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# Lifetimes of the 2893- and 3464-keV levels of $^{40}Ar$†

E. K. Warburton, J. W. Olness, and J. J. Kolata
*Brookhaven National Laboratory, Upton, New York 11973*
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The recoil-distance method has been used in conjunction with the $^{27}Al(^{18}O, p\alpha)^{40}Ar$ and $^{37}Cl(\alpha, p)^{40}Ar$ reactions to measure mean lifetimes of $4.2\pm2.0$ and $930\pm50$ ps for the $^{40}Ar$ 2893- and 3464-keV levels, respectively. The excitation energies of these two levels were deduced to be $2892.60\pm0.11$ and $3464.48\pm0.13$ keV, respectively. The 3464-keV level is assigned $J^\pi=6^+$ on the basis of the lifetime, the $\gamma$-ray angular distribution, and previous $^{38}Ar(t, p)^{40}Ar$ results. The $E2$ transition strengths of the $^{40}Ar$ $0^+$-$2^+$-$4^+$-$6^+$ ground-state band are compared to those of $^{42}Ca$ and to shell-model calculations.

[NUCLEAR REACTIONS $^{37}Cl(\alpha, p)$, $E=12$ MeV, $^{27}Al(^{18}O, p\alpha)$, $E=35$ MeV; measured recoil distance, $E_\gamma$, and $\sigma_\gamma(\theta)$. Deduced $J^\pi$, $T_{1/2}$, $B(E2)$, $E_x$. Natural and enriched targets, Ge(Li) detector.]

## I. INTRODUCTION

An $^{40}Ar$ $\gamma$-ray transition of 572 keV was recently observed in studies[1,2] of high-spin levels formed in nuclei near $A=40$ via heavy-ion fusion-evaporation reactions. This $\gamma$ ray was observed to be in coincidence with 1432- and 1461-keV $\gamma$ rays, resulting from the $4^+\to2^+\to0^+$ cascade, which connects the lowest three members of the $0^+$-$2^+$-$4^+$-$6^+$ ground-state band. No other $\gamma$ rays were observed in coincidence with any of these three; thus, a unique assignment can be made for a new $^{40}Ar$ level at 3464 keV which decays to the $4^+$ 2893-keV level by a 572-keV transition. Since this level is formed relatively strongly in the fusion-evaporation type of reaction, which is strongly selective[3] of yrast levels, it is quite likely the lowest-lying $J=5$ or 6 level of $^{40}Ar$.

Evidence for a new $^{40}Ar$ level at an excitation energy of $3468\pm5$ keV was also recently obtained[4] in the $^{38}Ar(t, p)^{40}Ar$ reaction. Angular distribution measurements in the $(t, p)$ reaction yielded a most probable assignment of $6^+$, although other natural-parity assignments with $J>4$ were also possible. We assume that our observations pertain to the same level; the 3464-keV level is therefore a good candidate for the $6^+$ member of the $^{40}Ar$ ground-state band and a measurement of its lifetime—which determines the $6^+\to4^+$ $E2$ matrix element—is of considerable interest. Clearly, a measurement of its lifetime is also of value in rigorously fixing the spin-parity assignment. Accordingly, such a lifetime measurement was undertaken utilizing the recoil-distance method (RDM) and the $^{37}Cl(\alpha, p)^{40}Ar$ reaction. At the same time some information was obtained on the lifetime of the $4^+$ 2893-keV level.

## II. EXPERIMENTAL PROCEDURE AND RESULTS

### A. 3464-keV level

The target consisted of 250$\mu$g/cm$^2$ of $BaCl_2$, enriched to 96.07% in $^{37}Cl$, evaporated onto a 2.4-mg/cm$^2$ Au foil which was stretched taut over the target frame. A 10-$\mu$g/cm$^2$ deposit of lead was initially evaporated onto the gold foil in order to provide a substrate to which the $BaCl_2$ would adhere. The target was positioned in a RDM apparatus[5] with the $BaCl_2$ on the downstream side and bombarded with 12-MeV $\alpha$ particles at a beam current of 25 nA. $\gamma$ rays were detected at 0° to the beam axis with a distance of 11 cm between the target and the front face of the 70-cm$^3$ Ge(Li) detector. Spectra were recorded and analyzed using an 8192 channel analog-to-digital converter (ADC).

