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High-spin states in ^{34}Cl

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High-spin states in ^{34}Cl were populated in the ^{27}Al (^{12}C, αn) ^{34}Cl fusion-evaporation reaction between 27 and 45 MeV incident energy and in the ^{31}P(α, n) ^{34}Cl reaction at 14.4 MeV. The decay scheme is obtained from γ-γ and n-γ coincidence measurements. The J^π assignments for the levels at 4743, 4824, and 5315 keV result from angular distributions, directional correlation ratios, and excitation functions. The lifetime of the 5315 keV level was measured in a recoil distance experiment.

NUCLEAR REACTIONS ^{27}Al(^{12}C, αn)^{34}Cl; measured γ-γ coinc and $\sigma(E\gamma, \theta)$ at E_{lab} = 40 MeV and $\sigma(E)$ from 27 to 45 MeV; ^{31}P(α,n)^{34}Cl, E_α = 14.4 MeV, measured n-γ coinc, ^{34}Cl deduced levels, J^π. Measured R. D. M., deduced τ. Natural targets, Ge(Li) detectors, liquid scintillator. Comparison with theoretical weak-coupling model.

I. INTRODUCTION

The spectroscopy of high-spin states is a major application of heavy-ion (HI) fusion-evaporation studies. The detection of γ rays from this type of reaction can give information on the localization of high-spin states, their decay schemes and lifetimes. The present data were obtained as part of a high-spin states investigation program[1-3] using high-spin selective[4] HI induced reactions. High-spin states in ^{34}Cl are studied by the reactions ^{27}Al(^{12}C, αn)^{34}Cl at E_{lab} = 27–45 MeV and ^{31}P(α, n)^{34}Cl at E_{lab} = 14.4 MeV. The $N = Z = 17$ nucleus which was studied is of particular interest because its self-conjugate nature imposes particular selection rules[5] on the γ transitions.

In a simple shell-model picture, ^{34}Cl is considered as an active proton-neutron pair outside closed $d_{5/2}$, $s_{1/2}$ shells. The ^{34}Cl level scheme has therefore been the subject of a number of theoretical investigations, including shell-model calculations[6-9] and vibration-particle coupling.[10] In the shell-model calculations, no state with J^π higher than 6$^+$ has been predicted. However, high-spin states were identified in the two nucleon transfer reactions ^{32}S(α, d)^{34}Cl (Refs. 11, 12) and ^{32}S(^{3}He,p)^{34}Cl (Ref. 13). Since this kind of reaction strongly populates states where the transferred proton and neutron enter the same orbit and couple to maximum angular momentum and zero isospin, simple configurations could be assigned to the high-spin states produced.

The present measurements were performed in order to obtain a more detailed picture of the high-spin states and in particular to study their deexcitation properties. The experimental procedure is described in Sec. II, data analysis and results are presented in Sec. III and a discussion is given in Sec. IV.

II. EXPERIMENTAL PROCEDURE

A. ^{27}Al (^{12}C, αn) ^{34}Cl reaction

Targets of 350 μg/cm^2 Al on thick Ta backings were bombarded with 27–45 MeV ^{12}C beams from the Strasbourg tandem accelerator. Measurements of the excitation function, angular distributions, and γ-γ coincidences were performed with two Ge(Li) of 16% and 20% relative efficiency. The γ-γ coincidence measurement was done at 40 MeV incident energy with the detectors placed at 0° and 90° to the beam. The experimental setup used in the lifetime measurement is the same as described in Ref. 14.

B. ^{31}P(α,n) ^{34}Cl reaction

This reaction was investigated at 14.4 MeV bombarding energy at the Strasbourg 7.5 MeV Van de Graaff accelerator, using a 200 μg/cm^2 red phosphorus target evaporated onto a thick Au foil. Neutrons were detected in a Ne 213 liquid scintillator placed at 60° in coincidence with γ rays detected in a Ge(Li) counter located at 0°. Pulse shape discrimination was performed after gating the signals from the liquid scintillation counter by fast coincidences with the Ge(Li) detector.

