Negative Parity States in ^{39}Cl Configured by Crossing Major Shell Orbits *

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Traditional "magic numbers" were once regarded as immutable throughout the nuclear chart. However, unexpected changes were found for unstable nuclei around $N = 20$. With both proton and neutron numbers around the magic number of 20, the neutron-rich ^{39}Cl isotope provides a good test case for the study of the quantum-state evolution across the major shell. In the present work, the negative parity states in ^{39}Cl are investigated through the β decay spectroscopy of ^{39}S. Newly observed γ transitions together with a new state are assigned into the level scheme of ^{39}Cl. The spin parity of $5/2^-$ for the lowest negative parity state in ^{39}Cl is reconfirmed using the combined γ transition information. These systematic observations of the negative parity states in ^{39}Cl allow a comprehensive comparison with the theoretical descriptions. The lowest $5/2^-$ state in ^{39}Cl remains exotic in terms of comparisons with existing theoretical calculations and with the neighboring isotopes having similar single-particle configurations. Further experimental and theoretical investigations are suggested.

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The discovery of "magic numbers" of protons and neutrons in nuclei may date back to 1934.[1] Until 1949, these numbers, such as 2, 8, 20, 28 and 50, were successfully explained by employing the spin-orbit interaction within the mean field approach.[2,3] The magic numbers were regarded as immutable throughout the nuclear chart, since they characterize very large energy gaps between the major shells grouped by quantum states in nuclei. However, along with the utilization of radioactive ion beams, the initial experimental studies of neutron-rich nuclei have already yielded unexpected results regarding the evolution of the quantum states in nuclei, including the weakening of the gaps between the traditional major shells and the appearance of new magic numbers (see Ref. [4] and references therein). When this happens, the specific effective interaction between valence nucleons around the major shells may result in some exotic states, which challenge the predictive power of the existing theoretical models. The initial unexpected case was found around the neutron magic number of 20.[5] Since then, the neutron-rich nuclei around $N = 20$ have attracted much experimental and theoretical attention.[6,7]

The neutron-rich nucleus of ^{39}Cl has 17 protons and 22 neutrons, just below and above the magic number 20. So far there have been a number of studies on the positive parity states of ^{39}Cl since they are associated with the normal configuration of one valence proton within the *sd* shell (positive parity) and two neutrons within the *pf* shell (also combined into positive parity). Only one state at 1697 keV was firmly identified to be of negative parity with definite spin assignment.[8] Based on a simple shell model picture, the spin of the lowest negative parity state in ^{39}Cl should be 7/2. This is exactly the case for the neighboring isotopes, such as ^{35,37}Cl and ^{37,39,41,43}K,[9–14] which possess similar valence nucleon configurations as for ^{39}Cl. However, the lowest negative parity state in ^{39}Cl was found to have a novel spin of 5/2.[8] This $5/2^-$ state in ^{39}Cl seems exotic and needs to be verified and explained together with other negative parity states.

In addition to the 1697-keV state, a few higher energy levels in ^{39}Cl also show some evidence of negative parity,[15,16] but clear assignments were not achieved.

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In the present work, we populate the excited states in ^{39}Cl through the β decay spectroscopy of ^{39}S. Since the valence neutrons of ^{39}S are basically in the pf shell with negative parity, their switch into protons via β decay should be in favor of populating the excited negative parity states in ^{39}Cl with allowed β transition.

The experiment was carried out at the projectile fragment separator (RIPS) beam line[17] at the RIKEN-RIBF facility.[18] A secondary beam of ^{39}S was produced by the projectile fragmentation reaction from a primary beam of ^{48}Ca at 63 MeV/nucleon on a 0.5-mm-thick ^{9}Be target, and collected via RIPS. A wedge-shaped aluminium degrader with a mean thickness of 148.8 mg/cm^2 was placed at the momentum dispersive focus plane F1. A secondary beam passing through a collimator with a 18-mm-diameter hole was implanted into a 0.5-mm-thick nonactive stopper which was tilted at an angle of 45° with respect to the beam axis. The beam particles implanted into the stopper were counted using two plastic scintillators with thicknesses of 0.5 and 1 mm, and placed upstream and downstream of the stopper, respectively. The typical rate of the implanted secondary beams was 6 kcps, with a purity of 71(7)% for ^{39}S. The main contaminants were ^{38}P and ^{36}Si. The beam was pulsed as beam-on and beam-off periodically in order to record the timing of γ rays delayed by the β decay of the mother nucleus.[19–21] The half-lives extracted from the decay time spectra can be used to identify the mother nuclei. The β-delayed γ rays of ^{39}S were detected using two high-purity Ge detectors installed at a distance of 30 cm from the stopper. The timing of each γ event was recorded relative to the start of the beam-on period.