The beam and recoiling reaction products were stopped in a gold "plunger." The target-plunger distance was varied between 4 and 13 300 $\mu$m (25.4 $\mu$m $=10^{-3}$in.). Thirteen spectra were recorded in this interval. Portions of a spectrum taken at 2061 $\mu$m are illustrated in Fig. 1. The 572- and 1432-keV $\gamma$ rays both display the fully stopped and fully shifted peaks (with intensities $I_0$ and $I_s$, respectively) characteristic of the RDM.[5] The intensities $I_0$ and $I_s$ were extracted from least-squares computer fits such as the one illustrated in Fig. 1. The resulting "decay curves," obtained by plotting $I_0/(I_0+I_s)$ as a function of the target-plunger distance ($\equiv D$), are shown in Fig. 2. These data were fitted with the function

$$I_0/(I_0+I_s)=N_0e^{-D/v\tau}+B \quad (1)$$

to obtain the product $v\tau$, where $v$ is the velocity

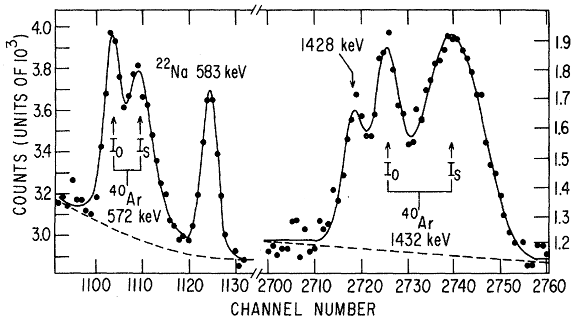


FIG. 1. Portions of the 0° Ge(Li) spectrum recorded at a target-plunger distance $D = 2061$ $\mu$m. The $^{22}$Na 583-keV transition arises from the $^{19}F(\alpha, n)^{22}Na$ reaction induced on $^{19}$F contamination of the plunger. The 1428-keV $\gamma$ ray ($E_\gamma = 1427.98 \pm 0.15$ keV) also emanates from the plunger; its origin is unknown. The solid curves are least-squares computer fits assuming, in each case, three peaks of predetermined shape superimposed on a parabolic background (dashed curves). The results give the positions and intensities of the three peaks.

of the recoil $^{40}$Ar nuclei and $\tau$ the mean life of the 3464-keV level. In the case of the 1432-keV $4^+ \to 2^+$ transition account should, in principle, be taken of the lifetime of the $4^+$ level. It turns out, however, that the mean life of the $4^+$ level is so short compared to that of the 3464-keV level that in practice it could have been neglected. Note that the decay curve for the 1432-keV $\gamma$ ray has an apparent intercept of ~0.4: This then is the fraction of the intensity of the 1432-keV transition due to feeding via the long-lived 572-keV cascade. The $\gamma$-ray peak corresponding to the 1461-keV $2^+ \to 0^+$ transition also showed a shape characteristic of the decay of the 3464-keV level. However, the 1461-keV line shape was not analyzed, since the presence of a contribution to the fully stopped peak from $^{40}K(\beta^+)^{40}Ar$ rendered this analysis considerably less accurate than that of the other two line shapes. The constant background apparent at large distances in Fig. 1, and represented by $B$ in Eq. (1), is due to large angle scattering of the beam in the Au foil and of both the beam and the $^{40}$Ar recoils in the target. The various corrections to Eq. (1) for finite solid angle, finite target thickness, relativistic effects, etc., were made routinely.[5,6] The most important correction was that due to the spread in $^{40}$Ar recoil velocity which gives rise to the greater width of the shifted peak compared to that of the stopped peak (see Fig. 1).

