeGA to the observed $\gamma$

TABLE I: Deduced $^{44}$S level energies $E_{\rm level}$ and $J^\pi$, energies of de-excitation $\gamma$ rays $E_\gamma$, $\gamma$-ray intensities $I_\gamma$ relative to that of the 1320 keV transition, partial knockout cross sections $\sigma$, and the corresponding direct population fractions BR relative to the inclusive knockout cross section from the present work.

| $E_{\rm level}$ [keV] | $J^\pi$ | $E_\gamma$ [keV] | $I_\gamma$ [%] | $\sigma$ [mb] | BR [%] |
|---|---|---|---|---|---|
| 0 | $0^+_{g.s.}$ | | | <1.3 | <10% |
| 1320(8) | $2^+_1$ | 1320(8) | 100(3) | 2.4(5) | 19(4) |
| 2150(13) | $(2^+_2)$ | 2150(13) | 21(2) | 2.2(2) | 17(2) |
| 2270(10) | $2^+_3$ | 950(6) | 42(3) | 3.5(3) | 28(4) |
| 2464(11) | $4^+_1$ | 1144(9) | 34(3) | 3.6(3) | 29(4) |
| 3301(12) | $(2^+_4)$ | 1031(6) | 9(2) | 0.9(2) | 7(2) |
| | | 1880(11) | 11(2) | | |
| | | 1945(12) | 13(2) | | |
| | | 2250(15) | <4 | | |

rays along with two exponential functions included to account for the empirically-observed prompt component of the background. The $\gamma$ rays seen in coincidence with $^{44}$S residues are listed in Table I along with intensities extracted from the fit, partial cross sections for populating states of $^{44}$S via one-proton knockout from $^{45}$Cl, and the corresponding direct population fractions.

A total cross section of 12.7(7) mb for knockout to excited states in $^{44}$S is given by the sum of the cross sections for producing the two $\gamma$ rays, at 1320 keV and 2150 keV, which directly feed the ground state. This, together with the inclusive knockout cross section allows us to place an upper limit on the cross section for direct population of the ground state of 1.3 mb. The cross sections for knockout to the ground state of $^{44}$S calculated using shell-model spectroscopic factors are 1.7(4) mb for a $J^\pi = 1/2^+$ ground state in $^{45}$Cl and 1.3(3) mb for a $J^\pi = 3/2^+$ ground state.

All of the $\gamma$ rays reported in the recent two-proton knockout study leading to $^{44}$S [17] were also observed in the present one-proton knockout experiment. The spin and parity assignments in Table I are from Ref. [17]. A related measurement to that of the present work was recently reported by Cáceres et al. [22] in which the same reaction was studied at a lower beam energy of 42 MeV/nucleon. Gamma rays were detected with the Château de Cristal array, which has greater efficiency but poorer resolution than SeGA. The inclusive knockout cross section of 13(3) mb reported in Ref. [22] is in excellent agreement with that of the present work. Observed $\gamma$-ray energies from Ref. [17] and energies and intensities from Ref. [22] are compared with those from the present work in Table II. Discrepancies are discussed below.

The 1880(11) keV and 1945(12) keV $\gamma$ rays seen in the present work correspond to the 1891(10) keV and 1929(7) keV $\gamma$ rays of Ref. [17]. In that study, the 1891 keV $\gamma$ ray was produced with significantly greater intensity than the 1929 keV $\gamma$ ray, while they have comparable intensities in the present work. On this basis, we conclude that they do not both de-excite the same state

TABLE II: Measured $\gamma$-ray energies $E_\gamma$ and intensities $I_\gamma$ from the present work, Ref. [17], and Ref. [22].

| Present work | | Ref. [17] | Ref. [22] | |
|---|---|---|---|---|
| $E_\gamma$ [keV] | $I_\gamma$ [%] | $E_\gamma$ [keV] | $E_\gamma$ [keV] | $I_\gamma$ [%] |
| 1320(8) | 100(3) | 1319(7) | 1321(10) | 100(8) |
| 2150(13) | 21(2) | 2150(11) | 2156(49) | 17(6) |
| 950(6) | 42(3) | 949(5) | 977(23) | 48(6) |
| 1144(9) | 34(3) | 1128(6) | 1198(25) | 18(3) |
| 1031(6) | 9(2) | - | 1006(25) | 12(3) |
| 1880(11) | 11(2) | 1891(10) | 1979(19)* | 24(5) |
| 1945(12) | 13(2) | 1929(7) | | |
| 2250(15) | <4 | - | 2262(38) | 21(5) |

*See text

as proposed in Ref. [17] but rather that they de-exite a pair of states populated with different relative cross sections by the single-proton and two-proton knockout reactions. We are unable to place these transitions in the level scheme.

