Nuclear lifetimes in ^{42}Ar†

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Excitation energies and nuclear lifetimes of states in ^{42}Ar have been measured by employing the reaction ^{40}Ar$(t, p)^{42}$Ar at a triton bombarding energy of 2.8 MeV. Protons were detected by an annular silicon surface barrier counter at an average angle of 174°, and coincident γ rays were detected by a 20-cm^3 Ge(Li) counter positioned at angles of 30 and 120°. The extraction of nuclear lifetimes by the Doppler-shift-attenuation technique was made possible by the use of a solid argon target operated at 15 K. Experimental results for excitation energies (keV) and lifetimes (psec) are: 1208.2 ± 0.3, $3.8^{+1.0}_{-0.8}$; 2486.7 ± 0.6, 0.40 ± 0.16; 2512.5 ± 0.5, $4.0^{+3.1}_{-1.2}$; 3014.6 ± 0.6, <0.12; 3096.4 ± 0.6, >5; 3557.8 ± 0.6, <0.09; 4006.1 ± 0.6, 3.3 ± 0.8; 4127.4 ± 0.7, 1.4 ± 0.3; 4287.0 ± 0.7, <0.05; 4633.7 ± 0.7, <0.05. The experimental results are in good agreement with the shell-model calculations of Gloeckner, Lawson, and Serduke.

[NUCLEAR REACTIONS ^{40}Ar(t, p), $E_t = 2.8$ MeV; measured $\sigma(E_p, E_\gamma, \theta_\gamma)$. ^{42}Ar deduced E_x, I_γ, τ_m. Solid Ar target; Doppler shift attenuation.]

I. INTRODUCTION

Recent interest in the structure of nuclei in the mass region near $A = 40$ has been prompted, in part, by the realization that ^{40}Ca is not representative of a good closed-shell nucleus. Interpretation of the structure of the low-lying levels of neighboring nuclei in terms of the shell model, then, poses a challenging problem. Gloeckner, Lawson, and Serduke[1] have attacked this problem for the Ar isotopes, and find that the configuration $(\pi d_{3/2})^{-2}(\nu f_{7/2};\ \nu p_{3/2})^n$ explains most of the known structure of low-lying levels although core-excited states are also present at rather low excitation energies (≈2 MeV). However, the experimental information required to test the theory of Gloeckner, Lawson, and Serduke[1] is incomplete. In particular, in the case of ^{42}Ar, no information on electromagnetic transition rates is available.

Pronko and McDonald,[2] who studied the γ-ray spectroscopy of low-lying ^{42}Ar levels, presented excitation energies and γ-ray branching ratios as well as spin assignments deduced from angular correlation measurements. Subsequently, Ajzenberg-Selove, Garrett, Hansen, Casten, and Flynn[3] measured double-stripping angular distributions with the ^{40}Ar$(t, p)^{42}$Ar reaction and reported excitation energies and J^π assignments. In this paper, we report the results of Doppler-shift lifetime measurements for 10 of the low-lying levels in ^{42}Ar which complement the experimental data of Refs. 2 and 3. More precise values for excitation energies and branching ratios have also been obtained. The experiment was performed utilizing the ^{40}Ar$(t, p)^{42}$Ar reaction ($Q = 7.04$ MeV) with a solid target of natural argon maintained at a temperature of 15 K. Section II describes the experimental procedure, and in Sec. III the lifetime results are presented and compared with the shell-model calculations of Gloeckner, Lawson, and Serduke.[1]

II. EXPERIMENTAL PROCEDURE

The experimental technique was similar to that used previously at this laboratory to measure lifetimes of states in ^{28}Mg.[4] Levels in ^{42}Ar were populated by the reaction ^{40}Ar$(t, p\gamma)^{42}$Ar employing a 2.8-MeV triton beam from the Lockheed 3-MV Van de Graaff accelerator. γ rays were detected by a 20-cm^3 Ge(Li) detector positioned at angles $\theta_\gamma = 30$ and 120°, and protons emitted at an average angle of 174° were detected in an annular silicon surface barrier counter. The front face of the proton detector was covered by 10.3 mg/cm^2 of aluminum foil which stopped elastically scattered tritons. Coincident proton–γ-ray events were recorded event-by-event on magnetic tape with the aid of a computer-based data acquisition system described by Chalmers.[5] Each event was characterized by three parameters: the proton pulse height, the γ-ray pulse height, and the time interval between the pulses as measured with a time-to-amplitude converter. The three analog-to-digital converters (ADC) required for processing the pulses were provided economically by a single TC 501 8000 channel ADC and a TC 520 multiplexer.[6] This system offers great flexibility and can readily be extended to include more parameters. Subtraction of random coincidences and gain stabilization of the spectra were performed in subsequent off-line analysis. A reference peak for gain stabilization was provided by the γ decay of the 1524-keV level in ^{42}Ca, which is populated in the $^{42}Ar \rightarrow {}^{42}K \rightarrow {}^{42}Ca$ β-decay sequence.

