

Lifetimes of the 6_1^+ states in ^{42}Ti and ^{46}Ca and $E2$ effective charges in $(1f_{7/2})^{\pm 2}$ nuclei

W. Kutschera,* B. A. Brown,† H. Ikezoe, G. D. Sprouse,‡ Y. Yamazaki, and Y. Yoshida
 Department of Physics, University of Tokyo, Bunkyo-ku, Tokyo, Japan
 and Cyclotron Laboratory, The Institute of Physical and Chemical Research, Wako-shi, Saitama-ken, Japan

T. Nomura§

Cyclotron Laboratory, The Institute of Physical and Chemical Research, Wako-Shi, Saitama-ken, Japan

H. Ohnuma

Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

(Received 20 May 1975)

The mean lifetimes of the 6_1^+ states in ^{42}Ti at 3041 keV and ^{46}Ca at 2974 keV have been measured with the pulsed beam method to be $\tau = 5 \pm 2$ ns and 15.2 ± 0.8 ns, respectively. The states were populated via the reactions $^{40}\text{Ca}(^3\text{He},n)^{42}\text{Ti}$ at $E_{^3\text{He}} = 12$ MeV and $^{48}\text{Ca}(\alpha, \alpha 2n)^{46}\text{Ca}$ at $E_\alpha = 50$ MeV. The deduced $B(E2, 6^+ \rightarrow 4^+)$ values result in proton and neutron effective charges which are in good agreement with other $(1f_{7/2})^{\pm 2}$ nuclei. However, the present lifetime result for ^{42}Ti is in disagreement with another measurement for this nucleus. A comparison of $E2$ effective charges extracted from all presently available $B(E2)$ data on the $6^+ \rightarrow 4^+ \rightarrow 2^+ \rightarrow 0^+$ transitions in $(1f_{7/2})^{\pm 2}$ nuclei is presented.

NUCLEAR REACTIONS $^{40}\text{Ca}(^3\text{He}, n\gamma)$, $E = 12$ MeV, $^{48}\text{Ca}(\alpha, \alpha 2n\gamma)$, $E = 50$ MeV; measured pulsed beam electronic timing; deduced $T_{1/2}$, $B(E2)$, effective charges. Natural and enriched targets, Ge(Li) detectors.

I. INTRODUCTION

In order to understand the large quantity of measured lifetimes in the $1f_{7/2}$ shell, it is important to study particular nuclei that should have simple shell model wave functions. ^{42}Ti and ^{46}Ca belong to the group of even-even $1f_{7/2}$ nuclei with two particles or holes outside the $N, Z = 20$ and 28 closed shells. This group includes the nuclei $^{42}\text{Ca}_{22}$, $^{46}\text{Ca}_{26}$, $^{42}\text{Ti}_{20}$, $^{50}\text{Ti}_{28}$, and $^{54}\text{Fe}_{28}$, which all show a low lying level sequence of $0^+, 2^+, 4^+, 6^+$. The decay schemes for the ground state bands of these nuclei determined from the present and previous experiments are shown in Fig. 1. In the most simple shell model picture these states might be described by a pure $(1f_{7/2})^{\pm 2}$ configuration. Although this is not expected to be a sufficient description for all states, the 4^+ and 6^+ states should have the smallest admixture of other configurations. Therefore, the measurement of the $6^+ \rightarrow 4^+$ transition probability can give rather unambiguous information about the effective $E2$ operator in this nuclear region.¹

There exist well established experimental data on the lifetimes of the 6_1^+ state only in ^{42}Ca , ^{50}Ti , and ^{54}Fe (see Table I). The present paper reports on the measurement of the 6_1^+ lifetimes in ^{42}Ti and ^{46}Ca using electronic timing techniques between the natural (microscopic) beam bursts of a cyclotron and γ rays measured with a Ge(Li) detector. The experiments were carried out with the variable energy cyclotron of the Institute of Physical and Chemical Research (IPCR).

