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PAR LA METHODE DU PARCOURS DE RECUL

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RECOIL-DISTANCE LIFETIME MEASUREMENT IN ^{37}Cl

MESURES DE DUREES DE VIE DANS ^{37}Cl PAR LA METHODE DU PARCOURS DE RECUL

J.C. MERDINGER, N. SCHULZ and M. TOULEMONDE

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Abstract. - Using the recoil-distance technique in the $^{27}Al(^{12}C,2p)^{37}Cl$ reaction, mean lives of (19.6 ± 3.0) ps for the $7/2^-$, 3103-keV state and (32.8 ± 2.0) ps for the $9/2^-$, 4011-keV state in ^{37}Cl have been measured. The strength of the M2 decay from the 3103 keV level appears to be the strongest among known M2 transitions in 2s-1d nuclei. An upper limit of 0.8 ps for the feeding time in the fusion-evaporation reaction $^{27}Al(^{12}C,pn)^{37}Ar$ was estimated from an attenuated Doppler shift measurement.

Résumé. - Des vies moyennes de (19,6 ± 3,0) ps et (32,8 ± 2,0) ps pour les états $7/2^-$ à 3103 keV et $9/2^-$ à 4011 keV dans ^{37}Cl ont été mesurées par la méthode du parcours de recul dans la réaction $^{27}Al(^{12}C,2p)^{37}Cl$. Parmi les transitions M2 connues dans les noyaux de la couche 2s-1d, celle issue du niveau à 3103 keV dans ^{37}Cl apparait comme étant la plus intense. Une mesure de déplacement Doppler atténué a permis d'évaluer une limite supérieure de 0,8 ps pour le temps de peuplement dans la réaction de fusion-évaporation $^{27}Al(^{12}C,pn)^{37}Ar$.

1. Introduction. - A search for $J^{\pi} = 7/2^{-}$ states in odd mass s-d nuclei and a study of their electromagnetic properties are currently underway in this laboratory [1]. In the cases where spin, lifetime, branching and mixing ratios are well established, it appears that the γ-decays of these states to the $J^{\pi} = 3/2^{+}$ ground states proceed via mixed M2-E3 transitions and that the partial M2 lifetimes are always retarded compared to the single-particle estimates [2]. In this paper we report on a recoil-distance method (RDM) measurement of the lifetime of the 3103 keV state in ^{37}Cl for which only a lower limit of 10 ps was known [3] at the time the present experiment was performed. The $7/2^{-}$ spin-parity assignment for this state, as well as the branching and mixing ratios for its ground state transition, have been determined in the past [3], so that the lifetime value directly leads to the magnetic quadrupole and electric octupole ground-state transition strengths.

A heavy-ion induced compound-nuclear reaction was chosen for populating the ^{37}Cl states. Such reactions involve large angular momenta transfer resulting in strong population of high-spin states, which are of interest here. Furthermore, such reactions yield large and forward directed velocities for the reaction products. Consequently only singles γ-ray spectra are needed for the RDM lifetime measurement. The bombardment of ^{27}Al by 31 MeV ^{12}C ions produced the ^{37}Cl states via the 2p exit channel. At that bombarding energy other exit channels were also open and lifetimes for states in ^{34}S, ^{36}Cl and ^{37}Ar were obtained as by-products.

2. Experimental procedure and analysis. - A 50 nA beam of ^{12}C ions from the M.P. Tandem Van de Graaff accelerator was used to bombard the aluminium targets. Gamma-rays were detected in a 84 cm^3 Ge(Li) detector. The detector system had an intrinsic resolution

of 2.8 keV for 1.33 MeV γ-rays.

A singles spectrum recorded at 31 MeV bombarding energy, where the yield for the 3103 keV line was found to be maximum, is shown in fig.1. A target evaporated onto a thick lead backing was used and the Ge(Li) counter was placed at an angle of 55^o to the beam direction. Most of the numerous lines present in this spectrum could be identified and attributed to transitions in ^{34}S, ^{35}Cl, ^{36}Cl, ^{37}Cl and ^{37}Ar.

2.1. Recoil-distance lifetime measurements. - The experimental set-up for the lifetime measurements is identical to that described in ref.4. A 100 $\mu g/cm^2$ self supporting stretched target was used. A 7 mg/cm^2 gold foil, sufficient to stop the recoil ions was stretched in the same manner as the target and used for the stopper. The beam was stopped in a thick tantalum foil mounted behind the stopper foil. The γ-rays were observed for various plunger distances with the Ge(Li) detector placed 7 cm from the target and at 0^o to the beam direction.

