Lifetimes of the first and second excited $3/2^-$ states in ^{41}Ca using the ^{2}H(^{40}Ca,p)^{41}Ca reaction

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A high velocity Doppler shift attenuation experiment was performed using an inverse reaction with a ^{40}Ca ion beam on a deuteron target. The mean lives of the two first $3/2^-$ levels at 1943 and 2462 keV have been determined as 0.79 ± 0.10 and 6.7 ± 0.8 psec, respectively. Concurrently, the lifetime of the 2670 keV level was found to be 4.5 ± 1.3 psec. An empirical electric quadrupole charge is extracted for the neutron from the $1943(3/2^-) \rightarrow$ g.s$(7/2^-)$ γ-ray transition probability using a shell model wave function in the fp space.

[NUCLEAR REACTION ^{2}H(^{40}Ca, $p\gamma$) $E = 60$ MeV; measured γ-ray doppler patterns. ^{41}Ca levels, deduced τ_m.]

Since ^{41}Ca ($Z = 20, N = 21$) is an important nucleus from the viewpoint of the nuclear shell model, considerable experimental[1-10] and theoretical work[11-15] has been performed on it. The surprisingly high density of negative parity levels indicates that core excited configurations play an important role in the structure of ^{41}Ca. This fact is in agreement with theoretical predictions for levels below 3.5 MeV. These core excited configurations are partly related to the effective neutron charge needed to bring the theoretical values, calculated in the $1f2p$ shell space, into agreement with experimental $E2$ strengths. However, discrepancies in the measured lifetime,[1-4,7,9] even though the experiments were carried out under similar conditions, do not enable one to extract a unique value of the empirical electric quadrupole polarization charge.[16,17] In this experiment our attention was focused on the lifetime determination of the first and second $\frac{3}{2}^-$ levels which carry 89% of the $p_{3/2}$ strength.[18] The lifetimes of these γ-decaying levels have been measured by the Doppler shift attenuation method (DSAM). To induce high velocity for recoiling ions, the ^{2}H(^{40}Ca,p)^{41}Ca inverse reaction has been used, circumventing some of the problems[19-24] encountered when nuclear lifetimes are evaluated from DSAM measurements with low velocity recoiling ions.

The experiments have been performed with a 60 MeV ^{40}Ca^{5+} beam accelerated by the MP tandem Van de Graaff at Strasbourg. The liquid nitrogen cooled target was bombarded with an intensity of 3 nA particle. The 5 μg/cm^2 deuterium target was gettered into a 200 μg/cm^2 layer of Ti deposited on two different backings (Al and Cu). Single γ-ray spectra were recorded at $\theta_\gamma = 0°$ by a 22% efficiency coaxial Ge(Li) with an energy resolution of 2.7 keV for γ rays of 1.33 MeV. γ rays deexciting the 1943, 2010, 2462, 2670, and 3050 keV levels in ^{41}Ca have been observed.

For DSAM analysis the theoretical line shape was computed according to the method described by Warburton *et al.*[25] taking into account all the corrections needed.[26] The stopping parameters were determined from a least square fit[25] of the experimental data deduced by Forster *et al.*[27] for Ca recoiling in Ti and Cu, and by Ward *et al.*[28] for Ca recoiling in Al. The estimated errors are, respectively, 5 and 10%. It has been shown that from these two different scalings of the stopping power[29] consistent values of lifetimes are deduced. The parameters for Ca recoiling in different stopping materials are listed in Table I.

Line shapes were extracted from spectra recorded at 0°. Other spectra have also been taken at 125° and 90° for survey purpose, e.g., to examine the background underlying transitions of interest. Three of the obtained line shapes are shown after background substraction in Figs. 1 and 2. Since no feeding from higher states to the

TABLE I. Parameters for energy loss.

Stopping material	K_n	K_e	K_3	$\frac{v}{c}$ (%)	A	B	C
Ti	0.808	3.24	−0.089	1.93	−7.60	8.70	0.697
Cu	0.744	2.73	−0.009	2.59	−5.24	5.75	0.386
Al	0.978	4.54	0.030	4.12	−8.71	8.68	0.625

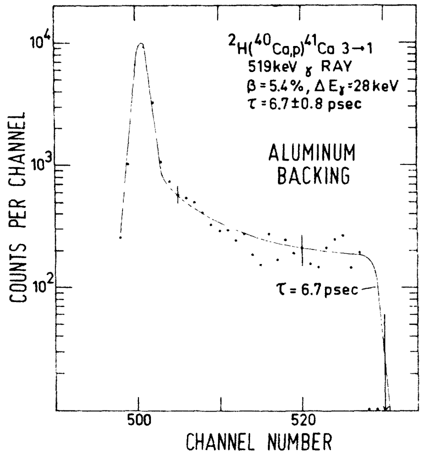

FIG. 1. The line shape, after background substraction, of the 519 keV transition from the third (2462 keV) to the first excited states (1943 keV) in ^{41}Ca(3→1 γ ray). The spectrum was recorded at 0° with an Al backed target. The energy scale is 1 keV/channel.