The mean velocity of the $^{40}$Ar recoils was extracted from the measured energy difference between the stopped and shifted peaks. The values obtained from the 572- and 1432-keV transition were in agreement and yielded $v/c = (0.554 \pm 0.010)\%$. Using this value, we find that the decay curves of Fig. 2 correspond to $890 \pm 55$ and $970 \pm 60$ ps for the 572- and 1432-keV transitions, respectively. These values are in fair agreement, and we adopt $930 \pm 50$ ps for the mean life of the 3464-keV level.

### B. 2893-keV level

From the RDM measurements with the $^{37}Cl(\alpha, p)$-$^{40}$Ar reaction only an upper limit ($\tau < 18$ ps) could be placed on the mean life of the 2893-keV $4^+$ level. The recoil velocity was in this case too low, and the absolute target-plunger distance not known accurately enough to obtain more information. An attempt was also made to measure this lifetime using the $^{25}Mg(^{18}O, n2p)^{40}Ar$ reaction at an $^{18}$O beam energy of 40 MeV. The attempt failed, however, because in this reaction the $4^+$ level is fed ~80% via the 572-keV cascade.

Our best data on the lifetime of the $4^+$ 2893-keV level result from $^{27}$Al + $^{18}$O RDM measurements undertaken previously[7] to obtain the $^{42}$Ca $4^+$ 2752-keV level lifetime. The recoil velocity of $v/c = 2.22\%$ obtained with $E(^{18}O) = 35$ MeV was 4 times that of the present $^{37}$Cl + $\alpha$ experiment and the absolute target-plunger distance was well known from the $^{42}$Ca measurements. In this case the 2893-keV level was fed ~40% directly and ~60% via the 572-keV cascade. Thus, in spite of the rela-

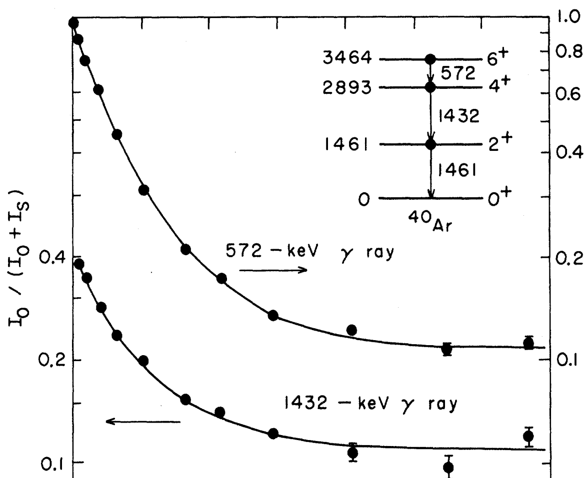


FIG. 2. The ratio $I_0/(I_0 + I_s)$ as a function of the target-plunger distance, $D$, for the 572- and 1432-keV transitions of $^{40}$Ar. Since the 2893-keV level decays in a time negligibly short compared to the 3464-keV level, both curves reflect the mean life of the 3464-keV level: $\tau = 930 \pm 50$ ps. For the shorter distances, $D < 5000$ $\mu$m, the error bars are comparable to the size of the datum points.

