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Gamma-ray lifetimes for parity doublets in ^{41}K, ^{41}Ca

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Lifetimes have been measured by direct timing for the 1582 keV, 3/2$^-$ level of ^{41}K($\tau < 38$ ps) and the 2010 keV, 3/2$^+$ level of ^{41}Ca($\tau = 730 \pm 18$ ps). These levels are members of closely spaced parity doublets. The sensitivity of measurements to determine the parity mixing within these doublets is discussed.

[NUCLEAR REACTIONS ^{41}K($p,p\gamma$), E_x=1582 keV, measured τ; ^{40}Ca($d,p\gamma$), E_x =2010 keV, measured τ. Direct timing.]

I. INTRODUCTION

The Weinberg-Salam unified model of the weak and electromagnetic interactions[1] is in excellent agreement with the results of a variety of recent high energy experiments involving lepton-lepton and lepton-quark interactions.[2] Measurements of parity violation in nuclear systems can test the predictions of this unified model for weak nucleon-nucleon (and hence quark-quark) interactions, and considerable experimental and theoretical effort has been devoted to this subject.[3]

Although measurements of parity violation in few-nucleon systems such as $p+p$ and deuterium[4-6] are easiest to relate theoretically to the basic weak nucleon-nucleon interaction, the size of parity violating effects is extremely small ($\lesssim 1 \times 10^{-4}\%$). Therefore, a number of experiments have been performed to search for parity mixing in energy levels of heavier nuclei, particularly in those cases where nuclear structure effects result in large enhancements in the parity violating observables. Initial experiments[7] in a number of cases in heavy nuclei produced definite results which were of the order of magnitude expected for parity violation according to the basic weak interaction models.

More recently, experimental results have been obtained[8-11] for a few cases in light nuclei where the parity mixing occurs predominantly between two closely spaced nuclear energy levels, for which the wave functions are quite well described by nuclear shell models. In these cases, experimental results can be related to the basic weak nucleon-nucleon interaction and the predictions of various weak interaction models may be tested. The particular cases studied to date are also favored experimentally because of large inhibitions in electromagnetic transition rates, resulting in relatively large parity violating observables.

The present paper described lifetime measurements for gamma decay of the long lifetime members of closely spaced parity doublets in ^{41}K and ^{41}Ca. The energy spacing in these cases is sufficiently small so that parity mixing with other nuclear levels can probably be neglected. In addition, the proximity of these nuclei to the doubly magic nucleus ^{40}Ca and the low excitation energy of the levels, implies that shell model calculations of their wave functions should be quite accurate. The purpose of the present work is to determine the electromagnetic transition rates and hence the sensitivity of possible experiments searching for parity mixing of these levels.

The low-lying energy levels of ^{41}K and ^{41}Ca are shown in Fig. 1. The doublets of interest in the present work are the $J^\pi = \frac{3}{2}^-$, $\frac{3}{2}^+$ pairs at 1582 and 1560 keV in ^{41}K, and at 1943 and 2010 keV in ^{41}Ca. The lifetimes of the short-lived $\frac{3}{2}$ levels have been measured to be about 600 fs (see Table I). Prior to the present measurement, only a lower limit was known for the lifetime of the 1582 keV, $\frac{3}{2}^-$ level of ^{41}K and the lifetime of the 2010 keV, $\frac{3}{2}^+$ level of ^{41}Ca was known to be about 800 ps.

The next section describes the measurements of the lifetimes of the long-lived $\frac{3}{2}$ levels in ^{41}K and ^{41}Ca by electronic timing, Sec. III lists the results, and in Sec. IV the results are discussed in terms of possible parity violation measurements.

