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γ-ray spectroscopy of $^{38}_{17}$Cl using grazing reactions

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Excited states of $^{38}_{17}$Cl$_{21}$ were populated in binary grazing reactions during the interaction of a beam of $^{36}_{16}$S$_{20}$ ions of energy 215 MeV with a $^{208}_{82}$Pb$_{126}$ target. The combination of the PRISMA magnetic spectrometer and the CLARA γ-ray detector array was used to identify the reaction fragments and to detect their decay via γ-ray emission. A level scheme for ^{38}Cl is presented and discussed within the context of the systematics of neighboring nuclei and is compared with the results of state-of-the-art shell-model calculations.

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I. INTRODUCTION

Nuclei near the $N = 20$ shell closure have been the subject of extensive research over the past 10 years. Much discussion and effort has focused on the neutron-rich species in this region since the underlying shell structure has been shown to deviate from that of the β-stable neighboring nuclei. The isotope ^{38}Cl with $Z = 17$ and $N = 21$ has, in its ground state, one neutron outside the $N = 20$ major shell closure and an unpaired proton occupying the $1d_{3/2}$ orbital. Thus, ^{38}Cl, although only one neutron from stability, is an interesting nucleus in which to study cross-shell shell-model interactions.

The isotope ^{38}Cl has been the subject of several experimental studies; see Table I. Although states have been observed up to an excitation energy of 8 MeV, all have been assigned spins $J \leqslant 5$. Recently, attempts have been made to study high-spin states in the neutron-rich chlorine isotopes using deep-inelastic reactions with thick targets [8–11]. Although these reactions were successful in populating medium-to-high spin-states in neutron-rich chlorine isotopes, such as ^{41}Cl [9,11], no states were observed to be populated in ^{38}Cl. This nonobservation may be attributed to the short half-lives (<1 ps) [6] of some of the lowest-lying states in ^{38}Cl.

Several shell-model calculations for ^{38}Cl have been reported in the literature. Initially, Woods [12] calculated the excitation energies of negative-parity states in ^{38}Cl up to an excitation energy of 2681 keV. In that work, two different interactions were used, both of which gave reasonable agreement with the available experimental data and reproduced the observed ordering of the states. More recently, a study by Retamosa *et al.* [13] was able to reproduce the multiplet of states based on the ground-state configuration, $\pi d_{3/2} \otimes \nu f_{7/2}$.

In order to identify higher-spin states ($J > 5$) in ^{38}Cl, the yrast and near-yrast decay sequences have been studied using binary grazing reactions with a thin target. The use of a large solid angle magnetic spectrometer, in combination with a high-efficiency γ-ray detector array, has enabled γ rays to be observed in coincidence with reaction products. This technique has permitted observation of the decay of states which had eluded detection in earlier deep-inelastic work [8–11]. Indeed, with the unambiguous observation of transitions corresponding to the decay of excited states of ^{38}Cl in the present work, the data from previous deep-inelastic studies has been revisited.

II. EXPERIMENTAL DETAILS

Excited states of nuclei in the neutron-rich $Z = 12$–20 region were populated during the bombardment of a ^{208}Pb target by ^{36}S ions at a laboratory energy of 215 MeV. The beam was delivered by the combination of the XTU-Tandem and ALPI accelerators at the INFN Legnaro

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TABLE I. A list of the previously reported experimental studies of ^{38}Cl.

Authors (year)	Ref.	Reaction
Paris, Buechner, and Endt (1955)	[1]	^{37}Cl(d,p)
Hoogenboom, Kashy, and Buechner (1962)	[2]	^{37}Cl(d,p)
Rapaport and Buechner (1966)	[3]	^{37}Cl(d,p)
Hardy *et al.* (1970)	[4]	^{40}Ar(p,^{3}He)
Engelbertink and Olness (1972)	[5]	^{37}Cl$(d,p\gamma)$
Spits and Akkermans (1973)	[6]	^{37}Cl(n,γ)
Warburton *et al.* (1986)	[7]	^{38}S β decay

National Laboratory and data were taken for six days with an average ^{36}S beam current of ∼7 pnA. The target consisted of isotopically enriched (99.7%) ^{208}Pb of thickness 300 μg/cm^2 evaporated onto a carbon backing which was 20 μg/cm^2 in thickness. Deexcitation γ rays from the decay of the reaction products were detected using CLARA [14], an array of up to 25 escape-suppressed Ge clover detectors arranged in a hemispherical configuration and covering the azimuthal angles between 98° and 180°, with respect to the entrance of the magnetic spectrometer (see below). For this particular experiment, 22 of the 25 clover detectors were available.