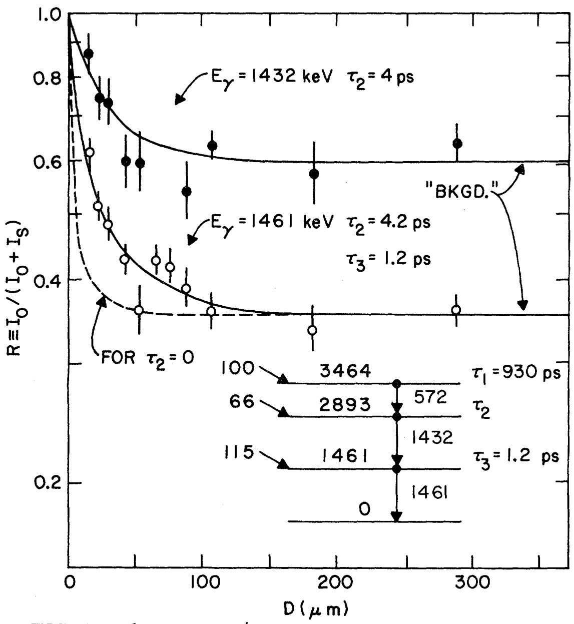


FIG. 3. The ratio $I_0/(I_0+I_s)$ as a function of target-plunger distance for $^{40}$Ar transitions observed in the $^{27}$Al($^{18}$O,$p\alpha$)$^{40}$Ar reaction at $E(^{18}\text{O})=35$ MeV. The recoil velocity is $v/c=0.022$, and the uncertainty in plunger distance $D$ is ~3 $\mu$m. The curves show the results of a least-squares fit to the data, as explained in the text, to determine the lifetime of the 2893-keV level: $\tau_2=4.2\pm2.0$ ps. Pertinent information on the relative feedings of these levels, and known lifetimes, is indicated.

tively weak intensity for formation of $^{40}$Ar in the $^{27}$Al($^{18}$O,$p\alpha$)$^{40}$Ar reaction,[1] a lifetime determination could be made.

The experimental data are shown in Fig. 3. Since the 1461-keV level is relatively short lived ($\tau=1.20\pm0.23$ ps[10]) useful information on the lifetime of the 2893-keV level is contained in the decay curves for both the 1432- and 1461-keV $\gamma$ rays. The results of a least-squares fit to these data, using the information summarized in Fig. 3, yields the result $\tau=4.2\pm2.0$ ps.

In both cases feeding via 572-keV transitions from the 3464-keV level was treated as a constant background, as indicated in Fig. 3, since the $930\pm50$ ps lifetime of this level results in negligible decay, with plunger distance, over the region of the measurement. For the 1432-keV transition, therefore, the fit is for a single decay component (variable $\tau_2$) plus background. For the 1461-keV transition we show the results of a two-component fit, with $\tau_2$ variable and $\tau_3$ fixed at 1.2 ps. The relative feedings of the various levels, which enter as parameters in the fits, are indicated in Fig. 3. These values are also consistent with the $\gamma$-ray intensities as determined independently.

The result of $4.2\pm2.0$ ps is in good agreement with the recent value of $4.2^{+2.6}_{-1.2}$ ps obtained by Southon, Fifield, and Poletti[8] using the Doppler-shift attenuation method (DSAM) in conjunction with the $^{40}$Ar($p,p'$)$^{40}$Ar reaction and a solid $^{40}$Ar target. It also agrees with the only other previous result—a DSAM measurement[9] yielding $4^{+8}_{-2}$ ps. We combine the measurements and adopt $4.2^{+2.0}_{-1.2}$ ps for the mean life of the $4^+$ 2893-keV level.

The mean life of the $^{40}$Ar $2^+$ 1461-keV level is given as $1.20\pm0.23$ ps in the compilation of Endt and Van der Leun.[10] This lifetime is not further defined by the present measurements, although it can be concluded from the data of Fig. 3 that $\tau<2$ ps, which is consistent with the value quoted.

### C. Accurate excitation energies

In the course of these measurements the energies of the 1432- and 572-keV $\gamma$ rays were obtained with more accuracy than values previously published.[2,10] The 1432-keV energy was measured relative to that of the 1461-keV $\gamma$ ray, given[10] as $1460.78\pm0.04$ keV: The result is $1431.76\pm0.10$ keV. The 572-keV $\gamma$-ray energy was measured relative to the $^{207}$Bi $\gamma$ ray of $569.67\pm0.02$ keV,[11] giving the result $571.88\pm0.08$ keV. Applying recoil corrections we obtain excitation energies for the three $^{40}$Ar levels involved of $1460.81\pm0.04$, $2892.60\pm0.11$, and $3464.48\pm0.13$ keV.

