Lifetime measurements and the high-spin structure of ^{36}Cl

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Abstract. High-spin states in ^{36}Cl were populated through the ^{24}Mg(^{14}N,2p)^{36}Cl reaction at $E(^{14}\mathrm{N})$=31 MeV. Lifetimes have been determined for fifteen states by applying the Doppler shift attenuation method. The results indicated the onset of collectivity in the high spin negative parity states. Large basis shell model calculations have been performed to understand the underlying structure of these states.

1. Introduction

Considerable experimental and theoretical efforts have been made in recent years to elucidate the role of particle-hole *sd*-*fp* cross-shell intruder configurations in the structure of the *sd* shell nuclei. At β stability, the experimental information, limited previously to low and medium spins [1], was extended at high spins and excitation energies, using heavy ion fusion-evaporation reactions and complex detection arrays [2, 3, 4, 5, 6, 7]. In this region the low-spin structure can be well reproduced by shell model calculations limited to the *sd* main shell with the USD residual interaction introduced by Wildenthal and Brown [8]. At high spins the excitations of particles from the *sd* shell to the *fp* shell have to be taken into account, and the experimental data serve as testing the proposed effective interactions [9, 10, 11]. The coexistence of spherical and deformed states is an interesting feature reported recently in several nuclei of the region [2, 3, 6] and described by large scale shell model calculations involving multi-particle – multi-hole intruder excitations from the *sd* to the *fp* shell. In order to investigate the evolution

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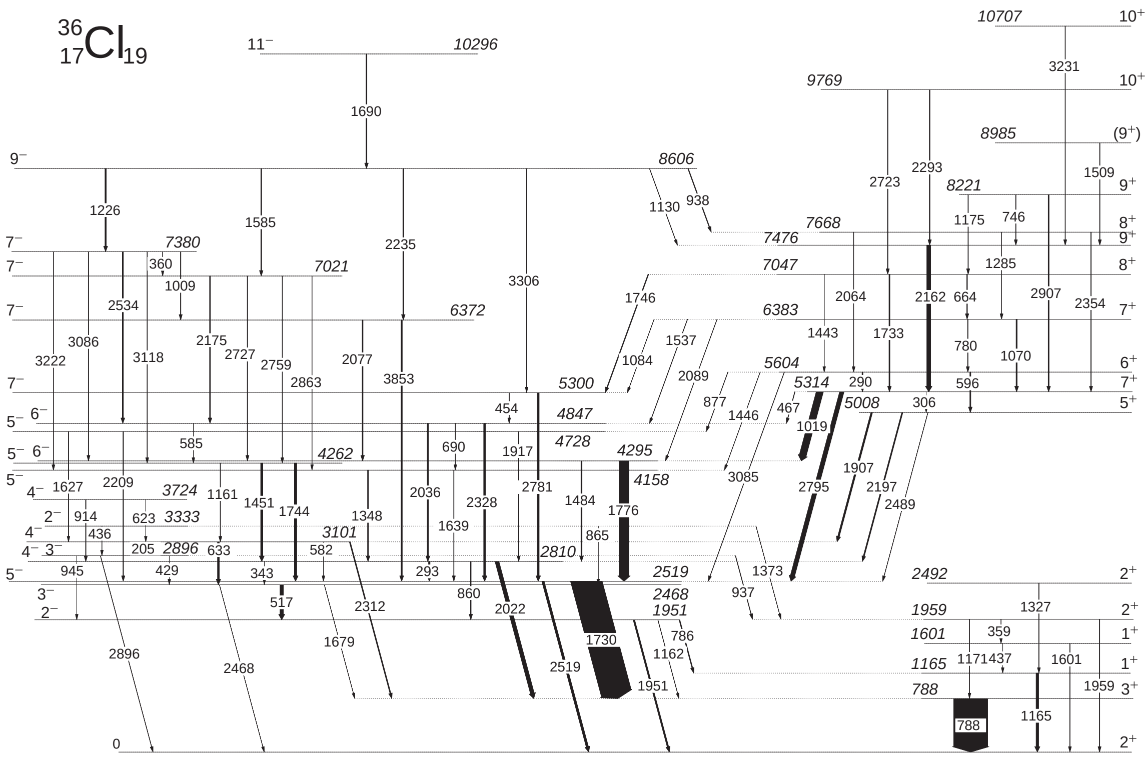

Figure 1. High-spin level scheme of ^{36}Cl.

of collectivity with increasing spins the determination of transition probabilities is of crucial importance. We report here results of lifetime and transition probability investigations for the high spin states in the odd-odd ^{36}Cl nucleus.

2. Experimental results

The high-spin states in ^{36}Cl were populated via the fusion-evaporation reaction ^{24}Mg(^{14}N,2p)^{36}Cl with a 31 MeV ^{14}N beam delivered by the XTU-Tandem accelerator at the INFN-Legnaro National Laboratory, Italy. The 99.7% isotopically enriched ^{24}Mg target, 1 mg/cm^2 thick, was evaporated on a 8 mg/cm^2 gold layer. The γ-rays emitted in the reaction were detected using the 4π-GASP array [12] composed of 40 Compton-suppressed large volume high-purity Ge detectors arranged in seven rings at different angles with respect to the beam axis. A complex decay scheme, considerably extended at larger spins and excitation energies with respect to previous studies [1], has been established for ^{36}Cl [5] (see Fig. 1).