The ^{46}Ca lifetime measurement is discussed in

Sec. II and the ^{42}Ti lifetime measurement is discussed in Sec. III. The results make a rather complete comparison of effective charges in $(1f_{7/2})^{\pm 2}$ nuclei feasible. This comparison is presented in Sec. IV.

II. ^{46}Ca 6_1^+ LIFETIME

The lifetime measurement in ^{46}Ca has been performed with the reaction $^{48}\text{Ca}(\alpha, \alpha 2n\gamma)^{46}\text{Ca}$. In order to find a suitable beam energy for this reaction a series of γ -ray singles spectra has been measured during the bombardment of a $^{48}\text{CaCO}_3$ target with α particles in the energy range of E_α

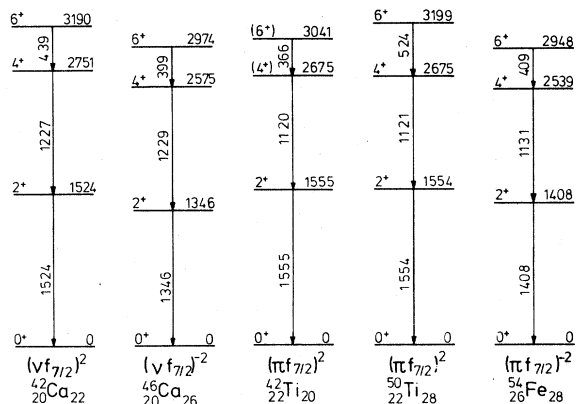


FIG. 1. Experimental spectra for even-even nuclei in the $1f_{7/2}$ shell. The level energies have been determined from the present and previous works quoted in Table I. The main shell model configurations for these levels are indicated.

TABLE I. $E2$ -decay properties of 2_1^+ , 4_1^+ , and 6_1^+ states in $(1f_{7/2})^{+2}$ nuclei.

Nucleus	Main configuration	Transition	E_γ (keV)	τ^a (ps)	Refs.	$B(E2)$ ($e^2 \text{ fm}^4$)	δe^b (e)
$^{42}_{20}\text{Ca}_{22}$	$(\nu f_{7/2})^2$	$2^+ \rightarrow 0^+$	1524	1.19 ± 0.04	c	83.4 ± 2.8	2.09 ± 0.02
		$4^+ \rightarrow 2^+$	1227	4.5 ± 0.5	d, e	65 ± 7	1.85 ± 0.10
		$6^+ \rightarrow 4^+$	439	7.79 ± 0.13 ns	c	6.42 ± 0.11	0.86 ± 0.01
$^{46}_{20}\text{Ca}_{26}$	$(\nu f_{7/2})^{-2}$	$2^+ \rightarrow 0^+$	1346	5.24 ± 0.54	f	35.1 ± 3.6	1.32 ± 0.07
				>8	g	<23	<1.1
		$4^+ \rightarrow 2^+$	1229 ^h	Not measured			
		$6^+ \rightarrow 4^+$	399	15.1 ± 0.8 ns	This exp., h	5.34 ± 0.28	0.76 ± 0.02
$^{42}_{22}\text{Ti}_{20}$	$(\pi f_{7/2})^2$	$2^+ \rightarrow 0^+$	1555	0.60 ± 0.10	i, j, k, l, m	150 ± 25	1.8 ± 0.3
		$(4^+) \rightarrow 2^+$	1120	>1.8	l, m	<230	<2.5
		$(6^+) \rightarrow (4^+)$	366	5 ± 2 ns	This exp.	25^{+1}_{-16}	$0.70^{+0.48}_{-0.25}$
				26 ± 5 ns	m	4.7 ± 0.9	-0.26 ± 0.07
$^{50}_{22}\text{Ti}_{28}$	$(\pi f_{7/2})^2$	$2^+ \rightarrow 0^+$	1554	1.4 ± 0.2	n	66 ± 8	0.76 ± 0.11
		$4^+ \rightarrow 2^+$	1121	7.7 ± 1.5	d	60 ± 12	0.68 ± 0.17
		$6^+ \rightarrow 4^+$	524	0.61 ± 0.02 ns	o, p	33.8 ± 1.2	0.87 ± 0.04
$^{54}_{26}\text{Fe}_{28}$	$(\pi f_{7/2})^{-2}$	$2^+ \rightarrow 0^+$	1408	1.38 ± 0.10	q, r, s	107 ± 8	1.18 ± 0.08
		$4^+ \rightarrow 2^+$	1131	5.7 ± 1.2	t	77 ± 16	0.85 ± 0.19
		$6^+ \rightarrow 4^+$	409	1.75 ± 0.03 ns	o, p, u	40.7 ± 0.7	1.00 ± 0.02