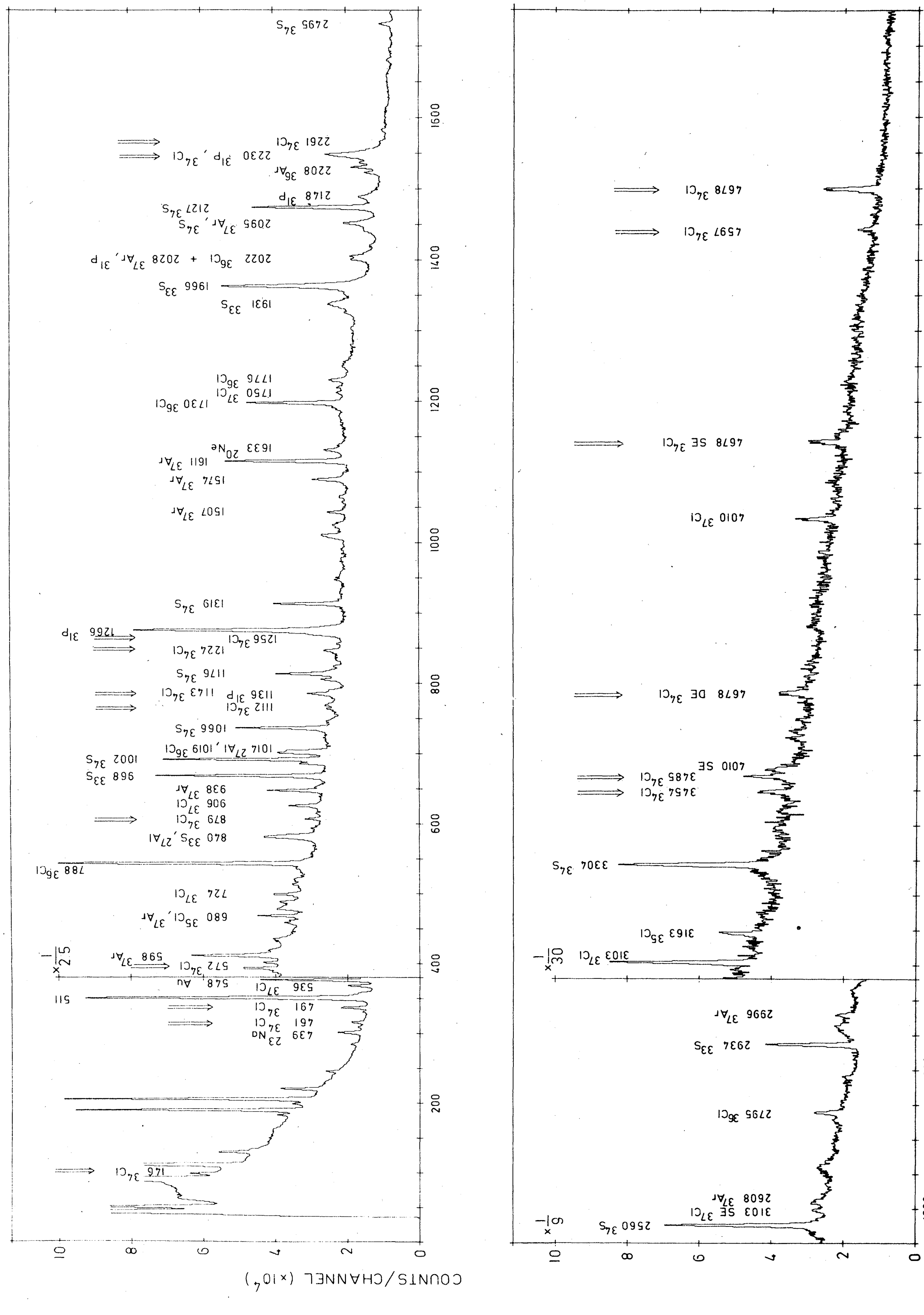

FIG. 1. γ-ray spectrum from the $^{27}Al+^{12}C$ reaction ($E_{^{12}C}=40$ MeV), recorded at 90°. Lines assigned to ^{34}Cl are indicated with double arrows.

TABLE I. Summary of γ-γ coincidence data from the $^{27}Al(^{12}C, \alpha n)^{34}Cl$ reaction at 40 MeV.