Projectile-like binary reaction products were separated and identified using the PRISMA magnetic spectrometer [15] which consists of an entrance detector, two magnetic elements, and a focal-plane detector system. The entrance detector is based on a position-sensitive micro-channel plate (25 cm from the target position) which provides the (x,y) coordinates and an initial timing signal for ions entering the spectrometer [16]. The ions then pass through a quadrupole magnet and are dispersed in a magnetic dipole before reaching the focal plane. At the focal plane, the ion trajectory and arrival time are measured as the ion passes through a gas-filled multi-wire parallel plate avalanche counter before the ion is stopped in a 10 × 4 element ionization chamber [17]. The ionization chamber provides measurements of the total energy and energy loss of the ion, allowing the atomic number, Z, of the ions to be determined. The time-of-flight and position information are used to trace the ion path through PRISMA and a correlation between γ rays detected in CLARA and ions at the focal plane is established through coincidence timing measurements. From a knowledge of the velocity vector of the emitting nucleus, γ-ray Doppler corrections can be made on an event-by-event basis, with the energy resolution of γ-ray photopeaks being typically 0.6% following correction. The magnetic spectrometer can be rotated in the reaction plane within a wide angular range of −20° to 120° with respect to the beam direction and, during this study, it was positioned at an angle of 56°. With a solid angle acceptance of ≈80 msr, PRISMA covered a range of angles between 50° and 62°, including the grazing angle, 60°, for this reaction channel. These features make PRISMA an ideal tool for studying multinucleon transfer reactions, where the differential cross sections of reaction products peak at angles close to the grazing angle.

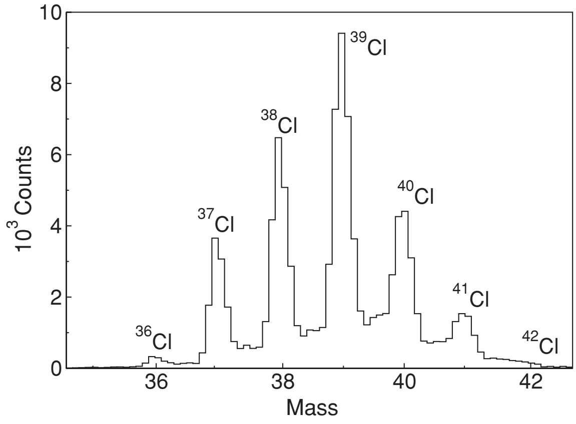

FIG. 1. Projection of a γ-A matrix onto the mass axis showing the isotopes of Cl which were identified in the present work.

III. RESULTS

Figure 1 shows the γ-A matrix (projected onto the mass axis) which resulted from the correlation of γ rays and detected Cl ions. Chlorine isotopes with masses in the range $A = 36$–42 were populated, with ^{39}Cl dominating. A software gate can be placed on any mass peak to obtain a γ-ray spectrum in coincidence with the reaction product being investigated.

The γ-ray energy spectrum of Fig. 2 shows transitions observed in coincidence with the detection of ^{38}Cl ions. Not all γ rays observed are associated with the projectile-like reaction product; γ-ray photopeaks corresponding to the deexcitation of the unobserved associated target-like products are, of course, also present and the associated peaks form broad structures as a consequence of the inappropriate Doppler correction of their energies. This is discussed in more detail in the next section. Measured energies of the observed γ rays and their efficiency-corrected relative intensities are listed in Table II. Some peaks were not particularly well defined and the large uncertainty associated with a number of intensity measurements reflects this. For the most problematic peaks,

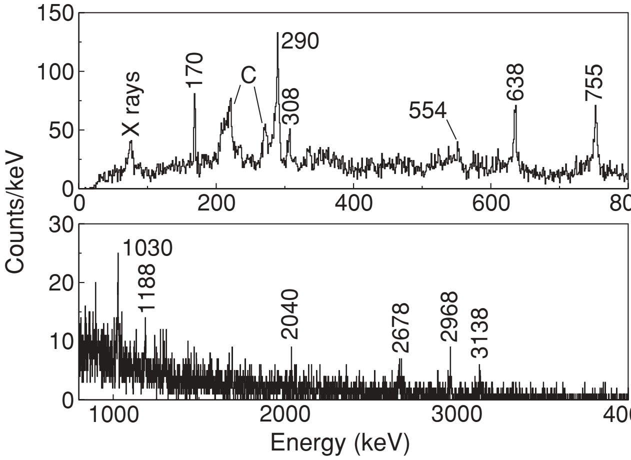

FIG. 2. Energy spectrum of γ rays corresponding to the decay of states of ^{38}Cl observed in the present work. The peaks marked with C result from the decay of targetlike reaction fragments associated with ^{38}Cl.

