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Electromagnetic transitions in neutron-rich ^{40}Cl

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In-beam γ rays from excited states of the neutron-rich ($T_z=3$) nucleus ^{40}Cl have been identified in a threefold coincidence experiment in which γ rays and light charged particles were observed. The resulting decay scheme is presented, and implications for the structure of low-lying levels in ^{40}Cl are discussed in light of recent data from charge-exchange and β-decay work. The ordering of levels would seem to be quite different from the predictions of recent shell-model calculations.

The most recent measurement of the mass of ^{40}Cl and the first observation of excited levels of this exotic neutron-rich nucleus were by Fifield *et al.*,[1] who used the (^{7}Li, ^{7}Be) and (^{11}Be, ^{11}C) charge-exchange reactions on ^{40}Ar. Dufour *et al.*[2] have observed four γ rays which they identify as emissions following the β decay of ^{40}S, but they have not suggested a decay scheme. In the present work, six additional transitions which can be attributed to ^{40}Cl are observed. An associated decay scheme is presented, and possible structure implications are discussed.

The new Argonne-Notre Dame γ-ray facility at the Argonne Tandem-Linac Accelerator System (ATLAS) was used to observe, in threefold coincidence, the emission of two charged particles and a γ ray from neutron-rich systems created via heavy-ion-induced fusion-evaporation reactions in reverse-kinematics mode. The facility consists of eight Compton-suppressed Ge detectors (CSG's) positioned above or below the horizontal reaction plane and two $E\Delta E$ Si surface barrier detector telescopes placed at forward angles. The target consisted of a 2.34 mg/cm^2-thick rolled Be foil with 10 mg/cm^2 of Pb evaporated onto the downstream side to stop most of the heavy reaction products. An additional Pb foil of 7.5 mg/cm^2 thickness served to stop the ^{36}S beam, which had an energy of 100 MeV upon entering the target. The $E\Delta E$ telescopes, each subtending a solid angle of 0.14 sr,

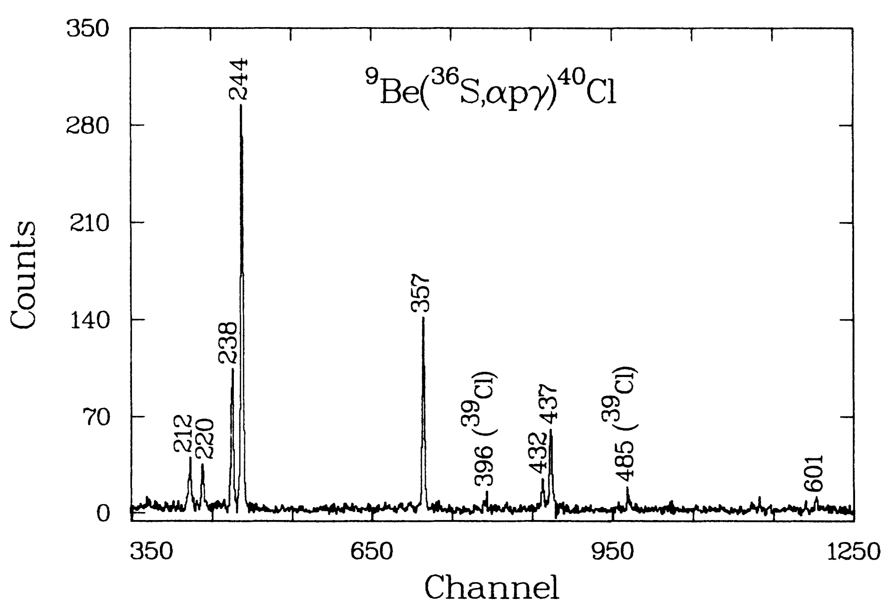

FIG. 1. Spectrum of γ rays in coincidence with an α particle and a proton. All labeled lines are attributed to ^{40}Cl unless otherwise noted. Energies are in keV. Random background from αxn and pxn evaporation channels has been subtracted (note zero offsets).

were placed in the forward direction at $\pm 30°$ to detect light particles ($Z \leq 3$) which had enough energy to traverse the beam stopper foil and the 54 μm-thick ΔE detectors. Four of the CSG's were positioned at polar angle $\theta = 90°$ with respect to the beam axis with azimuthal angles (ϕ's) of 15°, 165°, 195°, and 345°, respectively. The other four were positioned at $\theta = 147°$ with ϕ coordinates 28°, 152°, 208°, and 332°. Data were collected using the ATLAS acquisition code DAPHNE.[3] Energy and timing information from all CSG's and the telescopes were recorded for all twofold or higher-order coincidences among the CSG's and telescopes.