	461	491	572	879	1112	1143	1224	1256	2230	2261	3454	3485	4597	4678
461		×	×	×			×			×				
491	×			×			×			×				×
572	×				×	×	×	×			×	×	×	
879	×	×					×			×				
1112			×					×	×					
1143			×	×										
1224	×	×	×	×		×	×		×	×	×			
1256			×		×				×					
2230		×				×	×	×						
3454			×			×								
3485			×											
4678		×												

III. DATA ANALYSIS AND RESULTS

A. Decay scheme

γ-γ coincidence measurements

As shown in Fig. 1, γ-ray singles spectrum recorded at 90° reveals the numerous channels open in the $^{27}Al + ^{12}C$ reaction. The strongest lines correspond to ^{31}P, ^{33}S, ^{36}Cl, and ^{37}Ar nuclei. The

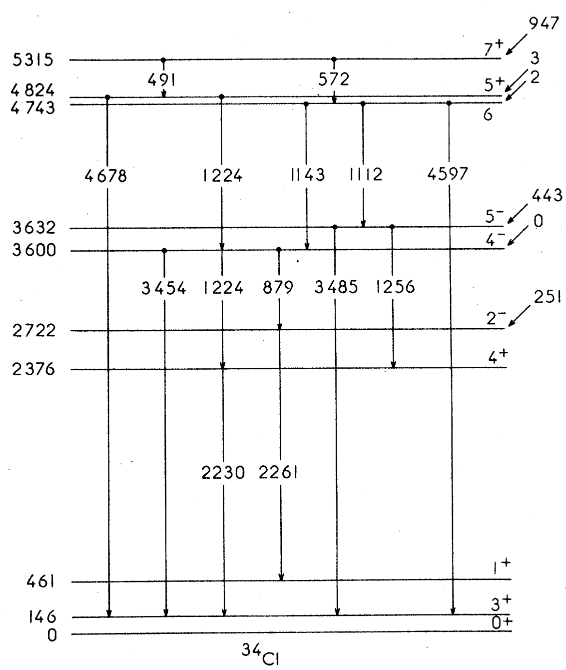

FIG. 2. ^{34}Cl energy levels and γ-ray transitions observed in the $^{27}Al(^{12}C, \alpha n)^{34}Cl$ reaction. Levels and γ-ray energies are in keV. The relative feedings intensities of the levels at $E(^{12}C) = 40$ MeV are given on the right. The spin-parity assignments for $E_x < 4$ MeV are from Ref. 15. The assignments for the three upper levels are discussed in the text.

coincidence matrix used to identify ^{34}Cl transitions is given in Table I. From these results, the decay scheme presented in Fig. 2 has been established. Excitation energies and comparison of branching ratios with previous values are given in Table II. All the observed levels up to 3632 keV have been reported previously.[15]

The 4824 keV level has been observed in proton radiative capture studies.[16,17] The decay scheme and branching ratios deduced from our measurements are consistent with the results of Ref. 17. This level has also been observed in the transfer reaction $^{32}S(^3He, p)^{34}Cl$ (Ref. 13).

In the $^{32}S(\alpha, d)^{34}Cl$ study, levels at 4.68, 4.79, and 5.28 MeV are quoted.[11,12] Since we found the 4.68 and 0.49 MeV γ rays to be in coincidence, we searched for a 0.11 MeV transition between the 4.79 and 4.68 MeV states, but no coincident 0.11 MeV γ ray was found. Internal conversion coefficients for a 0.11 MeV transition in ^{34}Cl are less than 0.1 (Ref. 18), so the transition cannot be strongly converted. We conclude that the 0.49 and 4.68 MeV transitions are consecutive in a cascade issuing from a level at 5.31 MeV. Our results (Fig. 2) imply that the levels given in the (α, d) studies[11,12] at 4.79 and 5.28 MeV are 30 keV too low.

The 4743 keV level, established by the γ-γ coincidence data, has not been previously reported.

n-γ coincidence measurements

The γ-ray spectrum in coincidence with neutrons from the $^{31}P(\alpha, n)^{34}Cl$ reaction is shown in Fig. 3. In addition to the 4.74, 4.82, and 5.31 MeV levels also observed in the $^{27}Al + ^{12}C$ reaction, a number of other lower lying levels are fed. In contrast with a previous study of the same reaction at 11 MeV (Ref. 19), strong excitation of many high lying levels is observed at 14.4 MeV. The decay scheme

TABLE II. Summary of informations on ^{34}Cl obtained in the present work and compared to previous results.