TABLE II. A list of the γ rays observed in this work ordered by excitation energy of decaying state.

E_i (keV)	E_γ (keV)	J_i^π	J_f^π	I_γ/I_{755}(%)
755	754.6(3)	3^-	2^-	100[a]
1309	637.7(5)	4^-	5^-	65(13)
1309	554.3(6)	4^-	3^-	18(7)
1617	307.6(5)	3^-	4^-	18(6)
1617	862.4(7)	3^-	3^-	11(3)
1785	1029.9(5)	(2, 3, 4)	3^-	35(6)
3349	2677.7(7)	(7^+)	5^-	48(9)
3349	2039.8(3)	(7^+)	4^-	15(5)
3639	290.2(2)	(5, 6)	(7^+)	30(10)
3639	2968.1(5)	(5, 6)	5^-	37(8)
3809	169.6(2)	(4, 5, 6)	(5, 6)	24(5)
3809	3138.4(6)	(4, 5, 6)	5^-	34(8)
4827	1187.9(6)	$(J \geqslant 5)$	(5, 6)	19(5)

[a]A 14% uncertainty is associated with the absolute intensity.

where fitting of Gaussian functions was not appropriate, the intensity was measured by manually setting backgrounds and summing counts between channels. An inspection of Fig. 2 reveals that the statistics are relatively poor; consequently, a $\gamma\gamma$ coincidence analysis was not possible.

However, the ordering of the observed transitions can be determined by revisiting the data obtained in a previous deep-inelastic study. In particular, the reaction under discussion involved the bombardment of a thick target of ^{160}Gd by 234 MeV ^{37}Cl ions [8,9]. The deexcitation of the resulting nuclei by emission of γ rays was detected using the EUROBALL array [18] and $\gamma\gamma\gamma$ correlations were obtained. The population of the ^{38}Cl channel in this reaction is expected to be strong, corresponding to the transfer of one neutron from the ^{160}Gd target to the ^{37}Cl projectile. However, as outlined in the introduction, the half-lives of the low-lying excited states of ^{38}Cl (5^- : 715 ms, 3^- : 220 fs and 4^- : 370 fs [19]) make it a particularly difficult nucleus to study using deep-inelastic reactions performed with a thick target since the decays of the first $J^\pi = 3^-$ and 4^- states occur in-flight. The resulting Doppler broadening means that the observed intensity of the transitions from these states is low, with only those γ rays emitted from the small fraction of stopped ^{38}Cl ions being observed experimentally. Double-gated γ-ray spectra involving those transitions first identified in the present work are shown in Fig. 3. The coincidence relationships between the transitions of 170, 290, and 2678 keV can be clearly seen from Figs. 3(a) and 3(b) while Fig. 3(c) suggests the 290- and 2040-keV transitions are in coincidence with the previously reported transitions of energies 554 and 638 keV.

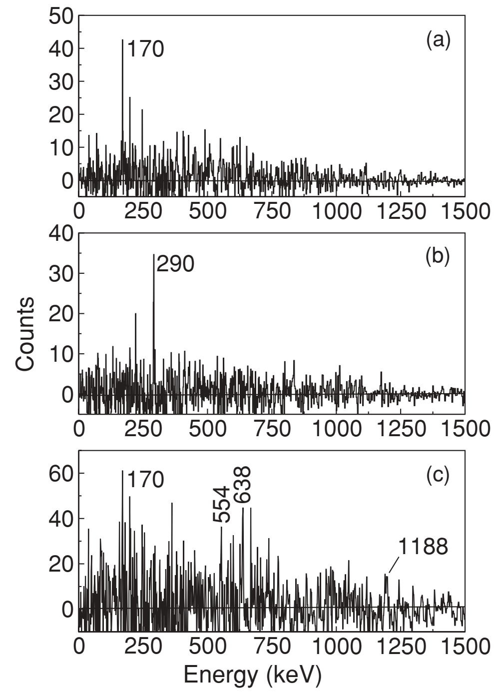

FIG. 3. γ-ray coincidence spectra with gates on (a) 290- and 2678-keV, (b) 170- and 2678-keV, and (c) 290- and 2040-keV transitions. The spectra were obtained as a result of a re-analysis of a previous deep-inelastic experiment. See Ref. [8,9] and text for more details.

IV. DISCUSSION

The level scheme for the yrast and near-yrast decay sequence of ^{38}Cl based on the present work is compared with the results of state-of-the-art shell-model calculations in Fig. 4. The calculations have been performed using the shell-model code ANTOINE [20] and involved an inert ^{16}O core and an effective interaction [21] which is based on results showing a reduction in the spin-orbit splitting of f and p orbitals in the vicinity of ^{47}Ar [22]. In this particular calculation, the valence protons are restricted to occupy the sd shell and neutron or proton particle-hole excitations across the $N = 20$ shell gap are not considered. As a result, in this $0\hbar\omega$ valence space, only negative-parity states of ^{38}Cl may be calculated.