A triplet of $\gamma$ rays at 1979(19), 2156(49), and 2262(38) keV is reported in Ref. [22]. The energy and intensity of the 2156(49) keV $\gamma$ ray agree with that of the 2150 keV $\gamma$ ray from the present work. We associate the 1979(19) keV $\gamma$ ray with the pair of $\gamma$ rays we observe at 1880 and 1945 keV which have a combined relative intensity in agreement with the intensity of the 1979 keV $\gamma$ ray of Ref. [22]. We are unable to account for the 2262(38) keV $\gamma$ ray. We have included a $\gamma$ ray at 2250 keV in the fit shown in Fig. 2. We place an upper limit of 4% on its relative intensity. It is doubtful that it corresponds to the 2262(38) keV $\gamma$ ray observed in Ref. [22] with a relative intensity of 21(5)%.

The 1144 keV $\gamma$ ray de-exciting the $4_1^+$ state, identified in Ref. [17], was also observed in the present work. The photopeak corresponding to this transition has a slightly broadened line shape with a low-energy tail, suggesting that it may de-excite a state with a lifetime on the order of 100 ps. The shell-model calculations discussed below predict a lifetime of 148 ps for the $4_1^+$ state — the only state with a calculated lifetime greater than 10 ps. A best fit to the measured line shape is obtained assuming a lifetime of 100(20) ps and an energy of 1144(9) keV. The energy of the photopeak in our Doppler-corrected spectrum is 1122(7) keV, which is consistent with the value of 1128(6) keV reported in Ref. [17]. We also identify the 1198(25) keV $\gamma$ ray observed in Ref. [22] with this $\gamma$ ray.

The 1144 keV $\gamma$ ray depopulating the $4_1^+$ state of $^{44}$S is the key result in this study. A tentative assignment of $J^\pi = 1/2^+$ was previously given for the $^{45}$Cl ground state based on systematics [32]. However, if the ground state of $^{45}$Cl were $J^\pi = 1/2^+$, then the observed proton knockout populating the $4_1^+$ state of $^{44}$S would require removal of a proton with at least $l = 4$. This is highly unlikely, thus suggesting that the ground state of $^{45}$Cl is not $J^\pi = 1/2^+$. In what follows, we use shell-model and reaction-model calculations to construct a strong argument that the ground state of the parent nucleus, $^{45}$Cl, has $J^\pi = 3/2^+$.

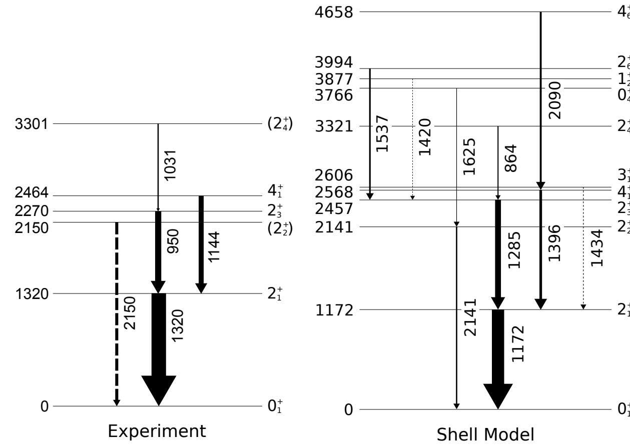


FIG. 3: Proposed level scheme of $^{44}$S based on the present work (left panel) and the shell-model level scheme described in the text (right panel). Only transitions with predected intensities above the measurement threshold of the present work, and the levels they involve, are included in the shell-model scheme.

The shell-model calculations performed for the present study use the SDPF-U interaction [33]. In these calculations, the lowest $1/2^+$ and $3/2^+$ states in $^{45}$Cl are nearly degenerate — only 132 keV apart — with the $1/2^+$ lower. We calculated spectroscopic factors for one-proton removal from both of these states to states in the daughter nucleus, $^{44}$S.

These spectroscopic factors were then folded into calculations of cross sections for the individual $^{44}$S states using the eikonal model described in Ref. [25]. The calculated cross sections for the individual states were adjusted by using a reduction factor determined by comparing the theoretical and measured inclusive cross sections for one-proton knockout to bound states of $^{44}$S. The assumptions of $J^\pi = 1/2^+$ and $3/2^+$ for the ground state of $^{45}$Cl give different theoretical inclusive cross sections, although they differ by only a small amount. With the assumption of a $J^\pi = 1/2^+$ ground state, the theoretical inclusive cross section must be multiplied by 0.44(4) to reproduce the measured inclusive cross section. If the ground state has $J^\pi = 3/2^+$, then the factor is 0.45(4).

The systematics of such "reduction factors", $R_s$, as a function of particle separation energies has been analyzed by Gade *et al.* [34, 35]. This systematics suggests $R_s = 0.42(2)$ for $^{45}$Cl assuming the difference between separation energies for protons and neutrons in $^{45}$Cl to be 10.3 MeV [36]. This is consistent with the values we extract from the observed inclusive cross sections with either assumed ground-state spin.