Energy level [a] (keV)	γ-ray energy [a] (keV)	Branching ratio a	Branching ratio b	Branching ratio c	Angular distribution a A_2(%)	Angular distribution a A_4(%)	Angular distribution b A_2(%)	Angular distribution b A_4(%)	$J_i^\pi \to J_f^\pi$	Mulipole mixing ratio	Mean lifetime (ps)
460.9(3)	460.9(3)		100	100	−25(4)						7.5 ± 0.5 [d]
3600.5(6)	3453.6(8)		47(2)	48	−22(8)	−11(8)	−12(3)	−1(3)	$4^- \to 3^+$		>2 [d]
	1223.8(8) [e]		7(1)	8					$4^- \to 4^+$		
	879.5(5)		46(2)	44	19(8)		30(3)	2(3)	$4^- \to 2^-$		
3631.6(6)	3485.2(8)	33(2)	45(2)	48	4(14)		9(8)		$5^- \to 3^+$		>3 [d]
	1256.0(1.5)	67(2)	55(2)	52	−29(7)		−22(3)	−4(3)	$5^- \to 4^+$		
4743.1(1.1)	4597.1(1.0)	27(3)							$6 \to 3^+$		>3 [a]
	1143.0(8)	43(2)			16(9)	−16(9)			$6 \to 4^-$	0.09(53)	
	1111.6(8)	30(2)			−8(20)				$6 \to 5^-$		
4824.2(1.1)	4677.7(1.0)	67(5)	81(4)	100	19(4)	−9(4).			$5^+ \to 3^+$	−0.03(10)	
	1223.8(8) [e]	33(5)	19(4)		−50(6)				$5^+ \to 4^-$		
5315.0(1.2)	571.8(3)	34(2)			−8(4)				$7^+ \to 6$	−0.03(12)	94 ±12 [a]
	490.9(3)	66(2)			14(2)	−8(2)			$7^+ \to 5^+$	0.00(5)	

[a] Present results.
[b] Reference 17.
[c] Reference 16.
[d] Reference 15.
[e] This γ ray is the unresolved sum of two transitions.