In the present experiment, we observed β-delayed γ rays from ^{39}S at energies of 396, 485, 874, 1300 and 1697 keV, which were reported previously in Ref. [15], as well as some γ rays from contaminants such as ^{36}Si. There are several candidates for γ rays from unknown origins. The origins of these γ rays were checked from the half-lives associated with the γ rays. For the extraction of the half-life from the decay time spectrum, see, for example, Refs. [22,23]. The determined half-lives of six new γ rays with energies of 1210, 1326, 1723, 2572, 3377 and 3834 keV are in good agreement with the known half-life of ^{39}S, 11.5(5) s.[15] These results are listed in Table 1. Among them, two γ rays of 1326 and 1723 keV were not reported in the previous β decay study of ^{39}S,[15] but observed in other studies[16,24] as direct transitions from the 1723-keV level to the 396-keV state and to the ground state, respectively, of ^{39}Cl. The 1745-keV γ ray has two possible parent nuclei of ^{39}S and ^{38}S. The contribution of ^{39}S (Table 1) is obtained by subtracting the contribution of ^{38}S[25] from the total yield. Table 1 also lists the γ ray intensities I_γ per decay of ^{39}S, which were deduced using the peak counts, the detection efficiency and the implanted number of ^{39}S. The detection efficiency was measured with a standard source of ^{152}Eu, and corrected with three known γ rays at 424.9 and 878.2 keV originating from a contaminant of ^{36}Si and at 3291 keV from its daughter ^{36}P.[26]

Table 1. Characteristics of γ rays identified to originate from ^{39}S, based on the present measurement. Their energies E_γ, half-lives $T_{1/2}$ and absolute intensities per decay I_γ are listed in columns 1, 3 and 4, respectively. Previously reported energies[15] are also listed in column 2 for comparison. Errors in the first and second parentheses of each I_γ indicate the statistic and the systematic uncertainties, respectively. The latter affects all the γ rays in a relatively equal way.

E_γ (keV)	E_γ (keV)[15]	$T_{1/2}$ (s)	I_γ
396.4(5)	396.50(20)	12.1(6)	0.389(12)(79)
484.5(5)	484.85(24)	10.5(9)	0.092(3)(19)
874.4(5)	874.31(18)	12.5(9)	0.140(5)(29)
1210.3(5)		10.4(11)	0.063(2)(13)
1300.8(5)	1300.52(16)	11.1(5)	0.435(13)(89)
1326.0(5)		10.1(37)	0.021(2)(4)
1696.9(5)	1696.62(17)	11.5(7)	0.315(10)(64)
1722.5(5)		9.9(23)	0.016(1)(3)
1745.0(5)			0.0021(7)(5)
2571.9(5)		9.6(14)	0.038(2)(8)
3377.4(5)		11.8(10)	0.081(3)(16)
3833.9(5)		12.6(14)	0.080(3)(16)

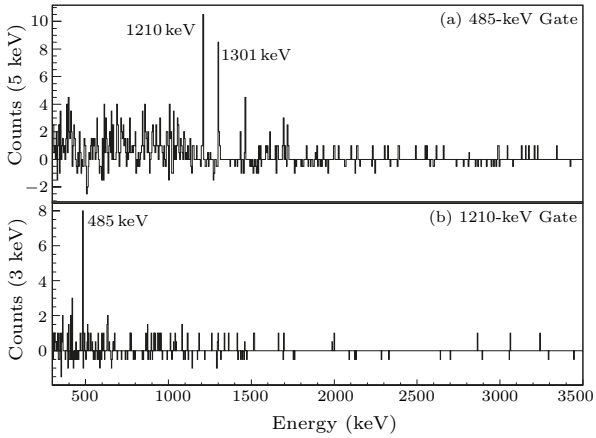

Fig. 1. γ ray spectra gated by (a) 485-keV and (b) 1210-keV γ rays, respectively.