2462 keV level is observed, the line shape of the 519 keV γ ray is only due to the lifetime of that level (Fig. 1). On the contrary, the 1943 keV level is fed by the 2462, 2670, and 3050 keV level. Under the experimental conditions, the 3050 keV level is populated too weakly to influence the present result, so the 1943 keV level is fed directly by

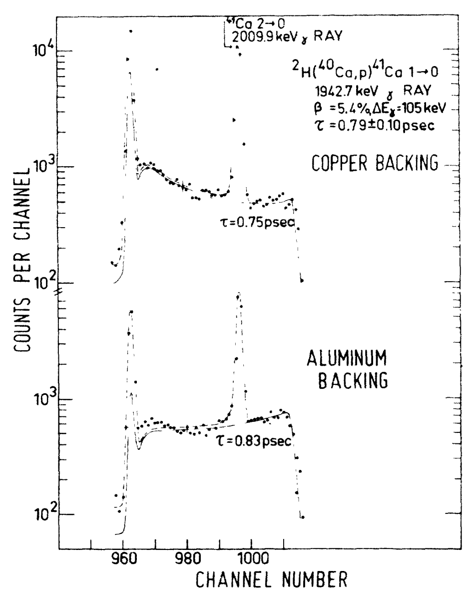

FIG. 2. Doppler γ-ray pattern of the 1943 keV transitions (1→0 γ ray) in Al and Cu slowing down materials. The energy scale is 2 keV/channel. 2→0 indicates the deexcitation of the second excited level.

TABLE II. Mean life (psec) results.

Level (keV)	Cu backing[a]	Al backing	Adopted value[b]
1943	0.75 ± 0.07	0.83 ± 0.08	0.79 ± 0.10[c]
2462	6.7 ± 1.0	6.7 ± 0.9	6.7 ± 0.8
2670	...	4.5 ± 1.3	4.5 ± 1.3

[a] Average of two measurements.
[b] The uncertainty of the initial velocity have been taken into account quadratically.
[c] In this case the adopted value takes into account a possible error due to feeding of the level by higher lying levels.

61% and by γ decay from the 2462 keV (30%) and the 2670 keV (9%) levels. The respective lifetime of the last two levels determined in the present experiment are (6.7 ± 0.8 and 4.5 ± 1.3 psec) allowing us to assume that these two feedings obscure mainly the stopped component of the 1943 keV γ-ray line shape. So only the pulse height region between 970 and 1010 channels was used to determine the mean lifetime of the 1943 keV level. However, the dashed curves are the results of the fits taking into account the upper level feeding and the presence of the 2010 keV γ ray deexciting the long lived [τ = 0.8 ± 0.2 nsec (Ref. 30)] second excited state. The solid curve in Fig. 2 shows the pure Doppler pattern of the 1943 keV γ ray resulting from the fit, in each case for the indicated mean lifetime value. The previous assumption on feeding explains that the theoretical curve is systematically lower than the experimental points in the 965–970 channel region. The complete results for the lifetime measurements are given in Table II.

As has been shown quite recently, lifetime values deduced from DSAM with the inverse reaction are in agreement with lifetime values deduced with the recoil distance method.[31] A comparison of the present results with previous DSAM done at low velocities[1–4,7,9] supports the result of Tabor *et al.*[7]

The ^{41}Ca nucleus has recently been discussed at length by Tabor *et al.*[7]; we shall therefore just mention the implication of the strength of the 2462 keV to ground state transition. This strength, less than 0.53 mW.u. (Weisskopf units), is a severe inhibition for an $E2$ transition and implies for this state a specific character which is not yet clearly understood.[11,12]

Using a shell model calculation[16] in the $1f2p$ space the empirical electric quadrupole polarization charge for the neutron e_n^{exp} is determined to be equal to 0.91 ± 0.06 from the 1943 $(\frac{3}{2}^-)$ → g.s. $(\frac{7}{2}^-)$ transition. This value represents an improvement by a factor of 5 from the previous estimation.[16] This value is bigger than the calculated estimate of the core polarization effects in the *fp* shell space[32-34] and indicates some deformation effects arising from core excited states in ^{40}Ca. More extended shell model calculations, are needed if we want to relate the effective charge to the giant quadrupole states.

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