States observed in the present work up to an excitation energy of 1785 keV were previously identified in the work of Refs. [5,6]. The 671-keV transition, from the isomeric (715 ms) first excited $J^\pi = 5^-$ state to the ground state, was not observed here since the lifetime of this state is longer than the flight time of ^{38}Cl ions through the CLARA reaction chamber. In this work, the level scheme has been extended by the addition of four states at energies of 3349, 3639, 3809, and 4827 keV. Seven previously unobserved transitions with energies of 170, 290, 1188, 2040, 2678, 2968, and 3138 keV have been added to the level scheme.

The first three excited states of ^{38}Cl were initially identified by Paris, Buechner, and Endt [1] using the ^{37}Cl(d, p) reaction. Hoogenboom *et al.* [2] later studied this reaction in more detail and measured the absolute differential cross sections and angular distributions of protons. This allowed spins to be inferred and parities to be determined for the previously observed energy levels, based on the measured orbital angular momentum quantum number of the transferred neutron and on shell model arguments. The J^π assignments, which are given in Fig. 4, suggest that the states are part of a quadruplet of levels, which includes the ^{38}Cl ground state, based on the shell-model configuration $\pi(1d_{3/2})^1\nu(1f_{7/2})^1$.

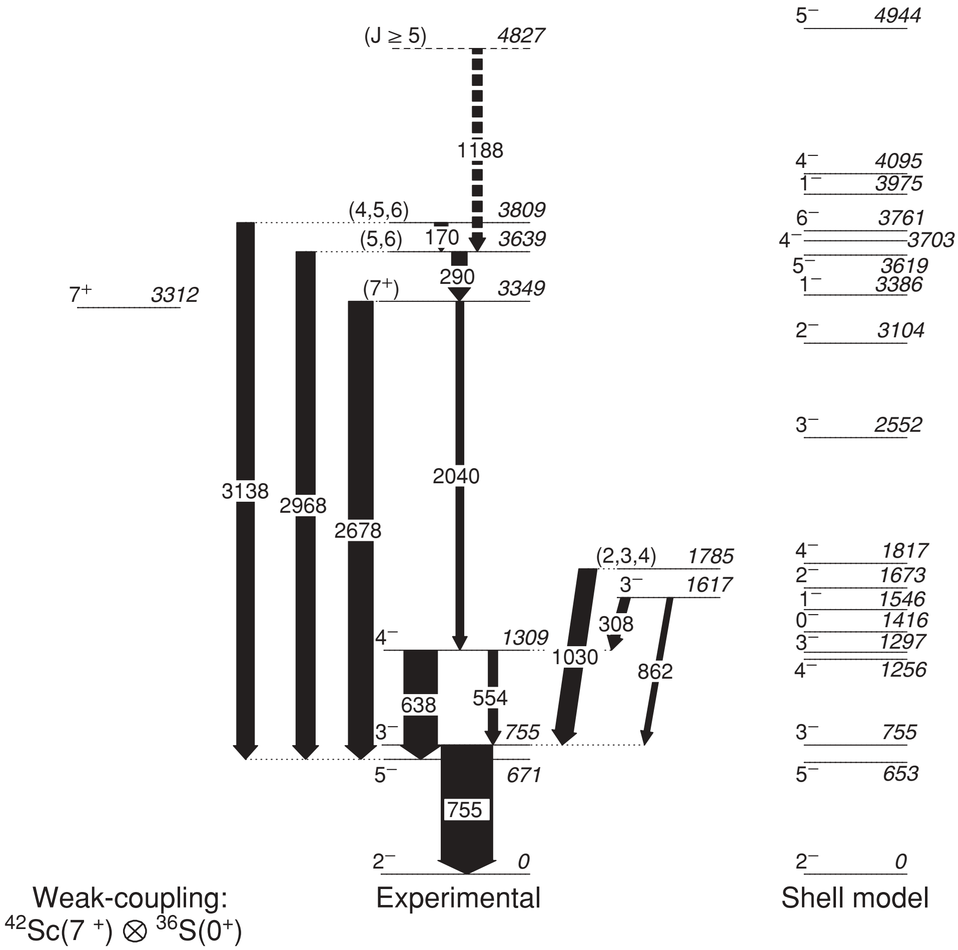

FIG. 4. The level scheme of ^{38}Cl based on the present work. Relative γ-ray intensities are indicated by the width of the arrows. The results of shell-model calculations are presented in addition to weak-coupling calculations. For states of excitation energy up to 1785 keV, J^{π} values are taken from earlier published works [2,5,6]. For states added as a result of the present work, proposed J^{π} values are given. See text for details.