II. EXPERIMENTS

The 1582 keV level in ^{41}K was populated via the ^{41}K($p,p'\gamma$)^{41}K reaction at $E_p = 3.22$ MeV with the pulsed beam facility of the Chalk River Nuclear Laboratories (CRNL) MP tandem accelerator. A beam burst duration of ~0.5 ns was used with an interval of 800 ns between successive bursts and

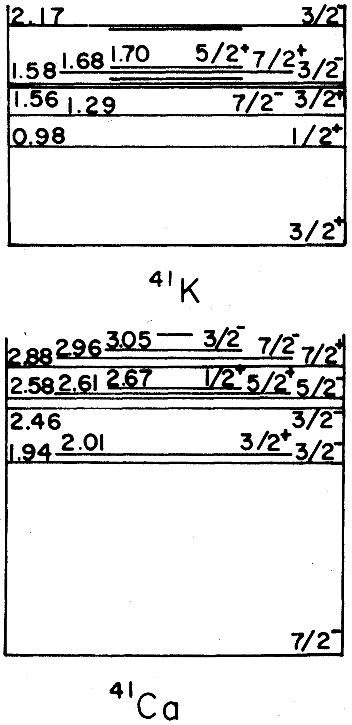

FIG. 1. Low-lying energy levels of ^{41}Ca and ^{41}K (from Ref. 15).

an average beam intensity of 20 nA. The target was a 1300 μg cm^{-2} layer of ^{41}KI (enriched to >94%) evaporated onto a thick gold backing. Gamma-ray levels were detected at 0° to the incident beam direction in an 86 cm^3 coaxial Ge(Li) detector placed with its front face 3.5 cm from the target.

The 2010 keV level in ^{41}Ca was populated via the ^{40}Ca$(d,p\gamma)^{41}$Ca reaction at $E_d = 3.0$ MeV with the pulsed beam facility of the Queen's University 4 MV Van de Graaff accelerator. A beam burst duration of ≤ 1 ns was used with an interval of 50 ns between successive bursts and an average beam intensity of 23 nA. The target consisted of a 100 μg cm^{-2} layer of natural calcium evaporated onto a thick gold backing. Oxygen buildup on the target was inhibited by evaporating a 100 μg cm^{-2} encapsulating layer of gold over the front face. Gamma rays were detected in a 48.3 cm^3 coaxial Ge(Li) crystal placed 10 cm from the target at 135° to the incident beam direction. At this angle the 2010 keV γ ray was well separated from the Doppler-shifted 2001 keV γ ray from the 3944 keV level (see Fig. 2).

In both experiments, signals from the Ge(Li) crystals were used to obtain timing as well as energy information. Gamma-ray timing signals were extracted by a timing filter amplifier and constant fraction discriminator, and provided the start signal for a time-to-amplitude convertor. The stop signal was derived from the beam pulsing system. The time and energy were stored in an event mode format for subsequent off-line analysis. Calibration of the time spectra was carried out with standard delay cables and a Tennelec TC850 time calibrator.

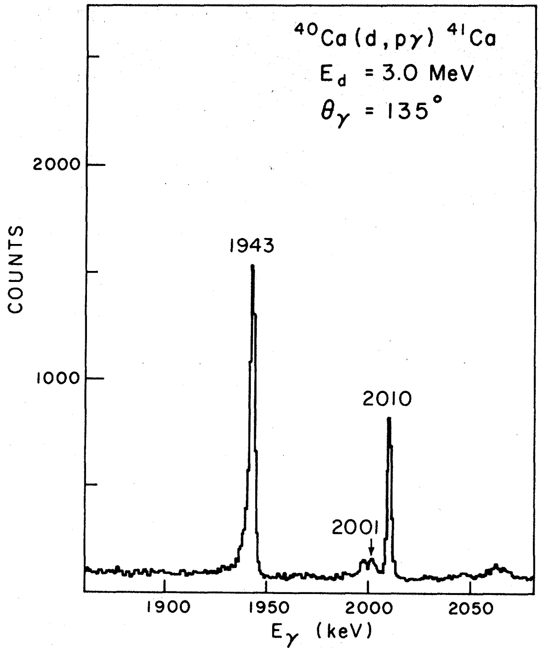

FIG. 2. Gamma-ray spectrum from the ^{40}Ca$(d,p\gamma)^{41}$Ca reaction at $E_d = 3.0$ MeV. At $\theta_\gamma = 135°$ the 2001 keV γ ray is clearly separated from the 2010 keV γ ray.

