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Lifetime of the 3464-keV level in ^{40}Ar

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Direct electronic timing has been used to measure the mean life of the 3464-keV state in ^{40}Ar. The state was populated by the ^{37}Cl$(\alpha, p)^{40}$Ar reaction at 10.6 MeV, and the mean life was determined to be 1.00 ± 0.03 nsec. The measured lifetime in conjunction with other γ-ray angular distributions and previous ^{38}Ar$(t, p)^{40}$Ar results allows an assignment of $J^\pi = 6^+$ to the level. The $E2$ transition strengths of the ^{40}Ar $6^+ \to 4^+$, $4^+ \to 2^{+\prime}$ and $2^+ \to 0^+$ transitions are compared to those in ^{42}Ca and to a weak-coupling calculation.

[NUCLEAR REACTIONS ^{37}Cl(α, p), $E = 10.6$ MeV. Measured particle-γ time delay. Deduced $T_{1/2}$, $B(E2)$, J^π. Enriched target.]

I. INTRODUCTION

Of all the stable nuclei in the s-d shell, the nuclear structure of ^{40}Ar is (except for ^{36}S) the least understood.[1] Its study should, however, lead to a much greater understanding of the interactions in particle-hole nuclei: In a weak-coupling model we can view the low-lying levels of ^{40}Ar as arising from the interaction of the $(f_{7/2})^2$ configuration of ^{42}Ca and the $(d_{3/2})^{-2}$ configuration of ^{38}Ar. Recent work at Auckland using the ^{40}Ar$(p, p'\gamma)^{40}$Ar reaction has led to the measurement[2] of a number of lifetimes of excited states using the Doppler-shift attenuation method (DSAM) in conjunction with a solid argon target. In addition,[3] spins, mixing ratios, and branchings have been investigated using the collinear p-γ angular-correlation method. The ^{40}Ar$(p, p'\gamma)^{40}$Ar reaction will not, however, populate high-spin states ($J \geq 5$) with any intensity. Consequently, high-spin states arising from the $(f_{7/2})^2(d_{3/2})^{-2}$ configuration must be investigated by some other reaction. In particular, the ^{37}Cl$(\alpha, p)^{40}$Ar reaction was chosen to investigate the properties of a state at 3.46 MeV for which the ^{38}Ar$(t, p)^{40}$Ar reaction seemed to show an $L = 6$ stripping pattern,[4,5] and which could be identified with a state at 3464 keV which was populated[6,7] in heavy-ion fusion evaporation reactions and which decayed by a 572-keV γ ray transition to the (4^+) state at 2893 keV. If this state at 3464 keV was indeed the 6^+ state then its lifetime would be expected to be approximately 1 nsec. We therefore undertook to measure its decay rate using a direct electronic timing method.

II. EXPERIMENT AND RESULTS

The nucleus ^{40}Ar was populated by bombardment of a ^{37}Cl target with 10.6 MeV α particles provided by AURA II, the folded tandem electrostatic accelerator[8] at the University of Auckland. The target consisted of 225 μg/cm^2 of BaCl$_2$ (enriched to about 75% in ^{37}Cl), evaporated onto a 10 μg/cm^2 thick carbon foil. Protons resulting from the ^{37}Cl$(\alpha, p)^{40}$Ar reaction were detected in an annular surface barrier counter at 180° with respect to the beam. This detector was shielded from the target by an aluminium foil of 18 μm thickness, which stopped all α particles except those resulting from elastic scattering on the barium. A number of the levels in ^{40}Ar were quite strongly excited, especially the levels at 3464- and 2893-keV excitation energy. The γ rays were detected in a 5 cm×5 cm NaI(Tl) crystal optically coupled to a 56 AVP photomultiplier. Pulses derived directly from the anode were used to drive a constant fraction discriminator which in turn provided the start pulses for a time-to-amplitude converter (TAC). The stop pulses were derived from the annular detector after suitable amplification via another constant-fraction discriminator. The slow rise times of the pulses from the annular detector gave rise to a relatively large time walk with energy. In order to monitor this, a two-parameter analysis of particle-γ delay times versus particle energy was undertaken. This enabled us to acquire several time spectra simultaneously: The walk was therefore determined as a function of particle energy, and in addition the prompt resolution function (PRF) was obtained at several particle energies (γ-ray pulses in a window from about 1.1 to 1.5 MeV were accepted).