A γ-ray spectrum generated under the $\alpha p \gamma$ coincidence requirement is shown in Fig. 1. The strongest lines in Fig. 1 can be attributed to ^{40}Cl with a high degree of confidence: fusion-evaporation calculations indicate the αpn evaporation channel leading to ^{39}Cl should be rather weak at this low bombarding energy, and known ^{39}Cl transitions are indeed very weak in our data. Sorting in the $\gamma\gamma$ coincidence mode has established that at least five of these stronger lines are from the same nucleus. A summary of energies and relative intensities for transitions we attribute to ^{40}Cl is given in Table I, and a decay scheme is shown in Fig. 2. Our proposed levels agree quite well with some of those deduced by Fifield *et al.*[1] from their charge-exchange work. Also shown are the results from one of the recent shell-model calculations of Woods.[4]

The four β-delayed γ-ray transitions reported by Dufour *et al.*[2] have energies of 211.6(4), 431.9(4), 677.5(5), and 888.6(4) keV. The first two of these were observed, albeit weakly, in our $\alpha p \gamma$ threefold coincidence data (see Fig. 1 and Table I). Neither was observed in coincidence with other ^{40}Cl γ rays, but this may be due to

TABLE I. Energies and relative intensities of γ rays attributed to ^{40}Cl from $\alpha p \gamma$ threefold coincidence data.

E_γ	Relative intensity	Transition
211.55(13)[a]	14(2)	212→0[b]
219.50(13)	11(2)	900→681
237.93(9)	34(3)	839→601
244.04(8)	100(7)	244→0
357.29(14)	47(4)	601→244
431.54(21)[a]	5(2)	...
436.76(17)	31(4)	681→244
601.30(28)	6(2)	601→0

[a]Also observed in the work of Dufour *et al.* (Ref. 2).
[b]Assumption based on relative β-decay intensities given in Ref. 2.

the weak population in our experiment of states which are strongly fed via β decay. The β decay of ^{40}S would be expected to proceed to $J=0$ or $J=1$ levels. Levels of such low spin are not likely to be excited strongly in either the charge-exchange reactions or the present work, nor are they likely to be linked via strong transitions to our strongly excited levels. The 212-keV line is the strongest transition reported in the β-decay work of Ref. 2, and is thus probably a transition to the ^{40}Cl ground state.

The ground state of ^{40}Cl is known to have $J^\pi = 2^-$ as a result of its β-decay scheme.[5] Fifield *et al.*[1] have suggested the (^{7}Li, ^{7}Be) reaction mechanism could be sequential, in which the pickup of a $d_{3/2}$ proton is followed by the stripping of a neutron into the $f_{7/2}$ shell, or vice versa.