The average axial velocity of the recoiling ions was determined from the energy differences between the stopped E_o and shifted E_s peaks. The corresponding areas, I_o and I_s, were obtained with a least-squares fitting program using Gaussian line shapes superimposed on a background fitted to a polynomial series. The experimental ratios $R = I_o/(I_o + I_s)$ of the unshifted peak area to the total area, were then calculated at each plunger distance. For cases where the shifted peaks were obscured by contaminants in the γ-spectra, the intensities I_o were normalized to the intensity of the stopped peak of the 1611 keV γ-rays deexciting the long-lived ^{37}Ar 1611 keV state, corrected for its own decay $\tau = 6.38 \pm 0.15$ ns [5].

The lifetime values were obtained by comparing the experimental values of the ratio R to the values calculated for a level which is fed both directly from the reaction and by γ-ray of 2.8 keV for 1.33 MeV γ-rays.

A singles spectrum recorded at 31 MeV bombarding energy, where the yield for the 3103 keV line was found to be maximum, is shown in fig.1. A target evaporated onto a thick lead backing was used and the Ge(Li) counter was placed at an angle of 55^{o} to the beam direction. Most of the numerous lines present in this spectrum could be identified and attributed to transitions in ^{34}S, ^{35}Cl, ^{36}Cl, ^{37}Cl and ^{37}Ar.

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The lifetime values were obtained by comparing the experimental values of the ratio R to the values calculated for a level which is fed both directly from the reaction and by γ-ray cascades from higher lying levels. In this calculation the small direct feeding-time (see Sec. 3.3) was neglected.

The direct and cascade population fractions were taken from the γ-ray spectrum recorded at 55°. Corrections due to γ-ray detection efficiency and to the motion of the recoiling nuclei were found to be negligible compared to the statistical errors.

2.2. Doppler shift attenuation measurement. - By bombarding the target evaporated on the thick lead backing, γ-ray singles spectra were measured at the angles of 0°, 55° and 90°. From there a value for the attenuation factor $F = 0.29 \pm 0.04$ was deduced for the 598 keV γ-ray transition decaying the 7071 keV level in ^{37}Ar. The error on the attenuation factor arises mainly from the presence of the 600 keV γ-ray line produced by neutron inelastic scattering on ^{74}Ge.

3. Results. - The values of the mean-lives obtained in the present work are listed in table I where they are compared to previous measurements.

3.1. The 5689 keV level in ^{34}S. - Using a mean recoil velocity of 1.91 % the lifetime value for the 5689 keV level was determined by analysing three γ-ray transitions, namely the 5689 ⟶ 4622 keV, the 4688 ⟶ 2127 keV and the 3304 ⟶ 0 keV transitions. This could be done because the lifetime of the lower states are much shorter than 1 ps [3]. Since the shifted peak for the 1067 keV γ-ray transition was much broader than the stopped peak the lifetime value was also calculated using the line shape of the shifted peak in the manner described by McDonald et al. [12]. The two values differed by 2.4 %. The analysis of the three transitions using a mean value for the recoil velocity yield an average value of $\tau = 52.9 \pm 2.4$ ps, where the error takes into account the difference obtained for the two different treatments of the 1067-keV γ-decay curve.

This value is in excellent agreement with the value obtained by the RDM in the $^{31}P(\alpha, p\gamma)$ reaction [6].

3.2. The 789 keV level in ^{36}Cl. - Two strong γ-rays from the decay of ^{36}Cl levels were observed in the spectra taken at 55^0, namely the 1730 keV and 789 keV γ-ray transitions from the 2519 ⟶ 789 ⟶ 0 keV cascade. Whereas a single value of 2.36 ± 0.16 ns is reported for the lifetime of the 2519 keV level, the two values reported for the lifetime of the 789 keV level differ by a factor of ten [3]. In the present χ^2 analysis of the 789 keV level decay curve a best value of 45 % is obtained for the population fraction of this level through the 2519 keV level whereas a value of 59 % is deduced from the photopeak intensities in the 55^0 spectrum taken at 31 MeV. This indicates that another 1730 keV line, which could not be identified, is underlying the 2519 ⟶ 789 keV γ-ray transition. This is corroborated by the normalized 1730 keV stopped peak versus stopper distance curve which does not display a simple exponential decay. So by using the value of 45 % for the cascade population and the value of $\tau(2519)$ = 2.36 ± 0.16 ns, a value of 32.3 ± 2.5 ps is obtained for the lifetime of the 789 keV level.