The principal features of the solid argon target are illustrated in Fig. 1. The cryostat, a slightly modified version of a commercial continuous-flow cryostat (Oxford Instruments Model CF 100), fits inside a specially designed casing which incorporates the mounting arrangement for the silicon annular detector and a quartz window. An argon target of predetermined thickness could be "evaporated" onto the 0.25-mm-thick gold backing by introducing a fixed quantity of argon gas into the 1-mm-i.d. stainless steel tube shown in the figure. The temperature of the gold backing could be varied between 4 and 60 K by adjusting the liquid helium flow rate, a temperature of 15 K being chosen because it gave a reasonable helium consumption rate but was still well below the temperature at which the vapor pressure of solid argon becomes appreciable (e.g., at 30 K the vapor pressure of argon is $< 10^{-6}$ Torr).[7] The temperature of the target was monitored by a calibrated carbon resistor furnished by Oxford Instruments.

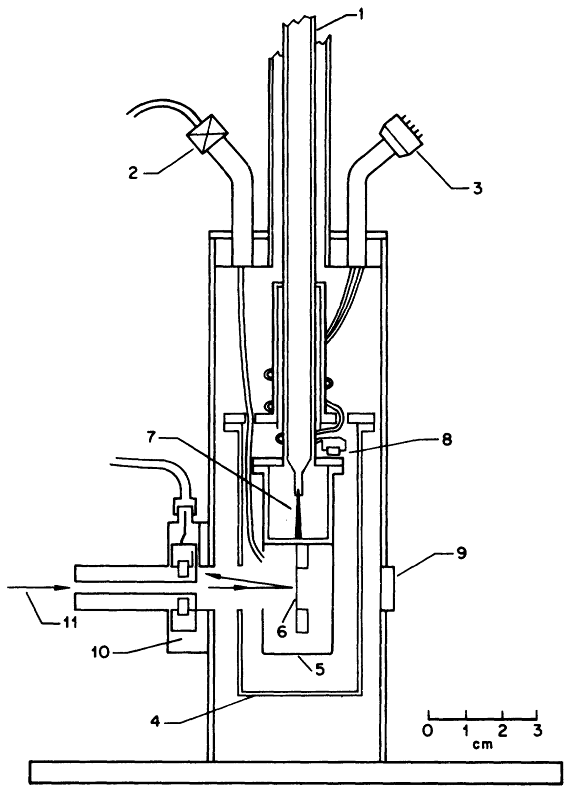

FIG. 1. Experimental arrangement for operation of the solid argon target: 1, helium transfer line; 2, inlet for argon gas; 3, electrical connections; 4, outer radiation shield; 5, inner radiation shield; 6, gold target backing; 7, needle valve for helium flow control; 8, temperature probe; 9, quartz window; 10, silicon surface barrier counter and mounting; 11, triton beam.

Several days of running time were invested to determine the stability of the solid argon targets under beam bombardment (before data accumulation was begun). The target condition was monitored by observing the proton singles spectrum, and a significant rate of target deterioration was found to occur for target temperatures in excess of 30 K. For a target temperature of 15 K and beam currents less than 50 namp, no measurable deterioration was observed during a period of 24 h, and these conditions were maintained during the actual lifetime measurements. Singles spectra taken before and after each period of data accumulation were compared to insure that no target deterioration had taken place. The thickness of the argon targets as a function of the amount of gas introduced was determined by observing the width of the ground-state proton group. Targets employed in the lifetime measurements were approximately 8 mg/cm^2 in areal density (1200-keV energy loss for a 2.8-MeV triton), and since the (t,p) cross section falls off rapidly with energy below 2.4 MeV, this thickness insured that all recoils were stopped in the argon layer.