The performance of the constant fraction discriminator is characterized by a residual correlation between detection time and γ-ray energy, which depends explicitly on the individual setup of the discriminators. It is therefore necessary to determine this characteristic response under the conditions encountered in the actual timing experiment and in the appropriate γ-ray energy region. The prompt calibration was therefore obtained by simultaneously accumulating the time spectra for several "prompt" ($\tau < 1$ ps) γ rays produced in the same reaction and in the same energy region as the γ ray of interest. Accordingly, the time spectrum corresponding to the photopeaks of the 661, 728, 1039, 1485, 1943, 2010, 2575, and 2605 keV γ rays in ^{41}Ca, and the 1560, 1582, and 1594 keV γ rays in ^{41}K were simultaneously accumulated, and the centroid position of each time peak determined.

In addition to the systematic energy dependence, it is necessary to account for the fact that the photopeak and the underlying background arise from different production and detection mechanisms, and can have a significantly different time characteristic. The contribution of underlying background to the relevant photopeaks was accounted for by generating the time spectrum from the background under the photopeak and subtracting it from the photopeak time spectrum. The background spectra were produced by taking the time spectra of an equal number of background channels immediately adjacent to the relevant photopeak. This correction was carried out both by using background channels higher than the photopeak and two sets with half the number of channels placed symmetrically about the peak. Differences between the two methods of background subtraction were significantly smaller than the statistical errors.

III. RESULTS

The 1560 and 1594 keV γ rays from ^{41}K were used to generate the prompt calibration line for the 1582 keV ground-state decay γ ray, and a comparison of the 1582 keV γ-ray decay time and the prompt calibration curve, shown in Fig. 3, shows no measurable time centroid shift for that γ ray. This limits the lifetime of the ^{41}K 1582 keV level to $\tau < 38$ ps.

The prompt γ rays from ^{41}Ca were used to provide a calibration curve for the 2010 keV ground-state decay. In this case, a significant time centroid shift is observed, as can be seen in Fig. 4, and leads to $\tau = 730 \pm 18$ ps for the lifetime of the 2010 keV level in ^{41}Ca. This value is in good agreement with, and more accurate than, the earlier measurements of $\tau = 800 \pm 200$ ps, obtained by the electronic timing technique,[12] and $\tau = 670 \pm 70$ ps obtained by the recoil distance technique.[13]

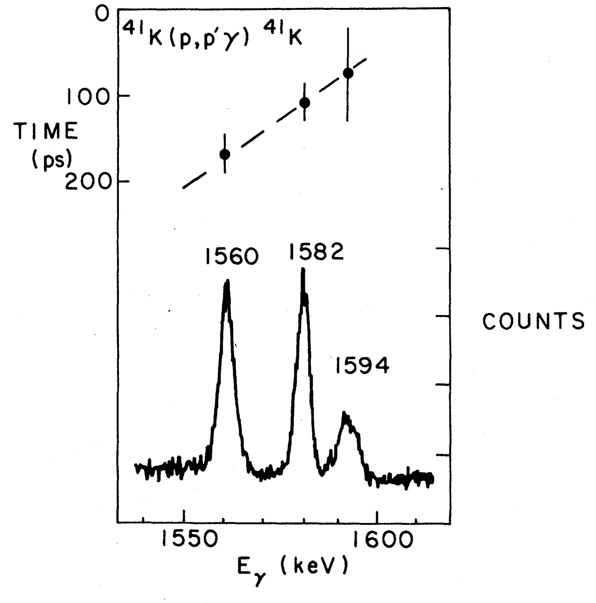

FIG. 3. Time centroids of the full energy peak as a function of γ-ray energy for the ^{41}K$(p,p'\gamma)^{41}$K reaction at $E_p = 3.22$ MeV.