This is supported by a consideration of states in $^{40}_{19}$K$_{21}$ [23]. While $^{38}_{17}$Cl$_{21}$ can be considered as a particle-particle nucleus, $^{40}_{19}$K$_{21}$ has a particle-hole configuration with two additional protons occupying the $1d_{3/2}$ orbital. The so-called Pandya transformation [24] can be used to calculate the energies of the $\pi(1d_{3/2})^1\nu(1f_{7/2})^1$ multiplet of ^{38}Cl states from the spectrum of $\pi(1d_{3/2})^{-1}\nu(1f_{7/2})^1$ states of ^{40}K. The success of this method, first reported by Goldstein and Talmi [23], was taken as proof that the low-lying multiplet in ^{38}Cl was based on the $\pi(1d_{3/2})^1\nu(1f_{7/2})^1$ configuration. Subsequent measurements [25] of the magnetic-dipole transitions between the low-lying states of ^{38}Cl, however, showed some discrepancies with this simplified picture. It was suggested [25] that, in order to explain the observations adequately, either surprisingly large (~30%) admixtures of $\pi(2s_{1/2})\nu(1f_{7/2})$ and $\pi(1d_{3/2})\nu(2p_{3/2})$ components are present, or contributions from configurations higher in the fp shell should be considered. The shell-model calculations performed in the present work support this hypothesis. The first excited $J^{\pi} = 3^-$ state is well reproduced by a state whose wave function consists of $\pi(1d_{3/2})\nu(1f_{7/2})$ (55%), $\pi(1d_{3/2})\nu(2p_{3/2})$ (21%), and $\pi(2s_{1/2})\nu(1f_{7/2})$ (14%) components. The other states of this multiplet are well reproduced by shell-model states predominantly ($\geqslant$67%) corresponding to the $\pi(1d_{3/2})\nu(1f_{7/2})$ configuration and having small admixtures of other configurations, each contributing $\leqslant$5% of the wave function. This may explain the observed branching ratio in the decay of the 1309 keV $J^{\pi} = 4^-$ state in which the transition to the $J^{\pi} = 5^-$ state is significantly favored over that to the 3^- state, despite both transitions being $M1/E2$ in nature.

In Fig. 5, the excitation energies of the $J^{\pi} = 5^-$ and 7^+ states of ^{34,36,38}Cl are plotted. One notable feature is the dramatic lowering of the $J^{\pi} = 5^-$ state in the chlorine isotopes as the number of neutrons is increased. The lowering of this

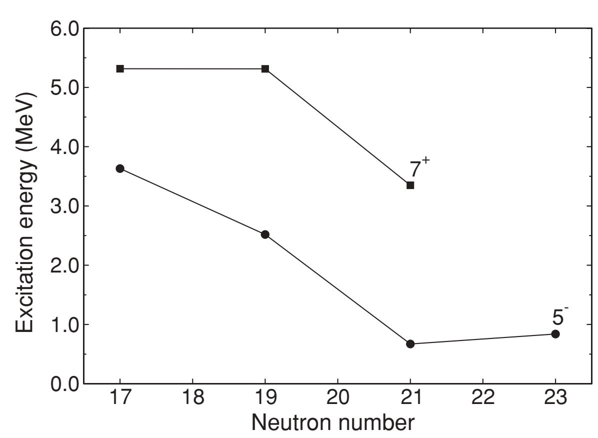

FIG. 5. Systematic trends of stretched $J^{\pi} = 5^-$ and 7^+ states in even-A Cl nuclei.

state from an energy of 2518 keV in ^{36}Cl to 671 keV in ^{38}Cl is what would be expected across a shell closure. As ^{38}Cl has a single neutron occupying the $1f_{7/2}$ orbital in its ground state, considerably less energy is required to produce a 5^- state than is necessary in the lower mass isotopes where a valence neutron or proton has to be promoted across the $N, Z = 20$ shell gap.