Figure 2 shows a proton spectrum in coincidence with γ rays with $E_\gamma \geq 400$ keV from the ^{40}Ar target. Individual proton groups do not necessarily appear as distinct peaks in the spectrum because of the target thickness, and most of the apparent peaks are composites although the uppermost peak in the spectrum is composed solely of protons populating the 1.21-MeV first excited state. In the process of data reduction, γ-ray spectra in coincidence with various regions of proton energy were obtained for analysis. In Fig. 2, the horizontal bars labeled 1–6 indicate the intervals used and the figure caption gives the corresponding excitation region in

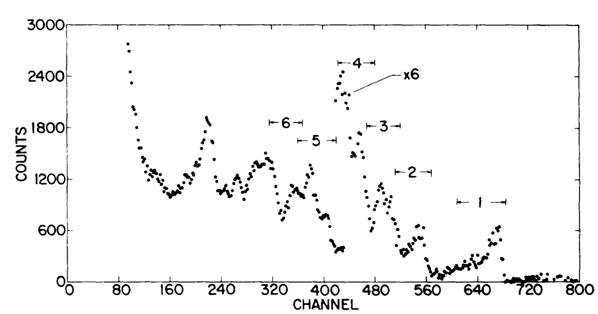

FIG. 2. Proton spectrum from argon target in coincidence with all γ rays with $E \gtrsim 400$ keV. The regions of excitation in ^{42}Ar defined by the horizontal bars include primarily the following levels: No. 1, 1.21 MeV; No. 2, 2.49 and 2.51 MeV; No. 3, 3.01 and 3.10 MeV; No. 4, 3.56 MeV; No. 5, 4.00, 4.13, and 4.28 MeV; No. 6, 4.63 MeV. Lower energy regions of the spectrum did not produce any coincident γ rays intense enough for Doppler-shift analysis.

^{42}Ar. The average triton energy responsible for the population of a particular level, which is needed for the calculation of the unattenuated Doppler shift, was obtained from an analysis of the particle spectrum gated by the appropriate γ-ray peak. The attenuated Doppler shifts were measured at angles of 30 and 120° and the attenuation factor $F_m(\tau_m)$ was computed from the ratio of the observed shift to the calculated full Doppler shift.

No experimental information is available on dE/dx for argon ions stopping in solid argon, so the theory of Lindhard, Scharff, and Schiøtt,[8] supplemented by the work of Blaugrund[9] which approximates the effects of nuclear scattering, was used to calculate the relationship between F_m and τ_m. The density of solid argon at 15 K was taken to be 1.76 g/cm^3.[7] The calculated curves of F_m vs τ_m which were used in the extraction of the lifetime values are shown in Fig. 3. An additional 15% uncertainty was included in all final lifetime values to allow for the uncertainty in the energy-loss parameters derived from the Lindhard theory.

In addition to the lifetime information reported in this paper, excitation energies for all observed levels up to 4.63 MeV excitation energy have been derived and branching ratios are reported for the decay of levels at 2.49, 3.01, and 3.56 MeV. The branching ratios were obtained by averaging the 30 and 120° data.

III. RESULTS

The experimental level spectrum of ^{42}Ar and the γ rays observed in this experiment are shown in Fig. 4. The spin and parity assignments are from Refs. 2 and 3; branching ratios and excitation energies are from the present work and are in substantial agreement with the results of Pronko and McDonald.[2] The systematic difference of about 2 keV which exists between the two sets of excitation energies is well within the limits of the quoted experimental uncertainties. The experimental information on nuclear lifetimes is summarized in Table I. It was not possible to distinguish γ rays from the 2.41-MeV level because of the accidental degeneracy between the transition ($2.414 \rightarrow 1.208$) and the transition ($1.208 \rightarrow 0$); therefore, no information was obtained on this level.

The level spectrum of Fig. 4 is reasonably well explained by the shell-model calculations of Gloeckner, Lawson, and Serduke,[1] which included the model space $(\pi d_{3/2})^{-2}(\nu f_{7/2};\ \nu p_{3/2})$.[4] Table II shows the agreement between the experimental and theoretical lifetime results. The two values shown for each theoretical lifetime correspond to the different sets of two-body matrix elements which result from two possible choices for the $p_{3/2}$ single-particle state in ^{37}S. The two sets of matrix elements, identified in Ref. 1 as sets A and B, are fully discussed there. The two lifetime values are almost identical for all transitions except the strongly retarded $4_2^+ \rightarrow 2_1^+$ transition. Effective charges $e_p = 1.87e$, $e_n = 1.94e$ were used in the cal-