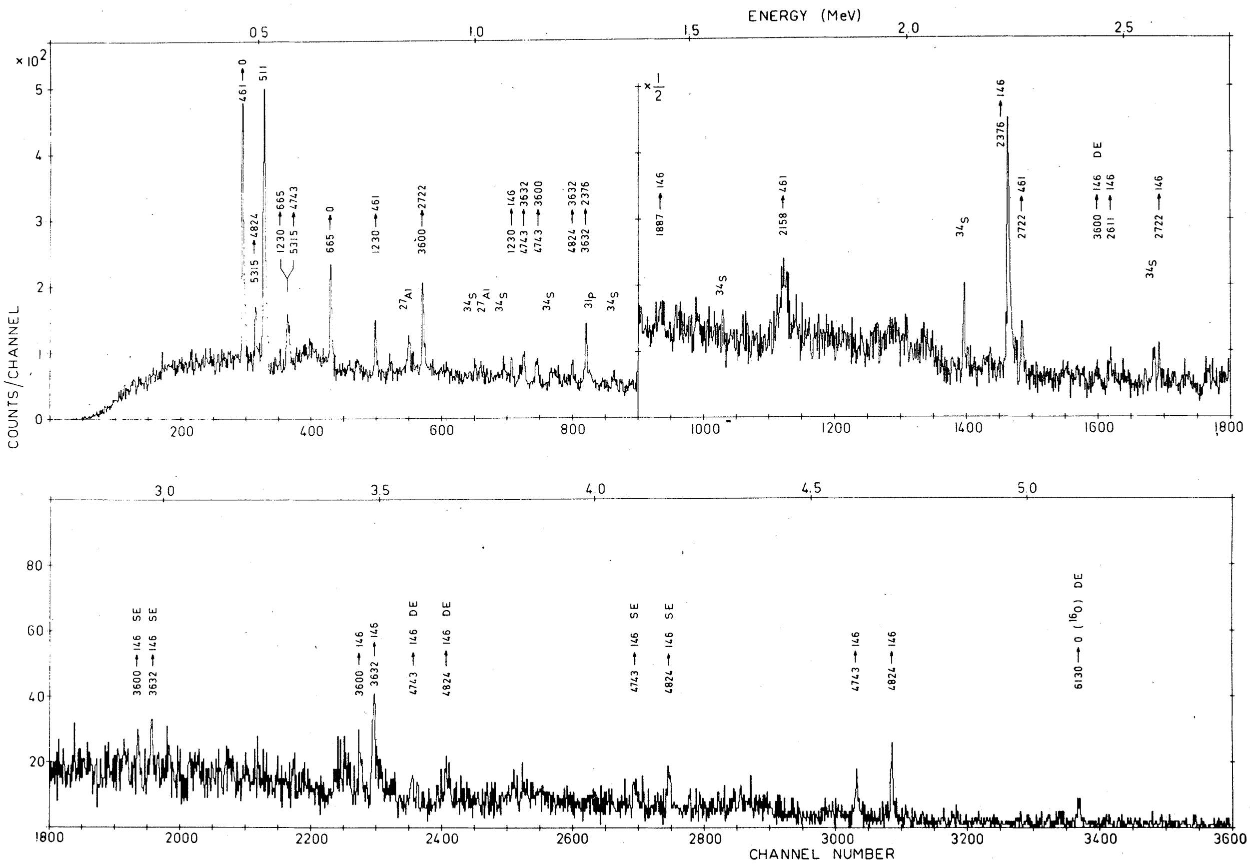

FIG. 3. γ-ray spectrum from the ^{31}P$(\alpha,n)^{34}$Cl reaction ($E_\alpha = 14.4$ MeV) recorded at 0°, in coincidence with neutrons detected at 60°. Lines assigned to ^{34}Cl are labeled by their corresponding transitions in keV. Weak background lines are indicated by the nucleus they belong to.

of Fig. 2 is consistent with results obtained in the n-γ experiment.

B. Spin assignments

The angular distributions were measured in the HI reaction at 40 MeV. The coefficients of the Legendre polynomials obtained from the fit to the distributions are given in Table II. Angular distributions and χ^2 analyses of the 5315 to 4824 keV and 4824 to 146 keV transitions are shown in Fig. 4. The χ^2 curves have been calculated using the indicated spin values, but since other spin values with the same absolute difference $|\Delta J|$ yield similar curves, the angular distributions determine only $|\Delta J|$ values. The alignment parameters of the 5315 keV level were considered as adjustable. The best fit parameters, $\alpha_2 = 0.34 \pm 0.04$ and $\alpha_4 = 0.36 \pm 0.04$, do not reflect a Gaussian population distribution of the magnetic substates. According to Ref. 20, the hypothesis of a Gaussian population distribution is not always valid. For the 4824 to 146 keV transition, the angular distribution suggests $|\Delta J| = 2$ but $|\Delta J| = 1$ cannot be excluded (Fig. 4). This last value would correspond to a multipole mixing ratio $\delta = -0.58$. The measured ratio of directional correlations (DCO) ratio, $R = W(\theta_1 = 0°, \theta_2 = 90°)/W(\theta_1 = 90°, \theta_2 = 0°)$ is 1.0 ± 0.2 (θ_1 and θ_2 are the detection angles of the first and the second γ rays in cascade). This measurement is in agreement with the theoretical value $R = 1.0$ for pure quadrupole transitions and excludes the $|\Delta J| = 1$ solution. Having established the $|\Delta J| = 2$ character of both transitions in the $5315 \rightarrow 4824 \rightarrow 146$ keV cascade, the known spin value of the 146 keV level ($J = 3$) restricts the possible spin of the 4824 keV level to 1 or 5 and the spin of the 5315 keV level to 3 or 7.

The rejection of $J = 3$ for the 5315 keV state is based on the comparison of the excitation functions shown in Fig. 5, for the radiations deexciting this level and the $J^\pi = 4^-$ level at 3600 keV. The curves reveal the characteristic increase in slope with higher spin values as described in Ref. 21 and indicate that the spin of the 5315 keV state is higher than 4.

The behavior of the excitation functions may be understood considering the kinematics of angular momenta in the heavy-ion reaction as illustrated in the grazing-collision plot[4] shown in Fig. 6. It is