In order to identify the cascade scheme of γ decay, the γ–γ coincident spectra were analyzed, as shown in Fig. 1 as an example. The coincident pairs of (485, 1210), (485, 1301), (396, 874), (396, 1301), (874, 1301) and (874, 1697) in units of keV were identified and displayed in the level scheme in Fig. 2. The newly observed strong 1210-keV γ ray, in coincidence with a strong 485-keV γ ray, is assigned to decay from a new level at 2996 keV to a known level at 1785 keV. The latter then decays in cascade with the 485-keV and 1301-keV γ rays to the ground state. Otherwise, if the 1210-keV γ ray is allocated below the 485-keV γ ray, the estimation will show that another strong γ ray of 90 keV should be observed. However, such a 90-keV γ ray did not appear in the spectrum. As for the remaining three new γ rays of 2572, 3377 and 3834 keV, we did not obtain any coincidence with other γ rays. The 2572-keV γ ray can be directly allocated to the decay of the existing 2572-keV level. Presently we can-

not make allocations for the 3377-keV and 3834-keV γ rays due to the lack of clear information for the high excited levels.

In Fig. 2, we also insert three transitions, as shown by the dashed lines, which were not observed in the present experiment, but reported previously in the literature.[15,16,24] The 421-keV γ ray from the 1722-keV level was reported in Refs. [16,24]. Its relative intensity is 14(10), as compared to 90(10) for the competitive 1722-keV γ ray.[24] The small relative intensity may not allow the 421-keV γ yield to be distinguished from the background. A similar situation happens for 444-keV[16,24] and 904-keV γ rays.[15,24] These three γ rays were taken into account in the following deduction based on their reported relative intensities. The specific values are $I_\gamma(421) = 0.003(2)$, $I_\gamma(444) = 0.0012(5)$ and $I_\gamma(904) = 0.029(11)$.

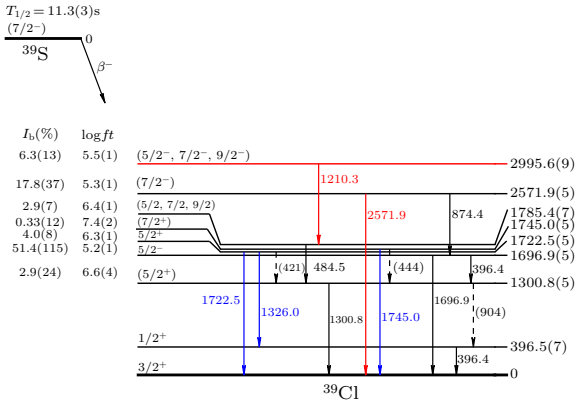

Fig. 2. The decay scheme for ^{39}S, established in the present experiment. Also listed are the β decay branching ratio I_β and comparative half-life log ft for each level. Red lines represent newly observed γ rays and level. Blue lines represent newly identified β-delayed γ rays. Dashed lines indicate γ rays, with energies of 421, 444 and 904 keV, reported in the literature[15,16,24] but not observed in the present experiment.

In the deduction of the β branching ratios I_β, we need to separate two possible contributions to the $I_\gamma(396)$, one from the decay between the 1697 and 1301-keV levels and the other between the 396 and 0-keV levels. Due to the relatively higher order forbidden β decay property for the 396-keV level, $I_\beta(396)$ can be neglected. Therefore, $I_\gamma(396; 396 \to 0) = I_\gamma(904) + I_\gamma(1326) = 0.050(12)$, which results in $I_\gamma(396; 1697 \to 1301) = 0.339(14)$. Using the known I_γ values, I_β and log ft values can be deduced, as shown in Fig. 2 and Table 2.

Based on the present data, we are able to propose spin-parity (I^π) assignments for the 1785, 2572 and 2996-keV levels. Here we adopt the tabulated (Fig. 2) I^π for the ground state of the mother nucleus ^{39}S,[8,15] and for the 0 (ground state), 396, 1301, 1697, 1722 and 1745-keV levels of the daughter nucleus ^{39}Cl.[8] Previously, I^π of the 1785-keV level was proposed to be $(5/2^-, 7/2^-)$,[15] based on log ft = 5.9. However, due to the present new observation of the 1210-keV γ ray which feeds into the 1785-keV level, this log ft value was modified to be 6.4(1). Since such a log ft value holds possibilities of either allowed or first-forbidden non-unique transition, the parity of the 1785-keV level remains undetermined while its spin may be $(5/2, 7/2, 9/2)$. For the newly observed 2572-keV γ transition, the favorable assignment is $I^\pi = (7/2^-)$, based on the present log ft value and related γ transition strengths. Although $9/2^-$ and $5/2^-$ are equally possible if considering only the β decay log ft, these two assignments can be excluded from the analysis of the γ transitions. If we assume $I^\pi = 9/2^-$ for the 2572-keV state, its γ transitions to the 1697-keV level and to the ground state will be E2 and E3, respectively, which violates the present experimental strength ratio of 3.9(1) (Table 1) based on the Weisskopf estimation. Similarly, the assignment of $5/2^-$ for the 2572-keV level also appears unlikely. Finally, for the newly identified 2996-keV state, the I^π assignment should be $(5/2^-, 7/2^-, 9/2^-)$, based on the log ft value of 5.5(1). This is comparable to the 1697-keV level which possesses a fairly similar log ft value.[15]

Table 2. Branching ratios I_β and comparative half-life log ft values for the β decay of ^{39}S. The literature values for I_β and log ft from Ref. [15] are also presented for comparison.