Above the $\pi(1d_{3/2})^1\nu(1f_{7/2})^1$ multiplet in ^{38}Cl, the next two excited states observed in the present study are the previously established [1,2,5–7] $J^\pi = 3^-$ and (2,3,4) states at 1617 and 1785 keV, respectively, shown in Fig. 4. Relative intensity measurements of the two γ-ray transitions depopulating the state at 1617 keV are in good agreement, within experimental uncertainty, with the previously reported branching ratios [5,6]. Engelbertink and Olness [5] observed a 946-keV transition from the 1617-keV state to the isomeric $J^\pi = 5^-$ state with a branching ratio of ≈6% relative to that of the 308-keV transition. This branching ratio implies that this decay is too weak to be observed in the present study. In Ref. [6], the state observed at 1785 keV was assigned a tentative J value of 2, 3, or 4 and positive parity. However, Warburton *et al.* [7] assigned a tentative $J^\pi = 4^-$ value to this state. The latter assignment seems to be supported by the shell-model calculations of the present work with 2^- and 4^- states calculated to exist in the vicinity of the experimentally observed energy of 1785 keV. Since only negative-parity states have been calculated here, this is not conclusive. Here, a γ-ray of energy 1030 keV is observed decaying from the state at 1785 keV to the $J^\pi = 3^-$ 755 keV state. Four additional transitions depopulating the state were first reported by Engelbertink and Olness [5]. The branching ratios reported in the previous work suggest that these transitions are too weak to be observed in the present work.

Four previously unreported excited states, with excitation energies of 3349, 3639, 3809, and 4827 keV, have been identified in this work. It has not been possible to determine the multipolarities of the γ rays emitted by these states and, hence, spin and parity could not be established. Nuclei in the vicinity of ^{38}Cl can be considered in order to understand the origins of the observed states. The $J^\pi = 5^-$ and 7^+ states in ^{34,36}Cl have been successfully populated in the past using the (α,d) reaction [26,27]. In this reaction the neutron and proton are preferentially transferred in a state of maximum alignment of angular momentum. The $J^\pi = 5^-$ and 7^+ states in both ^{34}Cl and ^{36}Cl were identified by Nann *et al.* [27] as stretched states $(J = \ell_\pi + \ell_\nu + 2s)$ corresponding to the configurations $\pi(1d_{3/2})\nu(1f_{7/2})$ and $\pi(1f_{7/2})\nu(1f_{7/2})$, respectively. The former configuration corresponds to the 671 keV state of $^{38}_{17}$Cl$_{21}$ while one would expect the latter to be observed as a highly excited state of this nucleus. As ^{38}Cl has a neutron occupying the $1f_{7/2}$ orbital in its ground state, the $\pi(1f_{7/2})\nu(1f_{7/2})$ excited state is expected at a lower energy than is observed in the lower-mass chlorine isotopes. Indeed, one would expect the evolution of the 7^+ states in the even-A chlorine nuclei to behave similarly to that of the 5^- states discussed above. A reduction of 1847 keV is observed in the energies of the $J^\pi = 5^-$ states in moving from ^{36}Cl to ^{38}Cl. Assuming a similar decrease in the energy of the 7^+ state, the three states observed in this work between 3 and 4 MeV are good candidates. Therefore, it is suggested that one of the states with energies of 3349, 3639, and 3809 keV corresponds to the $\pi(1f_{7/2})\nu(1f_{7/2})$ configuration and has $J^\pi = 7^+$.

A closer inspection of the γ-ray decay of the states at 3349, 3639, and 3809 keV places restrictions on the possible spin and parity values. This family of states is rather different from those at lower excitation energy. They are connected by low-energy transitions within each other and by an order of magnitude higher-energy transitions of similar intensity with the lower-lying states. This implies that the transitions to the low-lying states are retarded by a factor of around 1000 relative to the transitions between members of the multiplet of states. Thus, in terms of their microscopic structure, these states have, it is suggested, little overlap with those discussed earlier. It should therefore not be surprising if the restricted space shell-model calculation presented here is unable to reproduce the observed states. Two transitions were identified in the decay of the 3349-keV level. This state was observed to decay to the isomeric $J^\pi = 5^-$ level and to the $J^\pi = 4^-$ level with 76 and 24% of the total observed decay probability, respectively. This suggests that the 3349-keV state has $J \geqslant 3$. However, one would expect this state to have a spin value higher than 3 since the nature of grazing reactions means that yrast states are predominantly populated. The shell-model calculations show a $J^\pi = 1^-$ state at an excitation energy of 3386 keV. However, according to the arguments above, the observation of a $J^\pi = 1^-$ state at such a high excitation energy in the present work seems unlikely. In addition, the decay from such a state to the 4^- and 5^- states would be prohibitively hindered having multipolarities of $M3/E4$ and $E4$, respectively. In accordance with the above arguments and, in particular, those to follow, it is suggested that the 3349-keV state may have spin and parity of 7^+.