We display in Fig. 1 the decay curve, obtained in this manner, for particles populating the 3.46-MeV level (closed circles). Also displayed is the PRF obtained for particles populating the 2.89-MeV level. This second curve has been shifted

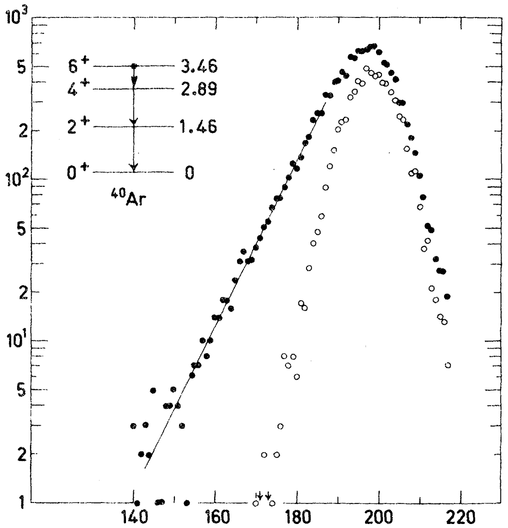

FIG. 1. The experimental decay curve obtained for protons populating the 3.46 MeV level in ^{40}Ar (closed circles). The open circles give the PRF obtained in a similar manner for protons populating the 2.89 MeV level (see text). A least-squares fit to various regions between channels 140 and 190 of the decay curve for the 3.46 MeV level gave values consistent with the value we quote in the present work of $\tau = 1.00 \pm 0.03$ nsec.

seven channels to compensate for the time walk with energy. Except for the 0.57 MeV γ ray from the 3.46-MeV level (which was below the γ-ray window), the γ-ray spectra from both levels are identical. The TAC spectrum for the 3.46-MeV level displays a clear exponential lifetime for well over two decades. The TAC spectra were calibrated against a 100 MHz oscillator whose output was fanned out and mixed with the start and stop pulses using two fast coincidence units. The method is described, for instance, by Poletti and Pronko.[9] With this calibration, a least-squares fit to the exponential decay yielded a mean life τ of 1.00 ± 0.03 nsec for the 3464 keV level.

III. DISCUSSION

The mean life measured by us ($\tau = 1.00 \pm 0.03$ nsec) is in reasonable agreement with a recent measurement by Warburton, Olness, and Kolata[10] using the recoil distance method (RDM). The value obtained by these workers was $\tau = 0.93 \pm 0.05$ nsec. For the purposes of further discussion we take a weighted average of the two results, yielding $\tau = 0.98 \pm 0.03$ nsec for the mean life of the 3464 keV level in ^{40}Ar. In view of the completely different measurement techniques used in the two experiments, the agreement between the two results is very satisfying. The measured lifetime in conjunction with other γ-ray angular distribution data and a previous result obtained using the $^{38}\mathrm{Ar}(t, p)^{40}\mathrm{Ar}$ reaction, as discussed in Refs. 5 and 10, fixes the spin and parity of this level as $J^\pi = 6^+$. Fairly obviously, this state should arise mainly from the $(\pi d_{3/2})^{-2} * (\nu f_{7/2})^2$ configuration. Calculations by Gloeckner, Lawson, and Serduke[5] with a $(\pi d_{3/2})^{-2}(\nu f_{7/2}, \nu p_{3/2})^2$ model space place the lowest 6^+ level in ^{40}Ar at ~3.4 MeV, in excellent agreement with the experimental value of 3.46 MeV.

The strengths of the $6^+ \rightarrow 4^+$, $4^+ \rightarrow 2^+$, and $2^+ \rightarrow 0^+$ $E2$ transitions in both ^{40}Ar and ^{42}Ca have now all been measured. In ^{40}Ar, as mentioned above, it is expected that these levels will arise mainly from the $(\pi d_{3/2})^{-2} * (\nu f_{7/2})^2$ configuration, while in ^{42}Ca they will be mostly $(\nu f_{7/2})^2$. We collect the measured $B(E2)$ values in Table I. Compared to ^{42}Ca, the ^{40}Ar $4^+ \rightarrow 2^+$ transition is hindered by about a factor of 2, while the $6^+ \rightarrow 4^+$ transition is enhanced by nearly the same factor. In a weak-coupling model we expect the ^{40}Ar states to be principally

$$
\begin{aligned}
|6^+\rangle &= \alpha|\pi d_{3/2}{}^{-2}0^+)*(\nu f_{7/2}{}^2 6^+), 6^+\rangle \\
&\quad + \beta|(\pi d_{3/2}{}^{-2}2^+)*(\nu f_{7/2}{}^2 4^+), 6^+\rangle, \\
|4^+\rangle &= \gamma|(\pi d_{3/2}{}^{-2}0^+)*(\nu f_{7/2}{}^2 4^+), 4^+\rangle \\
&\quad + \delta|(\pi d_{3/2}{}^{-2}2^+)*(\nu f_{7/2}{}^2 2^+), 4^+\rangle, \\
|2^+\rangle &= \epsilon|(\pi d_{3/2}{}^{-2}0^+)*(\nu f_{7/2}{}^2 2^+), 2^+\rangle \\
&\quad + \eta|(\pi d_{3/2}{}^{-2}2^+)*(\nu f_{7/2}{}^2 0^+), 2^+\rangle, \\
|0^+\rangle &= |(\pi d_{3/2}{}^{-2}0^+)*(\nu f_{7/2}{}^2 0^+), 0^+\rangle,
\end{aligned}
$$