Energy (keV)	I_β (%)	I_β (%)[15]	log ft	log ft[15]
1300.8(4)	3.0(24)	8.2(60)	6.6(4)	6.2
1697.2(6)	51.4(115	68.2(49)	5.2(1)	5.2
1722.5(4)	3.9(8)		6.3(1)	
1745.0(5)	0.33(12)		7.4(2)	
1785.3(6)	2.9(7)	10.8(13)	6.4(1)	5.9
2571.6(7)	17.8(37)	12.8(15)	5.3(1)	5.5
2995.6(7)	6.3(13)		5.5(1)	

The negative parity states of ^{39}Cl observed in the present experiment are compared with the theoretical calculations in terms of excitation energies and the Gamow–Teller transition strength B(GT). The shell model code KSHELL[27] was used with the ZBM2 interaction.[28] The valence nucleon model space consists of orbits across the major shell of $N(Z) = 20$, namely $2s_{1/2}$, $1d_{3/2}$, $1f_{7/2}$ and $2p_{3/2}$ orbits, for both protons and neutrons. In Fig. 3 the calculated results are compared with the experimental ones. The experimental B(GT) values were deduced based on the present log ft values (Table 2), while the calculated B(GT) values incorporate a quenching factor of 0.7.[29] Although the parity of the observed 1785-keV level is not determined in the present work, its B(GT) value is also presented by assuming a negative parity. By comparing the excitation energies, spin parities and B(GT) values, the observed 2572 and 2996-keV levels may correspond to the calculated 3072 and 2809-keV levels, respectively. However, the calculation could not reproduce the lowest negative parity state at 1697 keV with $I^\pi = 5/2^-$, though its B(GT) value of 0.027(6) is close to 0.046 for the predicted 1479-keV level with $I^\pi = 7/2^-$. Also, if negative parity is assumed for the observed 1785-keV state, it can-

not be reproduced by the calculation either, within a reasonable energy range. We considered several other available interactions for the shell model calculation, such as ZBM2M,[30] SDPF-MU[31] and SDPF-M,[32] but none of these could reproduce the $I^\pi = 5/2^-$ for the lowest negative parity state. These calculations always generate the $I^\pi = 7/2^-$ state.

Experimentally, the validity of the assignment of $I^\pi = 5/2^-$ for the 1697-keV level is also confirmed by the present data. If this state has $I^\pi = 7/2^-$, the γ transitions to the ground state and to the 1301-keV level will be M2+E3 and E1 types, respectively, corresponding to a very large deviation in strengths. However, the actual experimental value for the strength ratio is $I_\gamma(1697)/I_\gamma(396) = 0.92(5)$, which is consistent with the $I^\pi = 5/2^-$ assignment, but not $7/2^-$. Therefore the observed lowest negative parity state in ^{39}Cl remains an open problem for theoretical interpretation. It is worth noting that some of the previously observed exotic states in unstable nuclei have been successfully explained by the enhanced tensor force between the valence protons and neutrons.[33] The existence of the exotic negative parity state in ^{39}Cl may stimulate further studies on effective interactions for valence nucleons across the major shell.

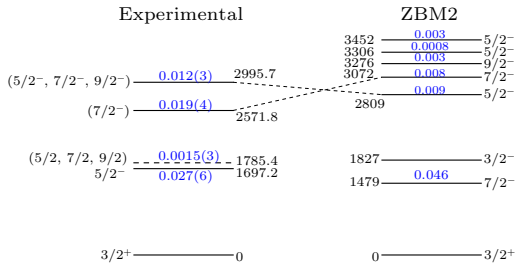

Fig. 3. Comparison between the experimental results and the theoretical calculations for the negative parity states in ^{39}Cl. Bold blue numbers upon the level lines represent the B(GT) values for β decay from ^{39}S. The 1785-keV level is also plotted with a B(GT) value estimated by assuming negative parity.