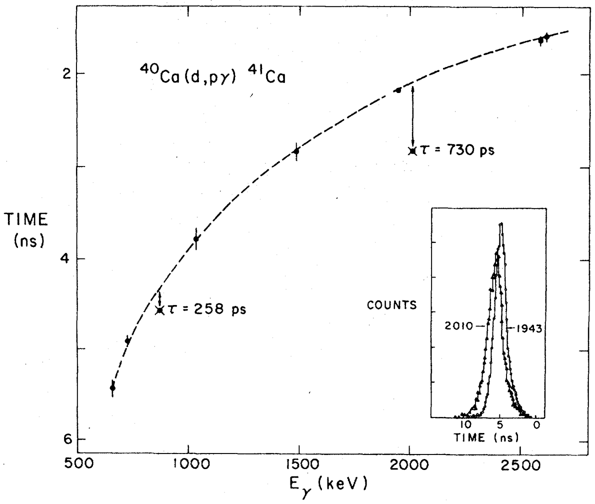

FIG. 4. Time centroids of the full energy peak as a function of γ-ray energy for the ^{40}Ca$(d,p\gamma)^{41}$Ca reaction at $E_p = 3.0$ MeV. The dashed curve is a least squares fit of a polynomial for the prompt ($\tau \lesssim 1$ ps) γ rays. The time spectra for the 1944 and 2010 keV γ rays (inset) clearly show the centroid shift for the latter transition. The delayed 871 keV γ ray is produced by the ^{16}O$(d,p\gamma)$-^{17}O reaction on the oxide layer on the target.

An independent check of the direct timing method was carried out by measuring the known lifetime of the 871 keV level in ^{17}O produced by the ^{16}O$(d,p\gamma)^{17}$O reaction on the oxygen surface layer on the Ca target. The centroid shift of the 871 keV γ ray was used to determine a lifetime of $\tau = 258 \pm 14$ ps, in excellent agreement with the average of previous measurements,[14] $\tau = 258 \pm 4$ ps.

IV. DISCUSSION

The parity mixing between these pairs of levels could be determined by measuring the circular polarization of the gamma-ray transition from the longer lifetime (unpolarized) $\frac{3}{2}$ level to the ground states. Alternatively, this $\frac{3}{2}$ level could be polarized (such as by polarization transfer from a polarized beam) and the asymmetry relative to the direction of polarization could be measured. (For a discussion, see Ref. 15.)

For either measurement, the parity violating observable is almost directly proportional to the ratio

$$\frac{\langle 1560\ \text{keV},\ \frac{3}{2}^{+}\|M1\|0,\ \frac{3}{2}^{+}\rangle}{\langle 1582\ \text{keV},\ \frac{3}{2}^{-}\|E1\|0,\ \frac{3}{2}^{+}\rangle}$$

in ^{41}K or

$$\frac{\langle 1943\ \mathrm{keV},\ \tfrac{3}{2}^{-}\|E2\|0,\tfrac{7}{2}^{-}\rangle}{\langle 2010\ \mathrm{keV},\ \tfrac{3}{2}^{+}\|M2\|0,\tfrac{7}{2}^{-}\rangle}$$

in ^{41}Ca.

In particular, for the circular polarization measurement,

$$P_\gamma(^{41}\mathrm{K}, 1582\ \mathrm{keV}) = 2\langle \tfrac{3}{2}^{+}|H^{w}|\tfrac{3}{2}^{-}\rangle\left\langle\left\|\frac{M1}{E1}\right\|\right\rangle\frac{1+\delta_+\delta_- + B_2(\tfrac{3}{2})P_2(\cos\theta)[-0.400+0.775(\delta_+ + \delta_-)]}{1+\delta_-^{\,2}+B_2(\tfrac{3}{2})P_2(\cos\theta)(-0.400+1.550\delta_-)}$$

and

$$P_\gamma(^{41}\mathrm{Ca}, 1943\ \mathrm{keV}) = 2\langle \tfrac{3}{2}^{+}|H^{w}|\tfrac{3}{2}^{-}\rangle\frac{\langle\|E2\|\rangle}{\langle\|M2\|\rangle}$$

$$\times\frac{1+\delta_+\delta_- + B_2(\tfrac{3}{2})P_2(\cos\theta)[-0.143+0.500\delta_+\delta_- - 0.463(\delta_- + \delta_+)]}{1+\delta_+^{\,2}+B_2(\tfrac{3}{2})P_2(\cos\theta)(-0.143+0.500\delta_+^{\,2}-0.926\delta_+)},$$

