**γ-ray spectroscopy of one-proton knockout from $^{45}$Cl**


1Department of Physics and Astronomy, Ursinus College, Collegeville, Pennsylvania 19426, USA
2National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA
3Department of Physics, Florida State University, Tallahassee, Florida 32306, USA
4Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA
5Department of Physics, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom

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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 γ-ray intensities, 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 γ-ray decay energy, makes a compelling case for a $J^\pi = 3/2^+$ ground state in $^{45}$Cl.

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 under the assumption of 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, as is 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 (SeGA) [30] of 32-fold segmented high-purity germanium detectors. The projectile-frame energy spectrum of γ-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 $\gamma$ 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 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 Cáreres 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)- and 1945(12)-keV $\gamma$ rays seen in the present work correspond to the 1891(10)- 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.

<table>
<thead>
<tr>
<th>$E_{\gamma}$ (keV)</th>
<th>$I_\gamma$ (%)</th>
<th>$E_{\gamma}$ (keV)</th>
<th>$E_{\gamma}$ (keV)</th>
<th>$I_\gamma$ (%)</th>
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<td>1320(8)</td>
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<td>1319(7)</td>
<td>1321(10)</td>
<td>100(8)</td>
</tr>
<tr>
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<td>21(2)</td>
<td>2150(11)</td>
<td>2156(49)</td>
<td>17(6)</td>
</tr>
<tr>
<td>950(6)</td>
<td>42(3)</td>
<td>949(5)</td>
<td>977(23)</td>
<td>48(6)</td>
</tr>
<tr>
<td>1144(9)</td>
<td>34(3)</td>
<td>1128(6)</td>
<td>1198(25)</td>
<td>18(3)</td>
</tr>
<tr>
<td>1031(6)</td>
<td>9(2)</td>
<td>–</td>
<td>1006(25)</td>
<td>12(3)</td>
</tr>
<tr>
<td>1880(11)</td>
<td>11(2)</td>
<td>1891(10)</td>
<td>1979(19)</td>
<td>24(5)</td>
</tr>
<tr>
<td>1945(12)</td>
<td>13(2)</td>
<td>1929(7)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2250(15)</td>
<td>&lt;4</td>
<td>2262(38)</td>
<td>21(5)</td>
<td></td>
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</table>

*See text.*
while they have comparable intensities in the present work. On this basis, we conclude that they do not both de-excite the same state as proposed in Ref. [17] but rather that they de-excite 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 γ rays at 1979(19), 2156(49), and 2262(38) keV is reported in Ref. [22]. The energy and intensity of the 2156(49)-keV γ ray agree with those of the 2150-keV γ ray from the present work. We associate the 1979(19)-keV γ ray with the pair of γ rays we observe at 1880 and 1945 keV, which have a combined relative intensity in agreement with the intensity of the 1979-keV γ ray of Ref. [22]. We are unable to account for the 2262(38)-keV γ ray. We have included a γ 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 γ ray observed in Ref. [22] with a relative intensity of 21(5)%.

The 1144-keV γ 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 by 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 γ ray observed in Ref. [22] with this γ ray.

The 1144-keV γ ray depopulating the 4^+_1 state of 44S is the key result in this study. A tentative assignment of J^π = 1/2^+ was previously given for the 45Cl ground state based on systematics [32]. However, if the ground state of 45Cl were J^π = 1/2^+, then the observed proton knockout populating the 4^+_1 state of 44S would require removal of a proton with at least I = 4. This is highly unlikely, thus suggesting that the ground state of 45Cl is not J^π = 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, 43Cl, has J^π = 3/2^+.

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 45Cl 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, 44S.

These spectroscopic factors were then folded into calculations of cross sections for the individual 44S 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 44S. The assumptions of J^π = 1/2^+ and 3/2^+ for the ground state of 45Cl give different theoretical inclusive cross sections, although they differ by only a small amount. With the assumption of a J^π = 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^π = 3/2^+, then the factor is 0.45(4).

The systematics of such “reduction factors,” R_j, as a function of particle separation energies has been analyzed by Gade and co-workers [34,35]. This systematics suggests R_j = 0.42(2) for 45Cl if one assumes the difference between separation energies for protons and neutrons in 45Cl 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.

Figure 3 shows a comparison of the pattern of γ-ray intensities observed in the present one-proton knockout experiment (left panel) with predictions made using the shell-model calculations, reaction-model calculations, and reduction factors described above with the assumption of a J^π = 3/2^+ ground state in 45Cl (right panel). All γ 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 → 0^+_s transition. The observed intensities along with shell-model predictions found by assuming both J^π = 1/2^+ and J^π = 3/2^+ for the ground state of 45Cl are listed in Table III. It is predicted that the γ 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 45Cl has J^π = 3/2^+, and that it will have a cross section too small to be observed (0.2 mb, 3%) if the ground state of 45Cl has J^π = 1/2^+. In the experiment, this γ ray was seen with a cross section of 3.6(3) mb (34%), providing a strong argument for a J^π = 3/2^+ ground state in 45Cl.

The values of J^π for the ground states of 37,39Cl have been confirmed to be 3/2^+ [37,38], and both ground states display large spectroscopic factors when populated in (d,^3He)
TABLE III. Measured $\gamma$-ray intensities from the present work compared with shell-model predictions described in the text by assuming $J^\pi = 1/2^+$ and $J^\pi = 3/2^+$ for the ground state of $^{45}$Cl.

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>$I_\gamma^\text{exp}$ (%)</th>
<th>Shell model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$I_{1/2^+}^\text{exp}$ (%)</td>
<td>$I_{3/2^+}^\text{exp}$ (%)</td>
</tr>
<tr>
<td>1320(8)</td>
<td>100(3)</td>
<td>100</td>
</tr>
<tr>
<td>2150(13)</td>
<td>21(2)</td>
<td>24</td>
</tr>
<tr>
<td>950(6)</td>
<td>42(3)</td>
<td>55</td>
</tr>
<tr>
<td>1144(9)</td>
<td>34(3)</td>
<td>2.6</td>
</tr>
<tr>
<td>1031(6)</td>
<td>9(2)</td>
<td>5</td>
</tr>
</tbody>
</table>

reactions, confirming the $d_{3/2}$ single-proton nature of these states. In both cases, $J^\pi = 1/2^+ 1/2$ single-proton states have also been identified by 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 $(d,^3\text{He})$ 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 $1/2^+$, 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 $^{45}$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 $^{43}$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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[38] B. Singh and J. A. Cameron, Nucl. Data Sheets 107, 225 (2006), data extracted from the ENSDF database revision of November 2005.