In summary, we have reinvestigated the negative parity states in ^{39}Cl through the β decay spectroscopy of ^{39}S. Seven γ rays of 1210, 1326, 1723, 1745, 2572, 3377 and 3834 keV were identified to originate from ^{39}S. The 1210 and 2572-keV γ transitions and the 2996-keV level are newly assigned into the level scheme of ^{39}Cl. Based on the $\log ft = 5.5(1)$ for the β transition to the 2996-keV level, I^π of $(5/2^-, 7/2^-, 9/2^-)$ is tentatively assigned to this state. Through the analysis of γ transition strengths, $I^\pi = (7/2^-)$ is assigned to the 2572-keV level, whereas the previous tentative allocations of $(9/2^-)$ and $(5/2^-)$ are excluded. The present combined data also support the $I^\pi = 5/2^-$ assignment for the lowest negative parity state at 1697 keV. These systematic observations of the negative parity states in ^{39}Cl allow a comprehensive comparison with the theoretical descriptions. The present shell model calculations with various available effective interactions could not reproduce the lowest negative parity state of $5/2^-$, although the higher energy levels at 2572 keV and 2996 keV are reasonably described. The lowest $5/2^-$ state in ^{39}Cl seems even more exotic when comparing with its neighboring isotopes of ^{35,37}Cl and ^{37,39,41,43}K with similar single-particle configurations, which always come up with a normal $7/2^-$ state in the lowest excitation region. This remains an open problem for theoretical studies in terms of the effective interactions and the valence nucleon model space.

Another interesting issue is the parity for the 1785-keV state. The previously extracted $\log ft$ value of 5.9 is now modified to 6.4(1), based on the newly observed γ transitions. Negative and positive parity are both possible for the 1785-keV level. The two possible assignments seem intriguing, since the formal would put further challenges to the theoretical description (see Fig. 3), whereas the latter would also generate interesting phenomena for the positive parity states. Therefore further experimental investigation on the parity of this state should be of major importance.

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References

[1] Elsasser W 1934 *J. Phys. Radium* **5** 635
[2] Goeppert-Mayer M 1949 *Phys. Rev.* **75** 1969
[3] Haxel O et al 1949 *Phys. Rev.* **75** 1766
[4] Yang X F et al 2016 *Phys. Rev. Lett.* **116** 182502
[5] Thibault C et al 1975 *Phys. Rev. C* **12** 644
[6] Gade A and Glasmacher T 2008 *Prog. Part. Nucl. Phys.* **60** 161
[7] Sorlin O and Porquet M G 2008 *Prog. Part. Nucl. Phys.* **61** 602
[8] Chen J 2018 *Nucl. Data Sheets* **149** 1
[9] Eswaran M A et al 1979 *Nucl. Phys. A* **325** 269
[10] Wirjoamidjojo S and Kern B D 1967 *Phys. Rev.* **163** 1094
[11] de Esch H P L and van der Leun C 1988 *Nucl. Phys. A* **476** 316
[12] Lopes J S et al 1968 *Nucl. Phys. A* **109** 241
[13] Jundt F et al 1971 *Phys. Rev. C* **4** 498
[14] Doll P et al 1976 *Nucl. Phys. A* **263** 210
[15] Hill J C et al 1980 *Phys. Rev. C* **21** 384
[16] Szilner S et al 2013 *Phys. Rev. C* **87** 054322
[17] Kubo T et al 1992 *Nucl. Instrum. Methods Phys. Res. Sect. B* **70** 309
[18] Yano Y 2007 *Nucl. Instrum. Methods Phys. Res. Sect. B* **261** 1009
[19] Li Z H et al 2009 *Phys. Rev. C* **80** 054315
[20] Li Z H et al 2005 *Phys. Rev. C* **72** 064327
[21] Lou J L et al 2008 *Chin. Phys. Lett.* **25** 1992
[22] Onishi T K et al 2005 *Phys. Rev. C* **72** 024308
[23] Ichikawa Y et al 2009 *Phys. Rev. C* **80** 044302
[24] Warburton E K et al 1973 *Phys. Rev. C* **7** 170
[25] Chen J 2018 *Nucl. Data Sheets* **152** 45
[26] Nica N et al 2012 *Nucl. Data Sheets* **113** 1
[27] Shimizu N 2013 arXiv:1310.5431v1[nucl-th]
[28] Caurier E et al 2001 *Phys. Lett. B* **522** 240
[29] Yuan C X et al 2012 *Phys. Rev. C* **85** 064324
[30] Bissell M L et al 2014 *Phys. Rev. Lett.* **113** 052502
[31] Utsuno Y et al 2012 *Phys. Rev. C* **86** 051301(R)
[32] Utsuno Y et al 1999 *Phys. Rev. C* **60** 054315
[33] Otsuka T 2013 *Phys. Scr.* **T152** 014007