where H^w is the weak parity violating Hamiltonian responsible for the parity mixing, $\frac{3}{2}^{+}$ and $\frac{3}{2}^{-}$ refer to the two members of the parity doublet, and δ_+ and δ_- are mixing ratios for the transitions from the $\frac{3}{2}^{+}$, $\frac{3}{2}^{-}$ components to the ground state. The energy difference between the members of the parity doublet is denoted by ΔE; $B_2(\frac{3}{2})$ is the statistical tensor for the state being excited. The notation and phase convention of Rose and Brink[16] are used.

From the data in Table I, including the present measurements, one can conclude that for the 1582 keV level in ^{41}K 5 ps $< \tau <$ 38 ps and for the 2010 keV level in ^{41}Ca $\tau = 727 \pm 18$ ps. Using this information, together with previous measurements of mixing ratios and the lifetime of the short-lived $\frac{3}{2}$ levels, one can calculate that for a circular polarization measurement at 55°, where $P_2(\cos\theta) \approx 0$,

$$P_\gamma(^{41}\mathrm{K}, 1582\ \mathrm{keV}) = (5.5 \pm 2.3) \times 10^{-4}\ \mathrm{eV}^{-1}\langle \tfrac{3}{2}^{+}|H^{w}|\tfrac{3}{2}^{-}\rangle$$

and

$$P_\gamma(^{41}\mathrm{Ca}, 2010\ \mathrm{keV}) = (1.1 \pm 0.2) \times 10^{-3}\ \mathrm{eV}^{-1}\langle \tfrac{3}{2}^{+}|H^{w}|\tfrac{3}{2}^{-}\rangle .$$

Although the relatively short lifetime for the ^{41}K, 1582 keV level results in a reduced sensitivity in this case, these sensitivities to parity mixing

TABLE I. Parameters of parity doublets in ^{41}K, ^{41}Ca.

Nucleus	Initial level (J^π)	Lifetime measurements	Final level (J^π)	Branching ratio (%)	Mixing ratio
^{41}K	1560.4 ± 0.2 ($\frac{3}{2}^{+}$)	600 ± 110 fs	0.0 ($\frac{3}{2}^{+}$)	82.4 ± 0.6	+0.27 ± 0.02
		(average)[a]	980 ($\frac{1}{2}^{+}$)	17.6 ± 0.6	−0.12 ± 0.04
			1294 ($\frac{7}{2}^{-}$)	<0.4	
	1582.3 ± 0.2 ($\frac{3}{2}^{-}$)	>4.5 ps[b]	0.0 ($\frac{3}{2}^{+}$)	84.2 ± 0.7	$+0.08^{+0.02}_{-0.03}$
		>1.5 ps[c]	980 ($\frac{1}{2}^{+}$)	15.8 ± 0.7	+0.06 ± 0.03
		<38 ps[d]	1294 ($\frac{7}{2}^{-}$)	<0.7	
^{41}Ca	1942.61 ± 0.11 ($\frac{3}{2}^{-}$)	570 ± 100 fs	0.0 ($\frac{7}{2}^{-}$)	100	
		(average)			
	2009.8 ± 0.2 ($\frac{3}{2}^{+}$)	800 ± 200 ps[e]	0.0 ($\frac{7}{2}^{-}$)	100	−0.13 ± 0.03
		670 ± 70 ps[f]			
		730 ± 18 ps[d]			

[a] All information from Ref. 17 unless otherwise noted.
[b] Reference 18.
[c] Reference 19.
[d] Present work.
[e] Reference 12.
[f] Reference 13.

matrix elements compare favorably to the sensitivities of cases previously investigated[8,9] in ^{18}F

$$[P_\gamma(1082\text{ keV}\to 0)=4.9\times 10^{-3}\text{ eV}^{-1}\langle 0^+|H^w|0^-\rangle]$$

and ^{19}F

$$[A_\gamma(110\text{ keV}\to 0)=1.8\times 10^{-4}\text{ eV}^{-1}\langle \tfrac{1}{2}^-|H^w|\tfrac{1}{2}^+\rangle]$$

but are less favorable than the very sensitive case[10] in ^{21}Ne

$$[P_\gamma(2789\text{ keV}\to 0)=9.5\times 10^{-2}\text{ eV}^{-1}\langle \tfrac{1}{2}^-|H^w|\tfrac{1}{2}^+\rangle].$$