3.3. The 7071 keV level in ^{37}Ar. - A lifetime value of τ_1 = 0.55 ± 0.12 ps has been determined for this level in the $^{34}S(\alpha, n\gamma)$ reaction [11]. In the present $^{27}Al(^{12}C, pn\gamma)^{37}Ar$ reaction no known higher lying levels could be identified and therefore the measured attenuation factor in the DSA measurement may be due to the lifetime of the 7071 keV level and to the feeding time τ_f, i.e. the time interval between the reaction and the population of this state. A value of 0.34 ± 0.20 ps for the feeding time may be deduced from the attenuation factor F using the two-component decay chain formula $F = (\tau_f F_f - \tau_1 F_1)/(\tau_f - \tau_1)$. By using this formula, one assumes that the feeding of the 7071 keV level may be approximated by an exponential decay. Furthermore, it should be remembered that large uncertainties remain in lifetime determination by the DSA

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3.4. The 6473 keV level in ^{37}Ar. - Lifetime values for this level have been determined using both the total area of the 323 keV γ-ray transition and the external normalisation. No difference within the statistical errors was observed between both values.

3.5. The 3103 keV and 4011 keV levels in ^{37}Cl. - Both the 4011 ⟶ 3103 keV and 4011 ⟶ 0 keV γ-ray transitions have been analysed (see fig.2) and yield a mean value of 32.8 ± [illegible] ps for the lifetime of the 4011 keV level. This value has been used in the analysis of the decay of the 3103 keV level, since [illegible] % of the feeding of this latter was found to proceed via the 4011 keV state. The present lifetime value, τ = 19.6 ± 3.0 ps, is in strong disagreement with a recent RDM result in the $^{34}S(\alpha, p\gamma)$ reaction [10], but support a less precise value obtained by direct timing using a pulsed beam [illegible].

4. <u>Discussion</u>. Transition strengths in ^{37}Cl deduced from the present lifetime measurements are reported in table II.

The strength of the M2 decay from the 3103 keV level appears to be the strongest among the known M2 transitions in 2s-1d nuclei. In fact the transition rate is close to the single-particle estimate. Several shell model descriptions for the first $7/2^-$ state have been used to predict the transition rate and the deduced values range from 0.3 to 5 W.u. [13]. The great majority of M2 transitions in nuclei with A > 30 is severely inhibited and this inhibition has been discussed by Kurath and Lawson [14]. They showed in particular that M2 transitions in the $d_{3/2}$ - $f_{7/2}$ region will be inhibited in the frame of the strong - coupling model. In this model the intrinsic excited state is formed by raising a particle from one of the orbitals k_c originating from the $d_{3/2}$ shell to an orbital k_f originating from the $f_{7/2}$ shell. Kurath and Lawson computed the values of the hindrance factor for the $7/2^- \rightarrow 3/2^+$ M2 transitions according to the different (k_d , k_f) sets involved. The smallest factor (~ 2) was found for $k_d = 3/2$ and $k_f = 7/2$, and these are indeed the Nilsson orbitals which would be involved in the M2 transition of ^{37}Cl if this nucleus had an oblate deformation.

Large and identical strengths for the E3 transitions arising from the 3103 and 4011 kev levels are observed. This may reflect the presence of a 3^- core excitation in the wave functions of the $7/2^-$ and $9/2^-$ states.

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TABLE I

Summary of recoil distance lifetime measurements

Nucleus	Level (keV)	τ (ps) present	τ (ps) others	Ref.
^{34}S	5689	52.9 ± 2.4	54 ± 5	6
^{36}Cl	789	32.3 ± 2.5	3.0 ± 0.8	3
			> 5	7
			30 ± 1	8
^{37}Cl	3103	19.6 ± 3.0	16 ± 9 a)	9
			48 ± 5	10
	4011	32.8 ± 2.0	31 ± 3	10
^{37}Ar	6473	9 ± 2	6.3 ± 0.6	11

a) Direct timing measurement using a pulsed beam.

TABLE II

Transitions strengths in ^{37}Cl

$J_i^\pi \longrightarrow J_f^\pi$	Transition strength (W.u.) a)			
	E2	E3	M1	M2
$7/2^- \rightarrow 3/2^+$		12.4 ± 2.4		0.69 ± 0.11
$9/2^- \rightarrow 3/2^+$		12.2 ± 0.8		
$9/2^- \rightarrow 7/2^-$	1.3 ± 0.1		$(5.9 \pm 0.4)\times10^{-4}$	

a) Branching and mixing ratios are from ref. 10.