The lifetimes of the new high-spin states have been investigated by the Doppler shift attenuation method. For this purpose spectra of interest were created from the asymmetric γ–γ matrices by gating on appropriate lower-lying transitions emitted from stopped nuclei. The analysis has been performed using the LINESHAPE computer code [13]. From lineshape analysis, lifetimes have been derived for 14 new levels in ^{36}Cl, as well as for the 4295 keV state previously known without measured lifetime. Examples of experimental lineshapes at different angles and the corresponding fits are illustrated in Fig. 2. The investigated states and the derived half-lives are shown in Table 1.

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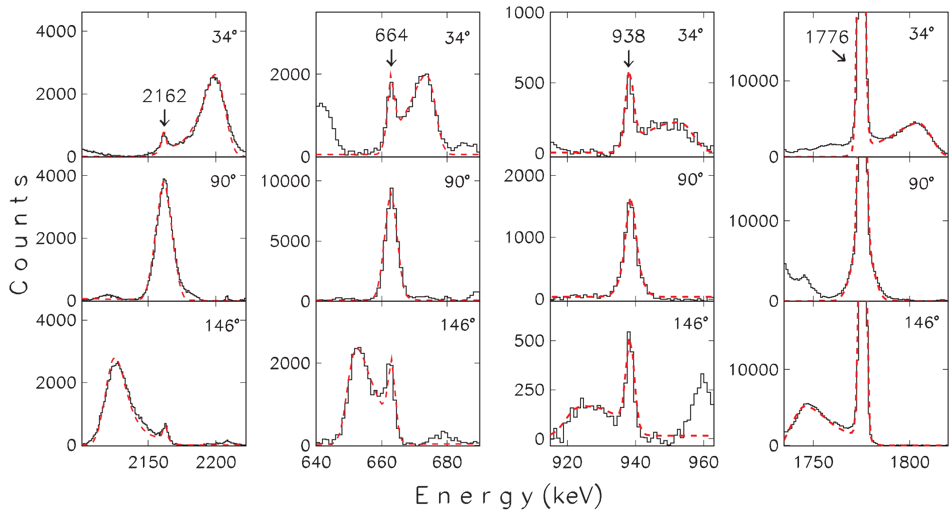

Figure 2. Illustrative experimental and fitted (red dashed line) lineshapes in ^{36}Cl.

3. Discussion

Using the measured half-lives and branching ratios (BR), the experimental $B(M1)$ and $B(E2)$ reduced transition probabilities have been derived (see Table 1). Small transition strengths, $B(E2) \approx$ 2-9 W.u., were obtained for all $E2$ transitions, excepting the 1226 and 1690 keV transitions de-exciting the 9^-_1 and 11^-_1 states, with values $B(E2)$(1227 keV)=16.9 W.u. and $B(E2)$(1690 keV)=24.2 W.u., respectively. To get insight into the underlying structures, we have performed shell model calculations using two effective interactions developed for this mass region, namely the *sdfp* interaction [10] and the PSDPF interaction [11]. The PSDPF interaction considers the full *psdpf* model space with a ^{4}He core, and only one nucleon is allowed to jump between major shells. More than one particle-hole excitation to the *fp* shell is allowed using the *sdpf* interaction and the model space spanned by the $s_{1/2}, d_{3/2}, f_{7/2}$ and $p_{3/2}$ orbits. The experimental reduced transition probabilities are compared in Table 1 with shell-model calculations. The agreement between experimental data and shell-model predictions is quite satisfactory. The *sdfp* calculations indicate that the positive-parity states with $J^\pi \geq 5^+$ involve two particle-hole intruder excitations to the *fp* shell. Negative-parity states are predicted to have one neutron in the $f_{7/2}$ orbit at low spin and the proton in the *sd* shell, but the excitation of three particles (protons and neutrons) to the upper *fp* shell becomes relevant already at spin $J^\pi = 7^-$. The large $B(E2)$ value of the $11^-_1 \rightarrow 9^-_1$ is reproduced by the *sdfp* calculations, in which the involved states are both described by the promotion of three nucleons into the *fp* shell. On the other hand, the PSDPF calculations, in which only one nucleon is excited in the *fp* shell, predict a much smaller $B(E2)$ value for this transition. In the *sdfp* calculations the wave functions of the 7^- states involve one neutron excited in the *fp* shell, with the exception of the 7^-_3 state where three nucleons are excited. A large $B(E2)$ value for the $9^-_1 \rightarrow 7^-_3$ is correspondingly predicted, while experimentally the $B(E2)$ is largest for the $9^-_1 \rightarrow 7^-_4$ transition. To reproduce the experimental findings one can consider an inversion of states, with the 7^-_4 observed state described by the calculated 7^-_3 state, and the 7^-_2 and 7^-_3 experimental levels described by the 7^-_4 and 7^-_2 calculated states, respectively. The 1226- and 1690-keV $E2$ transitions having enhanced $B(E2)$ values could be the lowest-lying members of a deformed band, similar to that observed recently in the odd-mass ^{35}Cl nucleus [6]. More experiments are needed to possibly evidence such a deformed structure in the odd-odd ^{36}Cl nucleus.