The 3639-keV state is observed to decay via two γ rays with energies 290 and 2968 keV. The intensity of the 290-keV decay could not be determined accurately as a result of the presence of a broad peak in the γ-ray spectrum, which has been identified as the result of γ-ray transitions within the complementary fragments ^{206,203}Tl. γ-ray transitions in the targetlike fragments contribute to the large background observed in the spectrum of Fig. 2. The efficiency-corrected intensities of Table II suggest the two transitions are of comparable strength with the 2968- and 290-keV transitions accounting for 55 and 45%, respectively, of the total observed decay strength from this level. That the two transitions are comparable in strength is rather surprising when one considers the γ-ray energies involved. This could be explained if the 2968-keV decay corresponds to a change in parity while the 290-keV γ-ray links states of the same parity. However, the shell-model calculations presented in Fig. 4 show that the state is well reproduced by a $J^\pi = 5^-$ state based predominantly (75%) on a $\pi[(1d_{5/2})^6(2s_{1/2})^{-1}(1d_{3/2})^2]_{5/2^+} \otimes \nu[(1f_{7/2})^1]_{7/2^-}$ configuration. This spin and parity seems unlikely in light of the suggested $J^\pi = 7^+$ for the 3349-keV state. Nonetheless, due to a lack of conclusive evidence and the conflicting arguments above, the parity of this state remains undetermined but the observed decay suggests this state most likely corresponds to $J = 5$ or 6.

The state observed at 3809 keV also decays via two γ-ray branches; the 170-keV transition (41% of the observed decay

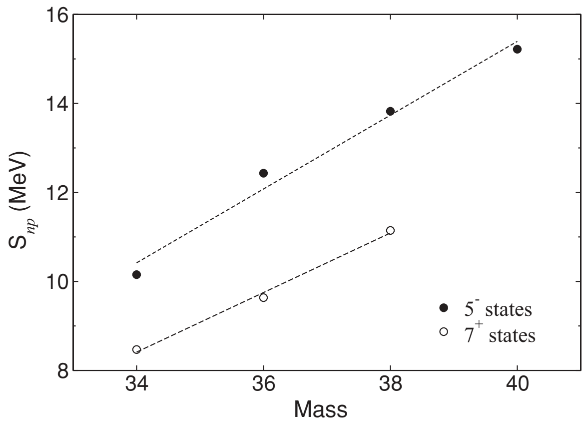

FIG. 6. Plot of neutron-proton separation energy as a function of mass number for available $J^\pi = 5^-$ and 7^+ states in even-A chlorine isotopes. The dashed lines represent linear least-squares fits to the data.

from this state) to the 3639-keV state and the 3138-keV transition (59%) to the 671-keV state. A comparison with the shell-model calculations suggests that this state may have spin and parity of 6^- with the dominant (88%) wave-function component corresponding to the $\pi[(1d_{5/2})^6(2s_{1/2})^{-1}(1d_{3/2})^2]_{5/2^+} \otimes \nu[(1f_{7/2})^1]_{7/2^-}$ configuration.

In the (α,d) experiments [26,27] used to populate states with stretched configurations in ^{34}Cl and ^{36}Cl, the neutron-proton np pair, transferred from the projectile to the target, can be treated as being coupled to ^{32}S and ^{34}S ground-state cores, respectively. Figure 6 shows the evolution of S_{np}, the separation energy of the np pair, with mass number for the two stretched states with $J^\pi = 5^-$ and 7^+ for the even-A chlorine isotopes being discussed here. Inspection of this figure shows a strong linear dependence for both 5^- and 7^+ states. This behavior is commonly interpreted within the Bansal-French-Zamick weak-coupling model [28,29] and is consistent with previous analyses of high-spin states based on two nucleon stretched configurations [30–32]. A quantitative estimate for the energy at which a $J^\pi = 7^+$ state is expected in ^{38}Cl can also be obtained by considering the Bansal-French-Zamick weak-coupling model. Excitations of nuclei relative to an inert core nucleus can be treated as representing the particle-hole configuration being investigated. This approach has been shown to be successful in reproducing particle-hole excitations in a number of p, sd, and fp shell nuclei [26,28,33–35]. In the present work, the first excited 7^+ state of ^{38}Cl was treated as a 2 particle-4 hole configuration with a maximally aligned neutron-proton $f_{7/2}$ pair outside of a $^{40}_{20}$Ca$_{20}$ core. The particle configuration is manifested in the low-lying 7^+ excitation of $^{42}_{21}$Sc$_{21}$ while the four proton holes in the $1d_{3/2}$ orbital have been represented by the ground state of $^{36}_{16}$S$_{20}$. Using the formalism and parameters outlined in Ref. [33], the energy of the weakly coupled 7^+ state in ^{38}Cl was calculated to be 3312 keV. This result lends further support to the suggested spin and parity of 7^+ of the observed state at 3349 keV.