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$7/2^- \rightarrow 3/2^+$		12.4 ± 2.4		0.69 ± 0.11
$9/2^- \rightarrow 3/2^+$		12.2 ± 0.8		
$9/2^- \rightarrow 7/2^-$	1.3 ± 0.1		$(5.9 \pm 0.4) \times 10^{-4}$	

a) Branching and mixing ratios are from ref. 10.

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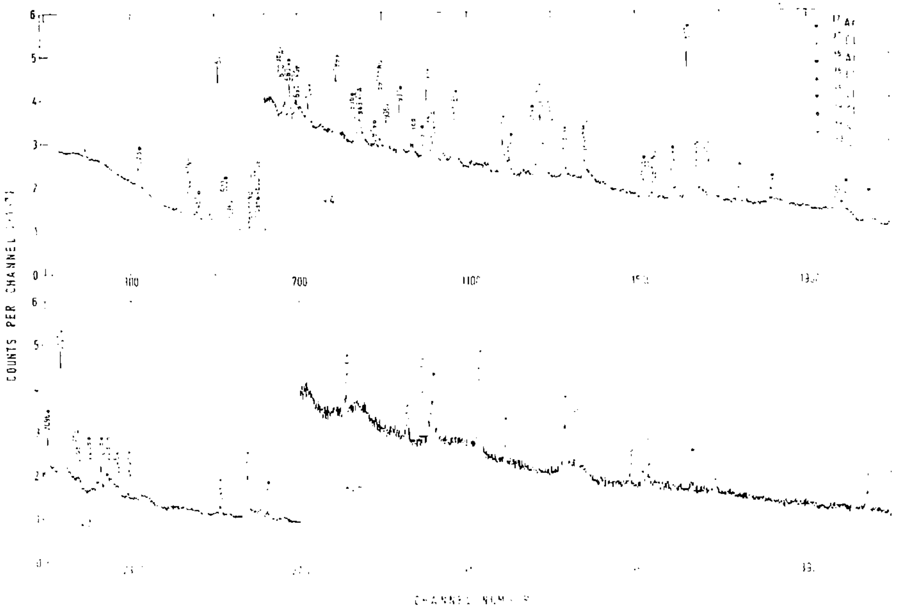
Figure Captions

1. Gamma-ray spectrum recorded at 55° with respect to the beam axis for the $^{27}Al + ^{12}C$ reaction at a bombarding energy of [illegible] MeV.

2. Intensity ratios as a function of stopper distance for three transitions in ^{37}Cl. The normalising factor I_n is the area of the stopped peak for the 1611 → 0 transition in ^{37}Ar, corrected for its decay.


COUNTS PER CHANNEL
700

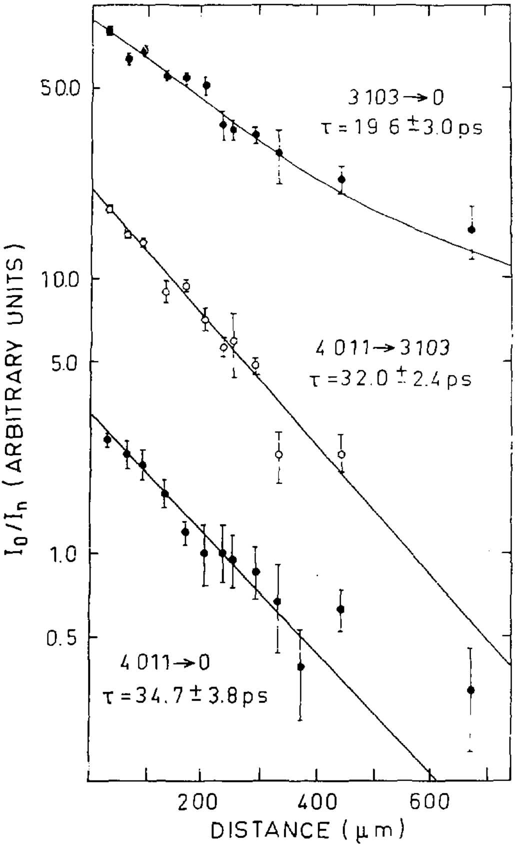

3103→0
τ = 19.6 ± 3.0 ps
4011→3103
τ = 32.0 ± 2.4 ps
4011→0
τ = 34.7 ± 3.8 ps
50.0
10.0
5.0
1.0
0.5
I0/In (ARBITRARY UNITS)
200
400
600
DISTANCE (μm)

FIG 2.