AN ANOMALOUS M1 TRANSITION IN ^{38}Cl*

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The observed enchangement of the M1 transition in ^{38}Cl between the 3^- state of the "$d_{3/2}$-$p_{3/2}$ multiplet" and the 4^- state of the "$d_{3/2}$-$f_{7/2}$ multiplet" is explained..

The analysis of the energies of the low-lying states of ^{38}Cl and ^{40}K was one of the early quantitative successes of nuclear shell model theory. [1, 2] If we speak in terms of an ^{16}O core, then the first states of ^{38}Cl should arise in lowest order from the configuration $(\nu d_{5/2})^6$, $(\pi d_{5/2})^6$, $(\nu s_{1/2})^2$, $(\pi s_{1/2})^2$, $(\nu d_{3/2})^4$, $(\pi d_{3/2})^1$, $(\nu f_{7/2})^1$, where ν denotes neutrons and π denotes protons. Similarly the lowest states of ^{40}K should arise from the configuration formed by adding two more protons to the $d_{3/2}$ orbit. The $d_{5/2}$ and $s_{1/2}$ orbits are thus always filled, as is the $\nu d_{3/2}$ orbit, and we describe ^{38}Cl in terms of $(\pi d^1_{3/2}-\nu f^1_{7/2})$ couplings and ^{40}K in terms of $(\pi d^{-1}_{3/2}-\nu f^1_{7/2})$ couplings.

In the early shell model analyses of this region, these simple configurations were assumed and it was shown that the observed energies of the 2^-, 3^-, 4^-, and 5^- states in ^{40}K can be obtained almost exactly by applying the appropriate particle-hole transformation rule to the energies of the first 2^-, 3^-, 4^-, and 5^- states of ^{38}Cl. The accuracy achieved in this transformation was then, and has been since, taken as confirmation that the wave functions of the states involved did indeed closely resemble the simple initial assumptions. Subsequent measurements [3, 4] have disclosed a higher lying multiplet in each nucleus which can be described in similar fashion as couplings of a $d_{3/2}$ particle (hole) with a $p_{3/2}$ particle, although the transformation of energies is not as accurate as for the lower sets of states.

Recently, however, measurements have revealed some characteristics of ^{38}Cl states which are difficult to reconcile with the simple description just outlined [5, 6]. Chief among these data is strong M1 transition from the 3^- state of the $(d_{3/2}-p_{3/2})$ multiplet to the 4^- state of the $(d_{3/2}-f_{7/2})$ multiplet. This transition is, of cource, l-forbidden to the extent that the wave functions of the states actually follow the description given heretofore. Other data which cast doubt on the purity of these ^{38}Cl states are the spectroscopic factors for (d, p) stripping on ^{37}Cl [7]. These experiments show some admixing of $l = 1$ into the supposed $(d_{3/2}-f_{7/2})$ 3^- state.

We have calculated energies and wave functions for ^{38}Cl, ^{39}K, and ^{40}K in a model space which includes active $d_{5/2}$, $s_{1/2}$, $d_{3/2}$, $f_{7/2}$, and $p_{3/2}$ particles, using the codes of French et al. [8]. The two-body matrix elements used in our Hamiltonian were calculated from the Sussex relative oscillator matrix elements [9] with space truncation effects added [10], and the single-particle energies were chosen to yield calculated spectra for ^{38}Cl, ^{39}K, and ^{40}K in simultaneous best agreement with the experimental spectra. The values for $d_{5/2}$, $s_{1/2}$, $d_{3/2}$, $f_{7/2}$, and $p_{3/2}$ are, respectively, −9.40, −4.90, −2.77, −2.52, and 0.00 MeV. Some of these results for ^{38}Cl and ^{40}K are summarized in fig. 1 and table 1. The experimental and predicted S-factors for the ^{37}Cl(d, p)^{38}Cl reaction are presented in table 2.

Our predictions for these observables (our M1 calculations use operators calculated from the bare-nucleon g-factors) are in uniform good agreement with the observed values. In particular, for ^{38}Cl the mixing of the $l = 1$ and $l = 3$ strengths for the 3^- states

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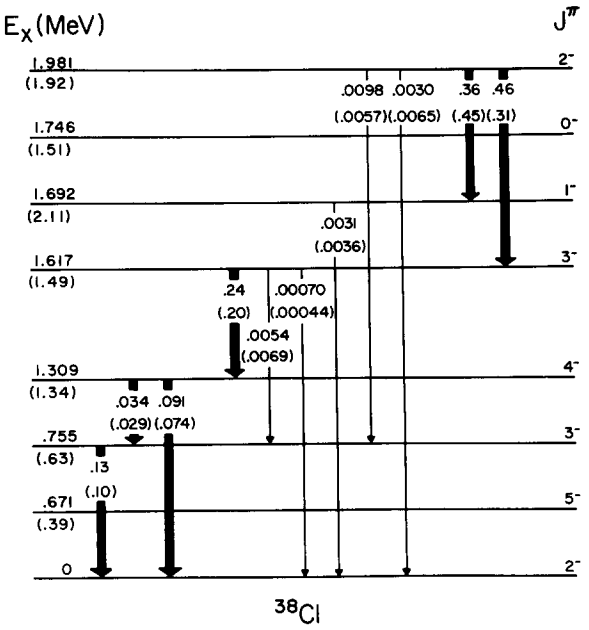

Fig. 1. The excitation energies and M1 transition strengths of ^{38}Cl. Predicted quantities are shown within brackets.

and, most strikingly, the anomalously large $3_2^- \to 4_1^-$ M1 transition strength are correctly predicted.