^a Averages of the values taken from the quoted references. For the 4^+ state in ^{42}Ca only the two most recent recoil distance measurements have been used, since older measurements report very conflicting results (see Ref. 17).

^b $\delta e = e_{\text{eff}} - 1$ for protons and $\delta e = e_{\text{eff}}$ for neutrons. Pure $(1f_{7/2})^{+2}$ configurations and harmonic oscillator radial wave functions ($\hbar\omega = 41A^{-1/3}$ MeV) have been assumed to extract the effective charges.

^c Reference 17.

^d A. R. Poletti, B. A. Brown, D. B. Fossan, P. Gorodetzky, J. J. Kolata, J. W. Olness, and E. K. Warburton, Phys. Rev. C **10**, 997 (1974).

^e K. P. Lieb and M. Uhrmacher, Z. Phys. **267**, 399 (1974).

^f M. Bini, P. G. Bizzeti, A. M. Bizzeti-Sona, P. Blasi, C. Rossi-Alvarez, and G. B. Vingiani, Nuovo Cimento Lett. **5**, 913 (1972).

^g J. A. Becker, T. T. Bardin, T. R. Fisher, B. A. Watson, and E. K. Warburton, Phys. Rev. C **10**, 99 (1974).

^h Reference 7.

ⁱ B. A. Brown, M. Marmor, and D. B. Fossan, in *Proceedings of the Topical Conference on the Structure of $1f_{7/2}$ Nuclei, Padova 1971*, edited by R. A. Ricci (Editrice Compositore, Bologna, 1971), p. 123.

^j M. Bocciaolini, P. Sona, and N. Tacceti, University of Florence (private communication), corrected value of Nuovo Cimento Lett. **1**, 695 (1971).

^k J. S. Forster, G. S. Ball, and W. G. Davies, Bull. Am. Phys. Soc. **16**, 555 (1971).

^l Reference 9.

^m Reference 10.

ⁿ O. Häusser, D. Pelte, T. K. Alexander, and H. C. Evans, Nucl. Phys. **A150**, 417 (1970).

^o Reference 1.

^p S. Cochavi, D. B. Fossan, S. H. Henson, D. E. Alburger, and E. K. Warburton, Phys. Rev. C **2**, 2241 (1970).

^q J. J. Simpson, J. A. Cookson, D. Eccleshall, and M. J. L. Yates, Nucl. Phys. **62**, 385 (1965).

^r O. F. Afonin, A. P. Grinberg, I. K. Lemberg, and I. N. Chugunov, Yad. Fiz. **6**, 219 (1967) [Sov. J. Nucl. Phys. **6**, 160 (1968)].

^s J. M. Moss, D. L. Hendrie, C. Glashauser, and J. Thirion, Nucl. Phys. **A194**, 12 (1972).

^t Reference 11.

^u R. Hensler, J. W. Tape, N. Benzzer-Koller, and J. R. MacDonald, Phys. Rev. Lett. **27**, 1587 (1971).