The practicability of possible measurements of parity mixing in ^{41}K and ^{41}Ca is obviously dependent on details of the reaction used to populate the levels and on the apparatus used. This is emphasized by the fact that the least sensitive case, ^{19}F, is the only one for which a statistically significant result has been obtained.[9]

However, if the parity mixing matrix elements in ^{41}K and ^{41}Ca were as large as those measured[9] for $^{19}\text{F}(\langle\frac{1}{2}^-|H^w|\frac{1}{2}^+\rangle=-0.33\pm 0.18\text{ eV})$, then the expected circular polarizations would be

$$P_\gamma(^{41}\text{K}, 1582\text{ keV})\approx 2\times 10^{-4}$$

and

$$P_\gamma(^{41}\text{Ca}, 2010\text{ keV})\approx 4\times 10^{-4}.$$

These P_γ may be compared with those attained recently in accelerator based experiments:

$$^{18}\text{F}:\ P_\gamma=(-7\pm 20)\times 10^{-4}\ \text{(Ref. 8)}$$

and

$$^{21}\text{Ne}:\ P_\gamma=(9\pm 51)\times 10^{-4}\ \text{(Ref. 10)}.$$

This sensitivity, and the possibility of accurate shell model calculations for these levels, suggests that these cases should be included in the short list of experiments that could provide quantitative information on the weak nucleon-nucleon interaction.

The ^{41}K case is of particular interest because the parity mixing occurs between two $T=\frac{3}{2}$ levels and therefore involves matrix elements in which the isospin changes by 0, 1, or 2 units. There has been some interest in isotensor ($\Delta T=2$) parity violating matrix elements because of the result[5] obtained for the circular polarization of gamma rays following the capture of thermal neutrons in hydrogen $[P_\gamma=(1.60\pm 0.45)\times 10^{-6}]$. The circular polarization in this case depends on mixing matrix elements with $\Delta T=0$ and 2, but the size of the $\Delta T=0$ matrix element is constrained by a measurement[11] in ^{16}O ($\Delta T=0$). The observed circular polarization in the $n+p\to d+\gamma$ case could be explained by a relatively large isotensor matrix element,[20] but this is not predicted[21] by basic calculations of the weak nucleon-nucleon interaction. Although the dependence of parity mixing on the $\Delta T=2$ matrix element has yet to be determined in the ^{41}K case, a measurement in this case might provide an additional determination of the size of isotensor parity mixing.

The ^{41}Ca case involves parity mixing of two isospin $\frac{1}{2}$ levels, and hence involves $\Delta T=0$, 1 matrix elements. If the Weinberg-Salam model of weak interactions is valid for quark-quark interactions, then $T=1$ matrix elements may be enhanced[21] by a factor as large as 20 over the size predicted by the previously accepted Cabibbo model without neutral currents. A measurement of parity mixing in ^{41}Ca could provide an additional test for the enhancement of $\Delta T=1$ matrix elements in a case of two state mixing with well defined wave functions.

The complete determination of the weak two-nucleon interactions responsible for the $\Delta T=0$, 1, 2 parity mixing matrix elements requires measurements for a number of cases with different isospin combinations. The experimental information available to date has been parametrized in terms of weak two-nucleon matrix elements[22] or weak meson-nucleon-nucleon vertices.[23] However, the present experimental uncertainties and theoretical nuclear structure difficulties are too large to define a possible enhancement of $\Delta T=1$ matrix elements arising from the Weinberg-Salam model.

To date, the number of experiments contributing to this information is small, and most provide only upper limits. More accurate measurements and results for new cases with well defined nuclear structure are required. Parity mixing measurements for the doublets discussed in the present work could provide valuable additional information.

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