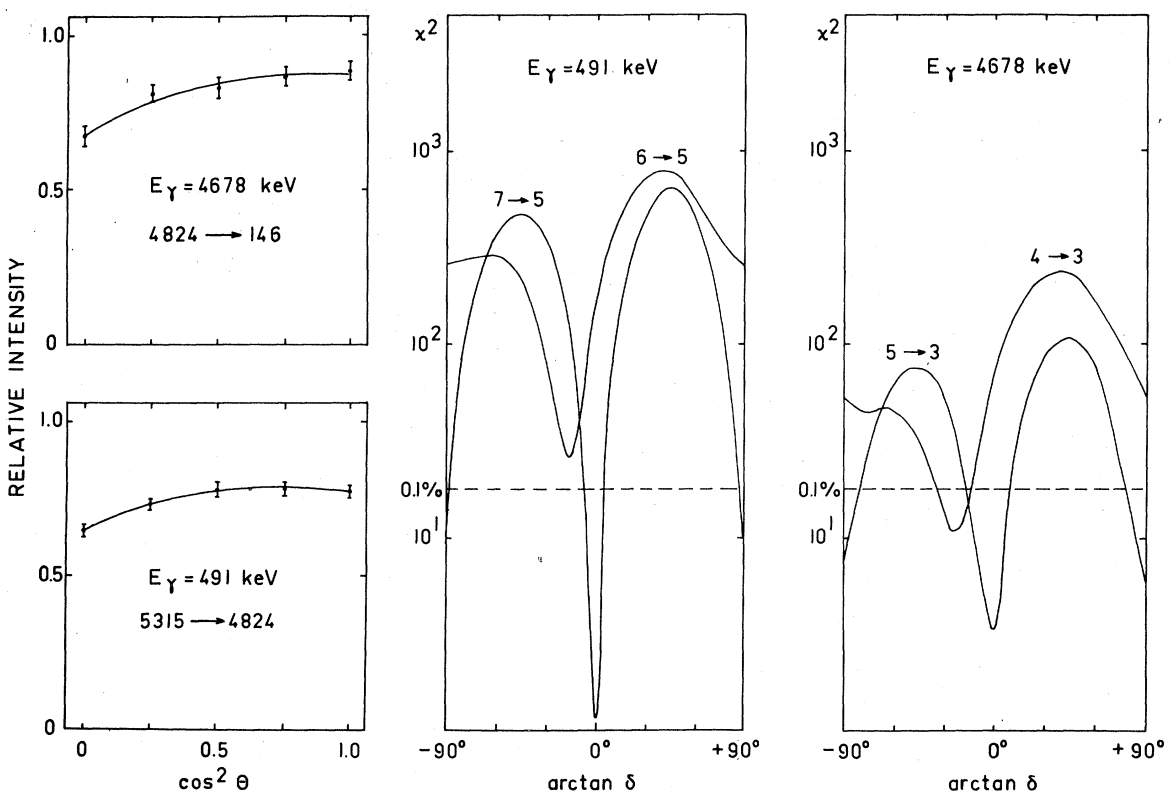

FIG. 4. Angular distributions measured in the ^{27}Al(^{12}C, αn)^{34}Cl reaction and corresponding χ^2 fits. Curves are labeled by spin values used in the calculations, but are typical for $|\Delta J| = 1$ and $|\Delta J| = 2$ transitions for high enough spins.

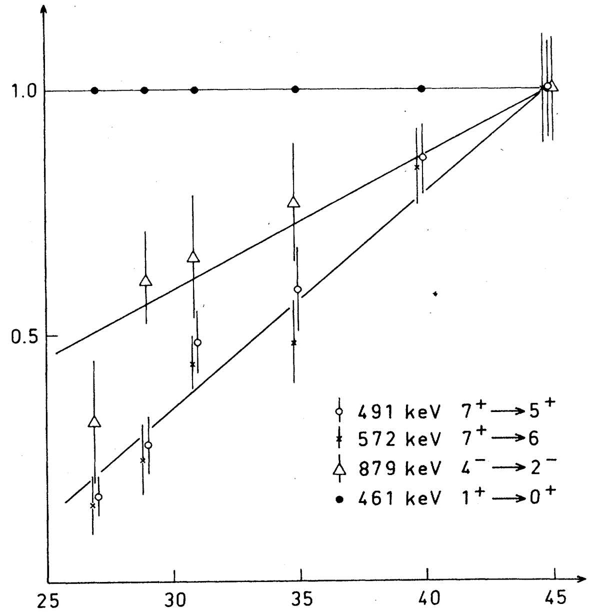

FIG. 5. Intensity of γ rays deexciting the studied levels relative to the intensity of the 461 keV transition, in ^{27}Al(^{12}C, αn)^{34}Cl reaction between 27 and 45 MeV.