= 25–50 MeV. The target consisted of about 10 mg/cm² $^{48}\text{CaCO}_3$ enriched with 97.2% ^{48}Ca and deposited on a 6 μm thick Mylar foil. The beam was stopped 5 m after the target in a heavily shielded Faraday cup. γ rays were measured with a true coaxial Ge(Li) detector of 32-cm³ active volume at 90° to the beam direction and 10 cm from the target. The typical resolution of the detector during the experiments was 2.5 keV full width at half-maximum (FWHM) at 1.33-MeV γ -ray energy.

Figure 2 shows the in-beam γ -ray spectrum during the bombardment of $^{48}\text{CaCO}_3$ with 50-MeV α particles. This beam energy was used for the lifetime measurement. The assignment of γ lines to the different nuclei was based on the excitation function measurements and information about high-spin states available from the literature. In particular, the results from the reactions $^{44}\text{Ca}-(^7\text{Li}, p2n)^{48}\text{Ti}$ (Ref. 2) and $^{50}\text{V}(t, \alpha)^{49}\text{Ti}$ (Ref. 3) have been used for comparison. The 6_1^+ state in ^{46}Ca has recently been assigned by high resolution

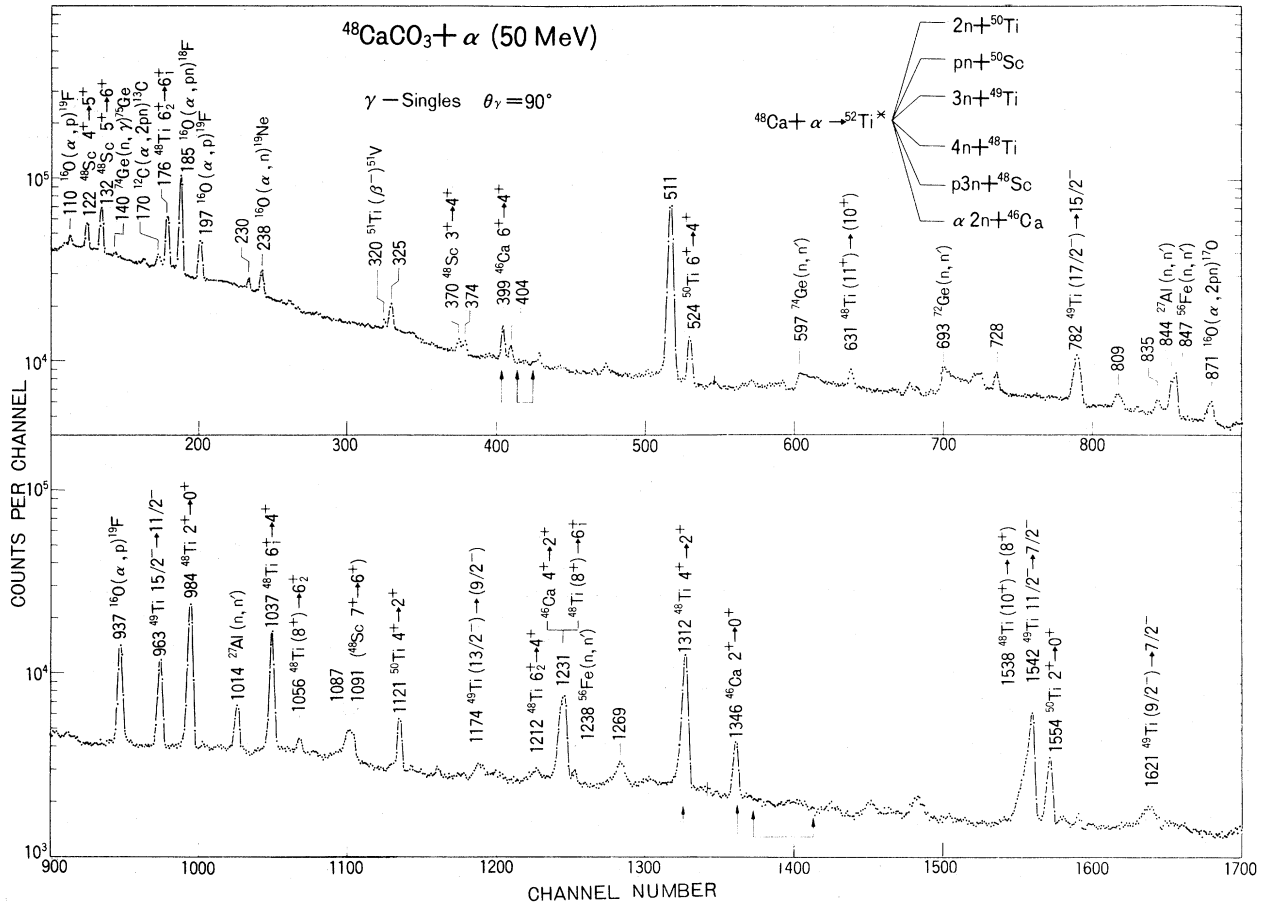


FIG. 2. In-beam γ -ray spectrum measured with a 32-cm³ Ge(Li) detector during the bombardment of a 10-mg/cm² thick $^{48}\text{CaCO}_3$ target with 50-MeV α particles. The schematic on the top right of the figure shows the main reaction channels induced on ^{48}Ca . The arrows in the γ -ray spectrum indicate the selected peaks and background regions to produce the time spectra shown in Fig. 3.

studies^{4,5} of the reaction $^{48}\text{Ca}(p, t)^{46}\text{Ca}$ and was found to lie at 2975 ± 2 and 2978 ± 4 keV, respectively. In addition, this level was measured⁶ by the $^{46}\text{Ca}(p, p')$ reaction to be at 2976 ± 1.5 keV. Together with the known energies⁴⁻⁶ of the 2_1^+ and 4_1^+ levels one expects a deexcitation γ cascade of the 6_1^+ state with γ -ray energies around 400 keV ($6^+ \rightarrow 4^+$), 1230 keV ($4^+ \rightarrow 2^+$), and 1347 keV ($2^+ \rightarrow 0^+$). The $6^+ \rightarrow 4^+$ and $2^+ \rightarrow 0^+$ transitions are clearly observed in the present reaction with γ -ray energies of 399.0 ± 0.5 and 1345.7 ± 0.8 keV, respectively, with an absolute intensity ratio of 1:2. The close lying γ line at 404 keV can be excluded from belonging to ^{46}Ca by the excitation function measurement. Unfortunately, the $4^+ \rightarrow 2^+$ transition⁷ (1229 keV) could not be resolved from the $(8^+) \rightarrow 6_1^+$ transition² (1231 keV) in ^{48}Ti .

Since the lifetime of the 6_1^+ state in ^{46}Ca was expected to lie in the ns region, the natural beam bursts of the 50-MeV α beam from the IPCR cyclotron with a pulse width of ≈ 1 ns and a pulse

period of 95 ns were well suited for an electronic lifetime measurement. Timing was performed with a time-to-amplitude converter (TAC), which was started with the γ -ray signals from the Ge(Li) detector and stopped with the rf signal from the cyclotron. Time spectra corresponding to several γ -ray energies were accumulated in different sections of computer memory by setting digital windows on the Ge(Li) pulse height distribution. In order to improve the time resolution of the Ge(Li) detector, the slow rise time pulses were rejected by pulse shape discrimination of the timing signal. In this procedure two timing signals from the Ge(Li) detector were generated by a leading-edge trigger (LET) and a constant-fraction trigger (CFT) and fed into a second TAC. Due to the different sensitivity to rise times, the output of this TAC allowed a selection of the fast rise time pulses, which were used to gate the time spectra generated in the other TAC by the CFT γ -ray signal and rf signal. The Ge(Li) detector and the