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Table 1. Experimental and calculated reduced transition probabilities B(M1) and B(E2).

E_{lev}^{exp} (keV)	$T_{1/2}^{exp}$ (ps)	J_i^π	J_f^π	E_γ^{exp} (keV)	BR %	$B(M1)(\mu_N^2)$ exp	PSDPF	$sdfp$	$B(E2)(e^2fm^4)$ exp	PSDPF	$sdfp$
5604	0.62(14)	6_1^+	7_1^+	290	33(6)	0.86(25)		0.826			
			5_1^+	596	42(5)	0.126(32)		0.384			
6383	0.24(5)	7_2^+	6_1^+	780	21(2)	0.070(18)		0.048	60(40)		2
			7_1^+	1070	51(4)	0.068(17)		0.304			
7047	0.34(6)	8_1^+	7_2^+	664	26(3)	0.102(22)		0.098			
			6_1^+	1443	5(1)				14(4)		12
			7_1^+	1733	40(4)	0.009(3)		0.051			
7476	0.18(3)	9_1^+	7_1^+	2162	100				67(11)		68 (9_2^+)
7668	0.07(2)	8_2^+	7_2^+	1285	26(2)	0.069(20)		0.077			
			6_1^+	2064	21(1)				45(14)		32
			7_1^+	2354	53(3)	0.023(9)		0.054	0.05(3)		0.51
8221	0.09(2)	9_2^+	9_1^+	746	23(5)	0.240(72)		0.002			
			8_1^+	1175	23(4)	0.057(16)		0.002	57(42)		4
			7_1^+	2907	54(6)				16(5)		7 (9_1^+)
4158	0.13(4)	5_2^-	4_1^-	1348	74(6)	0.091(25)	0.050	0.0002	9(4)	74	0.02
			5_1^-	1639	26(4)	0.018(6)	0.052	0.006			
4262	0.22(8)	5_3^-	4_2^-	1161	7(1)	0.008(3)	0.010	0.014			
			4_1^-	1451	42(1)	0.025(10)	0.014	0.005			
			5_1^-	1744	51(3)	0.017(6)	0.023	0.080			
4295	0.23(5)	6_1^-	4_1^-	1484	10(1)				34(8)	0.002	0.002
			5_1^-	1776	90(2)	0.016(5)	0.011	0.066	53(20)	82	17
4847	0.17(4)	6_2^-	5_3^-	585	2.2(1)	0.024(6)	0.0001	0.103	45(25)	0.02	3
			5_2^-	690	1.4(1)	0.010(3)	0.008	0.103			
			4_1^-	2036	38(1)				36(9)	2	44
			5_1^-	2328	58(2)	0.009(3)	0.013	0.058	5(3)	2	9
5300	0.16(5)	7_1^-	6_2^-	454	8(2)	0.211(84)	0.046	0.029			
			5_1^-	2781	92(7)				20(6)	15	7
6372	0.13(3)	7_2^-	6_1^-	2077	42(2)	0.014(3)	0.003	0.034			
			5_1^-	3853	58(4)				3(1)	3	6
8606	0.55(9)	9_1^-	7_4^-	1226	32(1)				119(22)	13	95 (7_3^-)
			7_3^-	1585	21(1)				22(4)	1	20 (7_2^-)
			7_2^-	2235	22(2)				4(1)	12	9 (7_4^-)
			7_1^-	3306	3(1)				0.08(3)	12	0.2
10296	0.24(4)	11_1^-	9_1^-	1690	100				171(29)	8	116

References

[1] Endt P M 1998 *Nucl. Phys.* A **633** 1, and references therein
[2] Svensson C E *et al.* 2000 *Phys. Rev. Lett.* **85** 2693
[3] Ideguchi E *et al.* 2001 *Phys. Rev. Lett.* **87** 222501
[4] Ionescu-Bujor M *et al.* 2006 *Phys. Rev.* C **73** 024310
[5] Aydin S *et al.* 2012 *Phys. Rev.* C **86** 024320
[6] Bisoi A *et al.* 2013 *Phys.Rev.* C **88** 034303
[7] Aydin S *et al.* 2014 *Phys. Rev.* C **89** 014310
[8] Brown B A and Wildenthal B H 1988 *Ann. Rev. Nucl. Part. Sci.* **38** 29
[9] Warburton E K, Becker J A and Brown B A 1990 *Phys. Rev.* C **41** 1147
[10] Caurier E, Langanke K, Martinez-Pinedo G, Nowacki F and Vogel P 2001 *Phys. Lett.* B **522** 240
[11] Bouhelal M, Haas F, Caurier E, Nowacki F and Bouldjedri A 2011 *Nucl. Phys.* A **864** 113
[12] Rossi Alvarez C 1993 *Nucl. Phys. News* **3** 10
[13] Wells J C and Johnson N R 1991, Report No. ORNL-6689, p. 44