where of course $\alpha^2 + \beta^2 = 1$, etc. The three transition strengths in ^{40}Ar are therefore defined in terms of α, γ, and ϵ and the known transition strengths of the corresponding transitions in ^{42}Ca and the strength of the $2^+ \rightarrow 0^+$ transition in ^{38}Ar. There can be many choices of α, γ, and ϵ which will give the experimental $B(E2)$ values in mass 40 in terms of those in mass 42 and 38. It is not our purpose to distinguish between them but rather to suggest a reason why the mass-40 $B(E2)$ values differ from the similar transitions in mass 42. If we choose some reasonable values for the coefficients and write, for instance, the first component of the 6^+ state as $|06, 6\rangle$ we can take

$$
\begin{aligned}
|6^+\rangle &= 0.86|06, 6\rangle + 0.51|24, 6\rangle, \\
|4^+\rangle &= 0.97|04, 4\rangle - 0.24|22, 4\rangle, \\
|2^+\rangle &= 0.97|02, 2\rangle + 0.24|20, 2\rangle, \\
|0^+\rangle &= 1.00|00, 0\rangle
\end{aligned}
$$

TABLE I. Transition strengths in ^{38,40}Ar and ^{42}Ca.

Transition		$B(E2)$ in $e^2f\text{m}^4$		
	^{38}Ar	^{40}Ar	^{42}Ca [a]	^{40}Ar (calc)
$2^+ \rightarrow 0^+$	23.6 ± 1.6 [b]	101.9 ± 19.5 [b]	83.2 ± 3.1	100
$4^+ \rightarrow 2^+$		$32.2 \pm^{9.2}_{15.3}$ [c]	58.7 ± 4.6	31
$6^+ \rightarrow 4^+$		13.6 ± 0.4 [d]	6.6 ± 0.2	13

[a] B. A. Brown, D. B. Fossan, J. M. McDonald, and K. A. Snover, Phys. Rev. C 9, 1033 (1974).

[b] Reference 1.

[c] Average of results in Refs. 2 and 10.

[d] Average of results in present work and Ref. 10.

as the wave functions of the mass-40 states. The three $B(E2)$'s in mass 40 are then given as

$$B(E2)^{40}_{6\to4} = [0.834b(6\to4)^{42} + 0.495b(2\to0)^{38} - 0.122b(4\to2)^{42}]^2 ,$$

$$B(E2)^{40}_{4\to2} = [0.941b(4\to2)^{42} - 0.233b(2\to0)^{38} - 0.058b(2\to0)^{42}]^2 ,$$

$$B(E2)^{40}_{2\to0} = [0.970b(2\to0)^{42} + 0.24b(2\to0)^{38}]^2 ,$$

where $b(a\to b)^A = +[B(E2)^A_{a\to b}]^{1/2}$, i.e., the positive square root of the corresponding $B(E2)$ value, and A is the mass value, while a and b are the initial- and final-state spins. The $B(E2)$ values thus calculated for the mass-40 transitions are given in the final column of Table I. The trend of the experimental values is followed, and in addition it can be seen that the same model can predict an enhancement in one transition but a hindrance in another.

A comparison similar to the above between the $E2$ transitions among the $(\pi d_{3/2})^{-2}(\nu f_{7/2})^3$ levels in ^{41}Ar and the $(\nu f_{7/2})^3$ levels in ^{43}Ca would be most interesting. The ^{41}Ar levels could be populated in the ^{37}Cl(^{7}Li, $2pn$)^{41}Ar or the ^{26}Mg(^{18}O, $2pn$)^{41}Ar reactions. γ rays of 1131.54 and 1698.03 keV already observed[6] and so far unidentified could possibly be the $\frac{15}{2}^- \rightarrow \frac{11}{2}^-$ and $\frac{11}{2}^- \rightarrow \frac{7}{2}^-$ transitions in ^{41}Ar. The evidence is circumstantial but strong and is based on the following considerations: (1) the systematics of heavy-ion fusion-evaporation reactions,[11] (2) a comparison of the Q values for exciting ^{41}Ar, ^{41}K, and ^{41}Ca in the bombardment of ^{26}Mg by ^{18}O, (3) a comparison of the energies of the γ rays with the expected energies derived by reference to the energies of the $(\nu f_{7/2})^3$ states in ^{43}Ca, and (4) the difficulty of making ^{41}Ar high-spin states in a reaction which labels the final nucleus unambiguously (e.g., an α, n or α, p reaction).

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