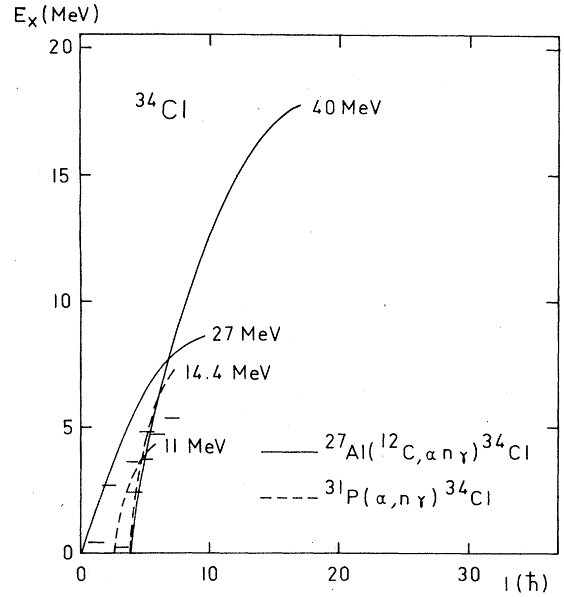

FIG. 6. Grazing-collision picture for the reactions ^{27}Al(^{12}C, αn)^{34}Cl at E(^{12}C) = 27 and 40 MeV and for ^{31}P(α,n)^{34}Cl at E_α = 11 and 14.4 MeV.

clear that the fraction of side-feeding decreases strongly in going from E_{lab} = 27 to 45 MeV and consequently the yield for the lower yrast transitions drops toward the value of the yield of their predecessors. It is further seen that the ^{31}P(α, n)^{34}Cl reaction at E_{lab} = 14.4 MeV is also selective for populating high-spin states.

Our J = 5 assignment for the 4824 keV level is in agreement with L = 4 for the transferred deuteron in the ^{32}S(^{3}He, p)^{34}Cl reaction[13] and in the ^{32}S(α, d)^{34}Cl reaction.[12] The value J = 7 for the 5315 keV state agrees with an L = 6 transfer in the ^{32}S(α, d)^{34}Cl reaction.[11,12] The positive parity of the two levels has been established from the even L values measured in the two nucleon transfer reactions.

The spin assignment of the 4743 keV level can be obtained from the multipolarity of the 572 keV (5315 → 4743) transition and from the decay scheme. As the 4743 keV level is fed from a J = 7 state by a pure dipole transition (see next section) and as an important part of the decay (27%) populates the 3$^+$ level at 146 keV, the spin value is restricted to J = 6. The angular distribution of the 4597 keV γ ray (4743 → 146) has been analyzed and reveals a strong anisotropy. However, the Legendre polynomial coefficients could not be obtained with enough accuracy to confirm the octupole character of the transition.

C. Lifetime measurements

The lifetime of the 5315 keV level was measurable by the recoil distance method. The data were obtained in a separate experiment with the ^{27}Al(^{12}C, αn)^{34}Cl reaction performed at 31 MeV. The relative intensity of the stopped peak as a function of the stopper distance is proportional to $\exp(-d/\bar{v}\tau)$ where $\bar{v}$ = 0.019c is the mean recoil velocity. The experimental data and the fit to the theoretical expression for τ = 94 ± 12 ps are shown in Fig. 7.

From the lifetime, transition strengths for the 491 and 572 keV radiations were deduced. The first transition has $E2$ character with a strength of 30 ± 4 W.u. (Weisskopf units). Since ^{34}Cl is a self-conjugate nucleus, this implies ΔT = 0. The transition is between levels of the same parity, in agreement with L = 6 and L = 4 transfers observed in the ^{32}S(α, d)^{34}Cl reaction.[11] The $M2$ transition strength (1028 W.u.) is far above the allowed limit.[22] The 572 keV transition has either $E1$ ($6.1 \pm 0.8 \times 10^{-4}$ W.u.) or $M1$ ($1.8 \pm 0.3 \times 10^{-5}$ W.u.) strength, which are both below the recommended upper limits[22] and do not allow characterization of the transition.

In the HI and α-particle induced reactions, the 4824 keV level has been found to be fed almost entirely by the γ rays from the 5315 keV level. Lifetime measurements on radiations deexciting the 4824 keV level are hampered by the long lifetime of the 5315 keV level and no lifetime for the lower level could be obtained.