## III. DISCUSSION

A mean life of 930 ps for an $^{40}$Ar 572-keV transition would correspond to an $M2$ strength of 65 W.u. (Weisskopf units).[12] Such a strength we reject as unreasonable[13] and so we conclude the 572-keV transition is dipole or $E2$. Accepting the $(t,p)$ conclusions[4] of $J>4$ with $(-)^J$ parity, we find acceptable assignments of $J^\pi=5^-$ and $6^+$. The angular distribution of the 572-keV transition was measured in the $^{25}$Mg($^{18}$O,$n2p$)$^{40}$Ar reaction at $E(^{18}\text{O})=40$ MeV. The result fitted to $W(\theta)=I_0\times[1+a_2P_2(\theta_a)+a_4P_4(\theta)]$ was characterized by $a_2=0.30\pm0.02$, $a_4=-0.09\pm0.02$. This angular distribution is as expected for a $6^+\to4^+$ transition from a highly-aligned state and completely in disagreement with that expected for a predominantly dipole $5^-\to4^+$ transition from an aligned state.[1,2] Thus, we conclude that the 3464-keV level has $J^\pi=6^+$.

The systematics of $E2$ transitions between "ground-state bands" in $1f_{7/2}$ nuclei has recently been explored.[14] Results for $^{40}$Ar can be most easily included in this survey by comparison to $^{42}$Ca. In lowest seniority the $J^\pi=4^+$ and $6^+$ $^{40}$Ar states are $[d_{3/2}(\pi)]^2_0+[f_{7/2}(\nu)]^2_J$, and so we expect the $0^+$, $2^+$, $4^+$, $6^+$ spectrum of $^{40}$Ar to resemble

TABLE I. $E2$ transition strengths in $^{40}$Ar and $^{42}$Ca.

| Transition | Transition strength $^{40}$Ar (W.u.) | $^{42}$Ca [a] (W.u.) | $B(E2)_{40}/B(E2)_{42}$ |
|---|---|---|---|
| $2^+ \rightarrow 0^+$ | $12.3 \pm 2.4$ | $9.40 \pm 0.35$ | 1.3 |
| $4^+ \rightarrow 2^+$ | $3.9^{+1.6}_{-1.3}$ | $6.63 \pm 0.52$ | 0.6 |
| $6^+ \rightarrow 4^+$ | $1.73 \pm 0.09$ | $0.74 \pm 0.02$ | 2.3 |

[a] Experimental data taken from Ref. 14.

that of $^{42}$Ca quite closely. The $E2$ strengths should also be quite similar—especially for the $6^+ \rightarrow 4^+$ transition. In actual fact, the $2^+$-$0^+$, $4^+$-$2^+$, $6^+$-$4^+$ spacings are similar: 1524, 1228, and 437 keV in $^{42}$Ca and 1461, 1432, and 572 keV in $^{40}$Ar. Also, as seen from Table I, the $E2$ strengths show a similar trend towards more collectivity for the lower spins. Insight into this behavior is provided by recent shell-model calculations of Strottman[15] utilizing a configurational space consisting of all the $2s$, $1d$, $1f$, and $2p$ shells except the $2p_{1/2}$ configuration and an additional effective charge for both neutrons and protons of $0.5e$. Strottman obtained $E2$ strengths for the $^{40}$Ar $2^+ \rightarrow 0^+$, $4^+ \rightarrow 2^+$, and $6^+ \rightarrow 4^+$ transitions of 4.9, 5.0, and 2.4 W.u. assuming 2h-2p states relative to the closed $2s$, $1d$ shell. It would appear that this description becomes more valid as the spin values increase. This is in agreement with our expectations that impurities, such as 4p-4h, are largest in the lower-spin states.

*Note added in proof:* The lifetime of the 3464-keV level has recently been measured[16] by direct electronic timing to be $1.00 \pm 0.03$ ns.

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