Fig. 3 shows a comparison of the pattern of $\gamma$-ray intensities observed in the present one-proton knockout experiment (right panel) with predictions made using the shell-model calculations, reaction-model calculations and

TABLE III: Measured $\gamma$-ray intensities from the present work compared with shell-model predictions described in the text assuming $J^\pi = 1/2^+$ and $J^\pi = 3/2^+$ for the ground state of $^{45}$Cl.

| | | Shell model | |
|---|---|---|---|
| $E_\gamma^{\mathrm{exp}}$ [keV] | $\mathrm{I}_\gamma^{\mathrm{exp}}$ [%] | $\mathrm{I}_\gamma^{1/2^+}$ [%] | $\mathrm{I}_\gamma^{3/2^+}$ [%] |
| 1320(8) | 100(3) | 100 | 100 |
| 2150(13) | 21(2) | 24 | 11 |
| 950(6) | 42(3) | 55 | 48 |
| 1144(9) | 34(3) | 2.6 | 21 |
| 1031(6) | 9(2) | 5 | 9 |

reduction factors described above with the assumption of a $J^\pi = 3/2^+$ ground state in $^{45}$Cl (left panel). All $\gamma$ rays predicted to have production cross sections of 0.50 mb or greater — approximately the threshold for observation in the present experiment — are included in the figures. This corresponds to an intensity threshold of 5% relative to the 1320 keV $2_1^+ \rightarrow 0_{g.s.}^+$ transition. The observed intensities along with shell-model predictions assuming both $J^\pi = 1/2^+$ and $J^\pi = 3/2^+$ for ground state of $^{45}$Cl are listed in Table III. It is predicted that the $\gamma$ ray de-exciting the $4_1^+$ state to the $2_1^+$ state will be produced with a cross section of 1.8 mb (21%) if the ground state of $^{45}$Cl has $J^\pi = 3/2^+$, and that it will have a cross section too small to be observed (0.2 mb, 3%) if the ground state of $^{45}$Cl has $J^\pi = 1/2^+$. In the experiment, this $\gamma$ ray was seen with a cross section of 3.6(3) mb (34%), providing a strong argument for a $J^\pi = 3/2^+$ ground state in $^{45}$Cl.

The values of $J^\pi$ for the ground states of $^{37,39}$Cl have been confirmed to be $3/2^+$ [37, 38], and both ground states display large spectroscopic factors when populated in ($d$,$^3$He) reactions, confirming the $d_{3/2}$ single-proton nature of these states. In both cases, $J^\pi = 1/2^+$ $s_{1/2}$ single-proton states have also been identified using the same reactions — at 1727 keV in $^{37}$Cl and at 396 keV in $^{39}$Cl.

The strong shift in the relative energies of the lowest-lying $1/2^+$ and $3/2^+$ states in $^{37}$Cl and $^{39}$Cl is driven in part by the shift in the gap between the single-proton energies of the two orbits as seen in ($d$,$^3$He) reactions on $^{40,42}$Ca (from 2.5 MeV in $^{40}$Ca to 1.9 MeV in $^{42}$Ca). This $d_{3/2} - s_{1/2}$ gap in the Ca isotopes continues to narrow as neutrons are added until the two orbits are nearly degenerate at $N = 28$ (in $^{48}$Ca).

Several shell-model calculations have predicted that the low-lying $1/2^+$ and $3/2^+$ states would invert in the $N = 24, 26$ and 28 Cl isotopes so that the $1/2^+$ state is the ground state. As a result, in the studies of Sorlin *et al.* [39] and Gade *et al.* [32] the ground states were tentatively assigned p$1/2^+$, and it was assumed that the first excited state in each (at 130 keV in $^{41}$Cl, 300 keV in $^{43}$Cl and 127 keV in $^{45}$Cl) had $J^\pi = 3/2^+$. In contrast the beta-decay study of Winger et al. [40] suggests a $3/2^+$ ground-state spin for $^{43}$Cl again confirming the close lying nature of these two states. In Ref. [41], the $B(M1\downarrow)$ value deduced from the measured lifetime of the 130 keV first-excited state of $^{45}$Cl can best be accounted for by assuming a $3/2^+$ ground state and $1/2^+$ first excited state. The present result demonstrates that, at least in the case of $^{45}$Cl, the tentative $1/2^+$ assignment may not be correct. Nevertheless, the most important conclusion of all of these shell-model calculations is that the lowest $1/2^+$ and $3/2^+$ states are nearly degenerate, and the present result does not disagree with that conclusion. It would be of interest to put the ground-state spins of the Cl isotopes on a firm footing experimentally, via laser spectroscopy e.g., to improve our understanding of proton shell structure near $N = 28$.

In summary, we have measured $\gamma$ rays from $^{44}$S following its population via the one-proton knockout reaction from $^{45}$Cl. The population of the $4_1^+$ state in $^{44}$S provides a compelling argument that the ground state of $^{45}$Cl has $J^\pi = 3/2^+$, rather than the $J^\pi = 1/2^+$ tentatively assigned previously.

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