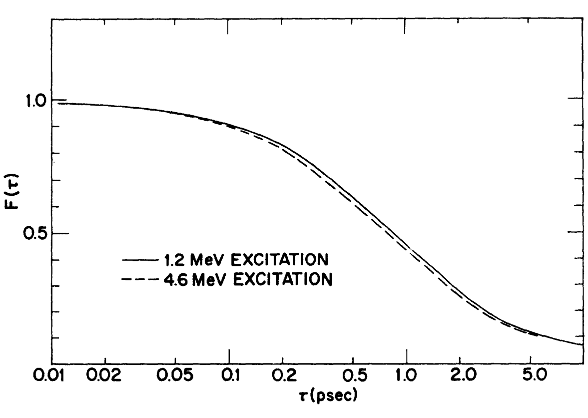

FIG. 3. Plot of F_m vs τ_m for ^{42}Ar stopping in argon. The energy loss parameters from the theory of Lindhard, Scharff, and Schiøtt are $K_e = 2.83$ and $K_n = 0.56$ keV cm^2/μgm. The calculation depends on the excitation energy of the nuclear level which changes the initial recoil velocity.

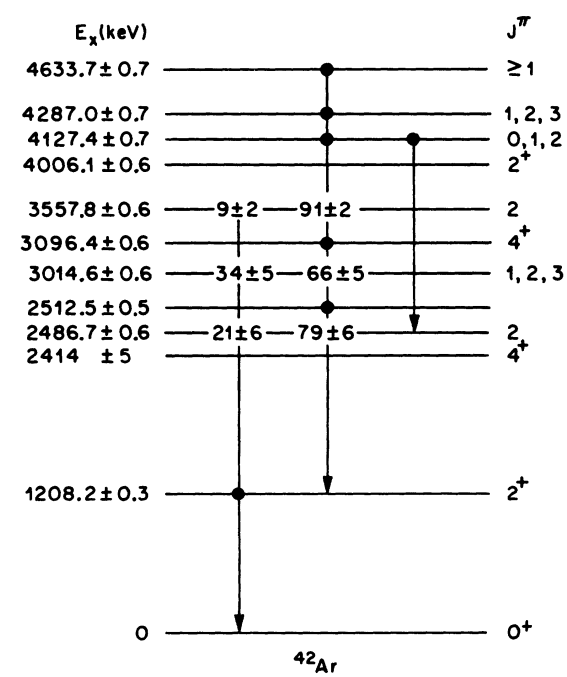

FIG. 4. Summary of information on excitation energies, J^π values, and γ-ray transitions for low-lying levels in ^{42}Ar. J^π values are from Refs. 2 and 3; excitation energies and γ-ray branching ratios are from the present experiment.

TABLE I. Summary of lifetime information for nuclear levels in ^{42}Ar. ΔE_γ is the attenuated Doppler shift measured between 30 and 120°, and F_m is the ratio of the attenuated shift to the calculated full shift.

E_x (keV)	E_γ [a] (keV)	ΔE_γ (keV)	$\bar{E}_t$ [b] (MeV)	F_m	τ_m [c] (psec)
1208.2 ± 0.3	1208.2 ± 0.13	1.47 ± 0.24	2.44	0.15 ± 0.025	$3.8^{+1.0}_{-0.8}$
2486.7 ± 0.6	1278.5 ± 0.47	6.75 ± 0.83	2.48	0.68 ± 0.08	0.40 ± 0.16
2512.5 ± 0.5	1304.3 ± 0.29	1.46 ± 0.54	2.51	0.14 ± 0.05	$4.0^{+3.1}_{-1.2}$
3014.6 ± 0.6	1806.4 ± 0.40	12.9 ± 0.75	2.47	0.95 ± 0.06	<0.12 [d]
3096.4 ± 0.6	1888.2 ± 0.37	0.84 ± 0.72	2.56	0.06 ± 0.05	>5
3557.8 ± 0.6	2349.6 ± 0.29	16.5 ± 0.55	2.45	0.95 ± 0.03	<0.09
4006.1 ± 0.6	1519.4 ± 0.22	7.65 ± 0.41	2.32	0.71 ± 0.04	0.03 ± 0.08
4127.4 ± 0.7	2919.2 ± 0.39	7.07 ± 0.76	2.47	0.34 ± 0.04	1.4 ± 0.3
4287.0 ± 0.7	3078.8 ± 0.403	22.2 ± 0.81	2.55	0.99 ± 0.04	<0.05
4633.7 ± 0.7	3425.5 ± 0.47	25.2 ± 0.94	2.50	1.04 ± 0.04	<0.05

[a] Uncertainties in this column are statistical only. Values quoted for E_x include calibration uncertainties.