The decay of a $J^\pi = 7^+$ state to the 5^- level at 671 keV would correspond to a mixed $M2/E3$ transition while the 2040-keV transition to the 1309 keV 4^- state would be of $E3$ character. In the study of the high-spin states of ^{40}K, Eggenhuisen *et al.* [36] observed similar competition between $M2/E3$ ($7^+ \rightarrow 5^-$) and $E3$ ($7^+ \rightarrow 4^-$) transitions, indicating that the present observations are reasonable.

The observed competition between the low-energy transitions of the 3639- and 3809-keV states and their high-energy decay to the 671-keV state may be explained if the three states between 3 and 4 MeV are treated as members of a multiplet based on the configuration $\pi(1f_{7/2})\nu(1f_{7/2})$. Since such a configuration would result in states of positive parity, it is suggested that the lowest-lying member of this multiplet would be the odd-J state with the largest spatial overlap, namely the $J^\pi = 7^+$ state. The other two proposed members of the multiplet are most likely to have $J^\pi = 4^+, 5^+$, or 6^+ since one state decays to the 7^+ state and both states decay to the 671-keV 5^- state. In their study of nucleon-nucleon matrix elements, Schiffer and True [37] showed that the 7^+ state is indeed the lowest state observed in a multiplet based on the $(1f_{7/2})^2$ configuration; the conclusions of Ref. [37] are supported by a more recent study performed by Daehnick [38]. Of the J^π values considered in the present discussion, the 5^+ state is the next most lowered with the 6^+ member of the multiplet experiencing the least lowering of all members. Based on this $(1f_{7/2})^2$ multiplet argument it is suggested that the 3639-keV state has $J^\pi = 5^+$ while the state observed at 3809 keV may have $J^\pi = 4^+$ or 6^+. Such spin and parity values would mean that the high-energy transitions of energy 2968 and 3138 keV would be $E1$ in nature while the 170- and 290-keV "intramultiplet" transitions would be $M1/E2$ and $E2$ transitions, respectively. This situation fits with the observed competition since the half-lives of the high-energy transitions would be subject to the 10^5 hindrance typical of $E1$ transitions. Taking the hindrance into account, the Weisskopf estimates for the high- and low-energy transitions become comparable. The nonobservation of a transition between the 3809 and 3349-keV states suggests that the spin and parity of the 3809-keV state is more likely 4^+ and not 6^+, assuming the above argument is valid.

The state of highest excitation energy observed in the present work is the tentative 4827-keV state. Its position in the level scheme can be supported by the observation that its decay is observed in coincidence with the 290- and 2040-keV transitions [Fig. 3(c)] but is not observed in coincidence with the 170-keV γ ray [Fig. 3(b)]. The shell-model calculations reproduce this state reasonably well with a third excited 5^- state consisting of a large (63%) $\pi[(2s_{1/2})^1(1d_{3/2})^2]\nu(1f_{7/2})$ component; however, significant contributions from the $\pi[(2s_{1/2})^0(1d_{3/2})^3]\nu(1f_{7/2})$ (14%) and $\pi[(1d_{5/2})^{-1}(2s_{1/2})^1(1d_{3/2})^3]\nu(1f_{7/2})$ (11%) components are also necessary in order to explain this state. However, if the three states immediately below this state belong to the proposed $(1f_{7/2})^2$ multiplet and the states at 3639 keV has $J^\pi = 5^+$ then the decay via the 1188-keV transition suggests that the 4827-keV state has $J \geqslant 5$.

V. SUMMARY

Grazing reactions, involving a ^{36}S beam at an energy of 215 MeV on a ^{208}Pb target, have been successfully used to populate excited states of ^{38}Cl. The CLARA γ-ray detector array in combination with the magnetic spectrometer PRISMA were used to identify the isotope and study the decay of its excited states via the emission of γ rays. In total, 13 γ rays were identified leading to the identification of nine excited states up to an excitation energy of ≈5 MeV. The previously reported yrast level scheme was extended by considering the γ-ray energies and intensities. An analysis of $\gamma\gamma\gamma$ coincidence data from a previous thick-target deep-inelastic experiment in which ^{38}Cl was populated has supported the level scheme presented here. Shell-model calculations corresponding to an improved *sdfp* interaction have been performed for ^{38}Cl. Spins and parities of the newly identified states have been suggested based on systematics of the neighboring isotopes and guided by the results of our shell-model calculations. A candidate for the stretched $J^{\pi} = 7^{+}$ configuration $\pi(1f_{7/2})\nu(1f_{7/2})$ has been identified based on the systematics of *np* separation energies of 7^{+} states populated in the (α,d) reaction and weak-coupling calculations. Evidence for the observation of other members of the multiplet resulting from the proposed $\pi(1f_{7/2})\nu(1f_{7/2})$ configuration is also discussed.

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