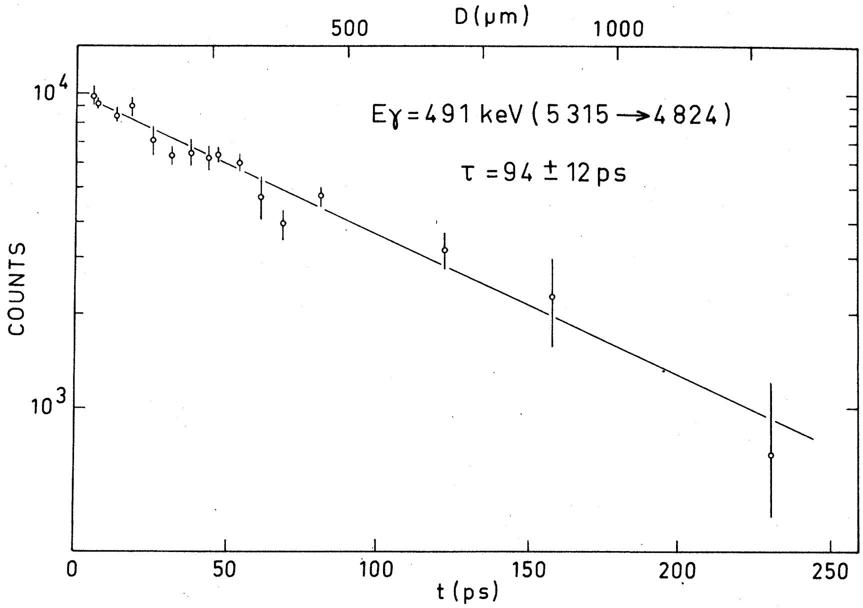

FIG. 7. RDM measured lifetime for the ^{34}Cl 491 keV (5315 → 4824) transition. The upper scale indicates the stopper distance and the corresponding time is on the lower scale.

No Doppler shift has been observed for the γ ray corresponding to the decay of the 4743 keV level despite the strong direct formation of this state in the $^{31}P(\alpha,n)^{34}Cl$ reaction. From this measurement the limit of the lifetime has been evaluated to be $\tau > 3.10^{-12}$ s.

IV. DISCUSSION

In first approximation, ^{34}Cl can be considered as an active neutron-proton pair outside a ^{32}S core. Since the 5315 keV level is strongly populated in two particle transfer reactions, the main configuration of the level is assumed to be

$$[^{32}S_{J^\pi=0^+,T=0}\otimes(f_{7/2})^2_{J^\pi=7^+,T=0}]_{J^\pi=7^+,T=0}.$$

Weak-coupling calculations underestimate the energy of the level. Using the parameters of Ref. 23, the energy of the configuration is 4.62 MeV compared to the experimental value of 5.31 MeV.

The proposed main configuration of the 4824 keV level is

$$[^{32}S_{J^\pi=0^+,T=0}\otimes(f_{7/2},p_{3/2})_{J^\pi=5^+,T=0}]_{J^\pi=5^+,T=0}.$$

That the nucleons are in different orbits is inferred from the relative cross sections of deuteron transfer reactions to the 4824 and 5315 keV levels.

The isoscalar $E2$ transition strength between the configuration of the 5315 and 4824 keV states calculated with effective charges $e_p=1.6e$ and $e_n=0.7e$ is 9.4 W.u. in reasonable agreement with the experimental result (30 W.u.).

From strong feeding in the proton transfer reaction $^{33}S(^3He,d)^{34}Cl$ with $L=3$, the proposed main configuration of the 3632 keV state (Ref. 13) is

$$[^{32}S_{J^\pi=0^+,T=0}\otimes(f_{7/2},d_{3/2})_{J^\pi=5^-,T=0}]_{J^\pi=5^-,T=0}.$$

The isoscalar $M2$ transition strength for the 7^+ to 5^- states is then predicted[24] to be 0.426 W.u. No 7^+ to 5^- $M2$ transition has been observed in ^{34}Cl in contrast with the results obtained for ^{36}Cl (Ref. 25), where such a transition has been measured with a strength of 0.42 W.u. In the ^{36}Cl case, the isovector part of the $M2$ operator must be taken into account. Experimentally isoscalar $M2$ transitions are inhibited by a factor of about 100 relatively to the isovector $M2$ transitions.[22]

As a final remark, the results from Ref. 25 for the $^{27}Al(^{14}N,p\alpha)^{36}Cl$ reaction and our results on the $^{27}Al(^{12}C,\alpha n)^{34}Cl$ reaction, point out a strong feeding of the 5^- and 7^+ yrast levels, both of which can be described by simple configurations. The electromagnetic decay properties for the $J^\pi=7^+$ level are in agreement with simple stretched configurations.

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