[b] $\bar{E}_t$ is the average triton energy for population of a particular level.

[c] Uncertainties in this column include a ±15% allowance for uncertainty in the energy loss parameters.

[d] Lifetime limits correspond to the 85% confidence level.

culation of $E2$ matrix elements and $M1$ matrix elements were calculated with the free nucleon values $\mu_p = 2.79\mu_N$ and $\mu_n = -1.91\mu_N$ for the neutron and proton magnetic moments.

In general, the agreement between the experimental and calculated lifetimes is good, particularly in view of the fact that no adjustments in the effective charges or magnetic moments were allowed in fitting the data; thus these data support the identifications made by Gloeckner, Lawson, and Serduke.[1] It should also be borne in mind that the 2.49- and 3.56-MeV levels, which are identified here with the 2_2^+ and 2_3^+ levels of the model space, may contain appreciable core-excited components since a core-excited 2^+ state is expected in the neighborhood of 3 MeV. A core-excited 0^+ state is also predicted at 1.8 MeV, but we find no evidence for such a state. If it exists, it is populated with an intensity less than 5% of the population of the ^{42}Ar ground state in this experiment. Possibly the 2.51-MeV level is the core-excited 0^+ level, which is consistent with our failure to observe any ground-state transition from this level.

The present work provides additional support for the identification of the 3.01-MeV level as the first 1^+ level, as suggested in Ref. 1. The observation of a ground-state transition from this level together with the measured lifetime limit (<0.12 psec) rules out a $J = 3$ assignment which would imply an $E3$ transition strength $> 10^4$ Weisskopf units. Therefore the 3.01-MeV level cannot be the 3_1^+ level, which remains as yet unobserved. The 2.51-MeV level is barred from identification with the model-space 1_1^+ level both by its lifetime of 4 psec

TABLE II. Experimental and theoretical lifetimes (in psec) for ^{42}Ar. The columns labeled $\tau(E2)$ and $\tau(M1)$ were calculated by Gloeckner *et al.* employing the methods outlined in Ref. 1. The two numbers for each lifetime correspond to different choices for the two-body matrix elements entering into the calculation identified in Ref. 1. as *A* and *B*.

		$\tau(E2)$		$\tau(M1)$		τ		
Transition	$E_i \to E_f$ (MeV)	*A*	*B*	*A*	*B*	*A*	*B*	τ(exp)
$2_1^+ \to 0_1^+$	$1.21 \to 0$	1.89	1.86			1.89	1.86	$3.8^{+1.0}_{-0.8}$
$2_2^+ \to 2_1^+$	$2.49 \to 1.21$	2.72	3.09	1.83	1.37	1.09	0.95	0.47 ± 0.18
$2_2^+ \to 0_1^+$	$2.49 \to 0$	2.85	2.47			2.85	2.47	2.7 ± 1.0
$1_1^+ \to 2_1^+$	$3.01 \to 1.21$	8.62	9.43	0.013	0.012	0.013	0.012	<0.13
$1_1^+ \to 0_1^+$	$3.01 \to 0$			0.49	0.37	0.49	0.37	<1.5
$4_2^+ \to 2_1^+$	$3.10 \to 1.21$	1885	8124			1885	8124	>5
$2_3^+ \to 2_1^+$	$3.56 \to 1.21$	0.45	0.39	0.11	0.15	0.088	0.11	<0.09
$2_3^+ \to 0_1^+$	$3.56 \to 0$	2.03	2.03			2.03	2.03	<0.6

and the fact that no ground-state transition is observed. The predicted retardation of the $4_2^+ \rightarrow 2_1^+$ transition is also experimentally confirmed, although unfortunately only a lower limit ($\tau > 5$ psec) for the nuclear lifetime could be obtained.

Note added in proof: The discrepancy in branching ratios for the 3015-keV state as given in this paper and in Ref. 2 has been resolved. The authors of Ref. 2 have determined a revised value of 38 ± 4 and $62 \pm 4\%$ for the branch to the ground and first excited states, respectively, from a reanalysis of their data.

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