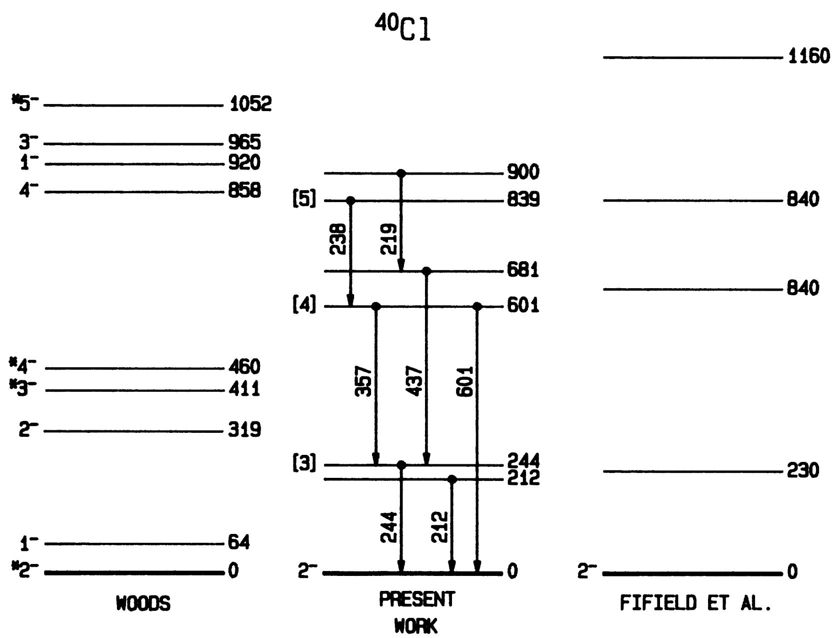

FIG. 2. Suggested decay scheme for transitions in ^{40}Cl. Preferred spins (see text for discussion) are shown in square brackets, but these are not to be viewed as assignments. Also shown are low-lying levels observed by Fifield *et al.* (Ref. 1) and a prediction of Woods (interaction I) (Ref. 4). The predicted states with a large direct overlap of the ^{37}Cl ground state coupled to the ^{43}Ca ground state are marked with an asterisk. Interaction II of Ref. 4 results in a similar ordering for the lowest levels.

This would strongly excite the negative parity multiplet of states having spins of 2, 3, 4, and 5, which arise from the coupling of the $\frac{3}{2}^+$ ground state of ^{37}Cl to the $\frac{7}{2}^-$ ground state of ^{43}Ca. The levels of 0, 0.64, 0.84, and 1.16 MeV have been identified as candidates for members of this multiplet by Ref. 1. They observe a weakly excited level at 0.23 ± 0.04 MeV which they attribute to $d_{3/2}$-$p_{3/2}$ or $d_{3/2}$-$f_{5/2}$ coupling. A $d_{3/2}$-$f_{5/2}$ coupling for such a weakly excited state would seem unlikely, however, since the cross sections for stripping a neutron into the $f_{5/2}$ and $f_{7/2}$ shells should be comparable: the orbital angular momentum transfer would be the same and the $\frac{5}{2}^-$ single-particle state in ^{43}Ca has an excitation energy of only 373 keV. A $d_{3/2}$-$f_{5/2}$ coupling should result in another strongly excited, low-lying negative-parity multiplet of states having spins of 1, 2, 3, and 4. The group at 0.64 MeV excitation in the spectra of Fifield *et al.*[1] is very strong, suggesting that both members of the (unresolved) 601–681 keV doublet may be strongly excited via charge exchange. These two levels, and the groups observed by Ref. 1 at 0.84 and 1.16 MeV excitation probably account for four of the five states having spins of 3, 4, or 5 as a result of $d_{3/2}$-f coupling. A $d_{3/2}$-$p_{3/2}$ coupling scheme would seem to be favored for the state(s) near 0.23 MeV by virtue of their weak excitation in the data of Ref. 1.

A preliminary analysis of our angular distribution data for the relatively strong $839 \rightarrow 601 \rightarrow 244 \rightarrow 0$ decay chain (see Fig. 2) indicates no evidence for stretched quadrupole transitions and a preference for dipole contributions. While gating on the $244 \rightarrow 0$ transition at $\theta = 90°$, intensity ratios $I(90°)/I(147°)$ of 1.06(11) and 1.15(14) were measured for the 357- and 238-keV transitions, respectively. This ratio should be about 1.2–1.4 for stretched dipoles and 0.8–0.9 for stretched quadrupoles. Further, strong $E1$ transitions between such low-lying states would seem unlikely, as this would require a precursor state of positive parity which, in turn, would require a valence proton in the fp shell or a single neutron hole in the sd shell. Thus, it seems reasonable to assume these transitions are primarily of the $M1/E2$ type having $\Delta J = 0$ or 1. Indeed, if this is an yrast decay chain, the levels at 244, 601, and 839 keV would have spins of 3, 4, and 5, respectively. If these conjectures are correct, and especially if the 244-keV level is a $d_{3/2}$-$p_{3/2}$ state with spin 3, the ordering of levels is quite different from that predicted by Woods,[4] since those calculations show the $d_{3/2}$-$f_{7/2}$ 3^- state to be the yrast $J = 3$ state (see Fig. 2). This would be somewhat surprising, since calculations by Ref. 4 using the same interactions for other Cl isotopes (including odd-odd ^{38}Cl) were relatively successful in predicting properties of low-lying states. As pointed out in Ref. 4, however, there is evidence for sizable configuration mixing in the low-lying states of ^{38}Cl. It is only reasonable to expect such mixing to be strong in the more neutron-rich ^{40}Cl as well. Perhaps it is so strong that the ordering of energy levels is affected, even though such was apparently not the case in early calculations for ^{38}Cl. Our angular correlation data are currently being analyzed in greater detail, with the hope that counting statistics will be sufficient to provide further information on the spins and parities of excited states in ^{40}Cl.

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