The difficulty of accounting for this M1 transition, enhanced when it should be severely retarded according to simple ideas, has been frequently noted recently [11, 12]. It is thus of interest to see how the correct strength emerges from the present wave functions. The components in the wave functions of the 3_2^- and 4_1^- states which are the important contributors to this strength are as follows, with amplitudes preceding the component specification (we now revert to isospin notational conventions):

$$-0.37[(d^5_{3/2})_{3/2,\,3/2} f_{7/2}] \to -0.87[(d^5_{3/2})_{3/2,\,3/2} f_{7/2}]$$

$$-0.39[s^{-1}_{1/2}(d^6_{3/2})_{1,1} f_{7/2}] \to -0.13[s^{-1}_{1/2}(d^6_{3/2})_{2,1} f_{7/2}]$$

and

$$0.33[s^{-1}_{1/2}(d^6_{3/2})_{0,1} f_{7/2}] \to 0.25[s^{-1}_{1/2}(d^6_{3/2})_{0,1} f_{7/2}]$$

Since the weightings of these three pairs of components from the M1 single-particle matrix elements are about 1 to 3 to 3, respectively, we see that the excitations from the $s_{1/2}$ to the $d_{3/2}$ orbit are of comparable importance to the mixing between $f_{7/2}$ and $p_{3/2}$ excitations in contributing allowable paths for the M1 transition. (The $s_{1/2}$ particles, as well as $f_{7/2}$ and $p_{3/2}$, have their spins parallel to the orbital angular momentum, thus producing strong isovector contributions to the M1 strengths [13]. And, of course, in another sense these $s^{-1}_{1/2}$ components are vital because they provide the fragmentation of the wave functions from which the coherent strength necessary to reproduce the observed enhancement can be built up. The dominating aspect of the coherent of these fragments is emphasized

Table 1
M1 transitions in ^{40}K

$J_i^\pi \to J_f^\pi$	M1 strength (W.U.)		
	Argonne [5]	Frankfurt [6]	Theory
$3_1^- \to 4^-$	0.150	0.170	0.087
$2_1^- \to 3_1^-$	0.127	0.140	0.091
$5^- \to 4^-$	0.030	0.030	0.027
$2_2^- \to 2_1^-$	0.0130	0.0100	0.0045
$2_2^- \to 3_1^-$	0.0026	0.0023	0.0016
$3_2^- \to 2_1^-$	0.0033	0.0020	0.0048
$3_2^- \to 3_1^-$	0.0046	0.0025	0.0053
$3_2^- \to 4^-$	0.0030	0.0016	0.0012
$1^- \to 2_1^-$	0.0076	0.0038	0.0222
$0^- \to 1^-$	0.47	0.20	0.91

Table 2.
Spectroscopic factors of the ^{37}Cl(d, p)^{38}Cl reaction

E_x(MeV)	J^π	Exp [5]		Theory	
		$S(l=3)$	$S(l=1)$	$S(l=3)$	$S(l=1)$
0.0	2^-	0.85		0.88	0.03
0.67	5^-	0.78		0.92	
0.76	3^-	0.59	0.09	0.72	0.17
1.32	4^-	0.70		0.81	
1.62	3^-		0.40	0.15	0.46
1.69	1^-		0.81		0.80
1.75	0^-	1.08			0.94
1.98	2^-		0.70	0.007	0.76

when we consider that the $2_2^- \rightarrow 2_1^-$ transition has individual contributions of equivalent size to those for the $3_2^- \rightarrow 4_1^-$ and that those for the $3_2^- \rightarrow 3_1^-$ transition are actually considerably larger (as pointed out by Erne [14]). However, in these cases the signs of the individual components are such that the various contributions cancel each other.

The general conclusions from the present calculations are:

1) The $(d_{3/2} - f_{7/2})$ and $(d_{3/2} - p_{3/2})$ multiplets in ^{38}Cl are about 80% pure, with considerable $f_{7/2} - p_{3/2}$ mixing only between the 3^- states.

2) The 5%–20% admixtures of the $s_{1/2}^{-1}$ configuration in these ^{38}Cl states are vital to account for the observed anomalous Ml strength between the 3_2^- and 4_1^- states.

3) The purity of the anomalous multiplets in ^{40}K is considerably higher, and, in consequence, no anomalies in M1 strength are predicted, again in accordance with observation.

4) The difference between ^{38}Cl and ^{40}K are consequences of the freedom to excite particles within the sd-shell which exists for ^{38}Cl and which does not exist for ^{40}K. In other words, the differences are due to the break-down of some of the assumptions upon which the particle-hole transformation is based, e.g., that ^{32}S is a good closed shell nucleus. Since both experiment and the present calculations definitely indicate that these differences exist, it should be clear that close agreement of excitation energies in a pair of spectra conjugate under the particle-hole transformation rule in no way guarantees equivalent similarity of their wave functions.

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