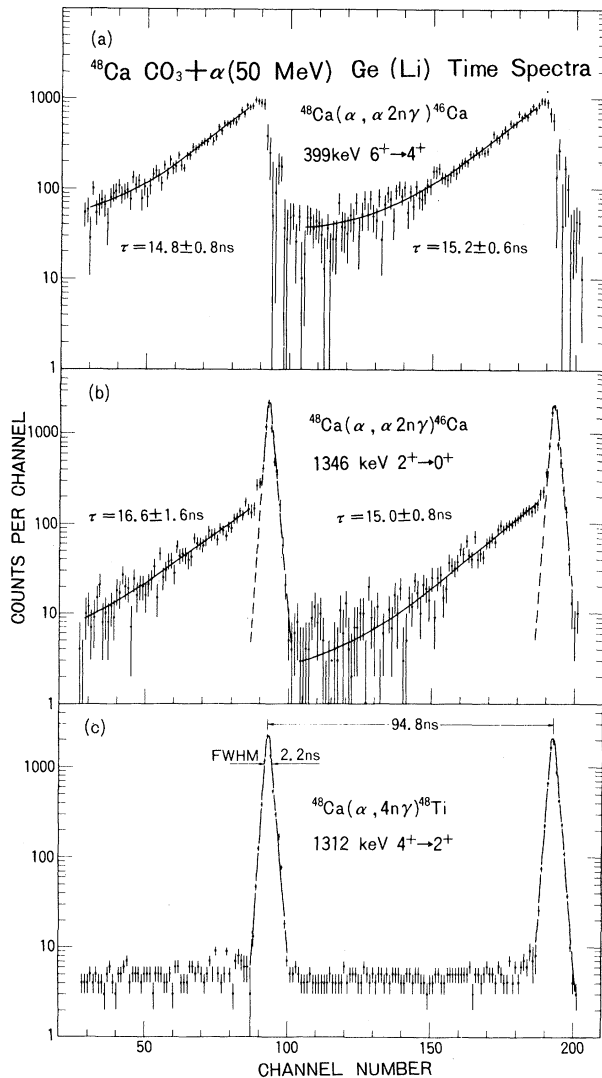


FIG. 3. Time spectra measured for relevant delayed and prompt γ -ray transitions from the spectrum shown in Fig. 2. Since every second rf signal is used to stop the TAC, two time distributions appear in each time spectrum. A normalized background time spectrum region has been subtracted from the three spectra. The extracted lifetimes are the result of a χ^2 fit with a constant plus exponential.

fast timing circuits were encased in a wire cage to avoid severe rf noise pickup from the cyclotron resonator.

Figure 3 shows the time spectra for the $6^+ \rightarrow 4^+$ and $2^+ \rightarrow 4^+$ transitions in ^{46}Ca and the $4^+ \rightarrow 2^+$ transition in ^{48}Ti . The transition in ^{48}Ti does not show any significant delayed component and thus gives an excellent measure of the Ge(Li) time resolution in the γ -ray energy region of 1.3 MeV. The FWHM of 2.2 ns in the prompt peak is an upper limit of the Ge(Li) time resolution since the beam burst itself has a pulse width of around 1 ns. This

very good time resolution is mainly due to the rejection of slow rise time pulses as described above. The two transitions in ^{46}Ca clearly show a delayed component. After the background subtraction no prompt peak is seen for the $6^+ \rightarrow 4^+$ transition. The shape of the prompt peak in the $2^+ \rightarrow 0^+$ transition is taken from the $4^+ \rightarrow 2^+$ transition in ^{48}Ti . The solid curves in the delayed part are the results of a χ^2 fit with a constant plus exponential, where the constant takes care of insufficient background subtraction and small intrinsic timing tails of the Ge(Li) detector. From the four independent fits an average of

$$\tau(6_1^+ ^{46}\text{Ca}) = 15.2 \pm 0.8 \text{ ns}$$

has been deduced. The error includes both statistics and uncertainties in time calibration and background subtraction.

After completion of the present lifetime measurement⁸ we learned of another lifetime measurement⁷ of the same state with the reaction $^{48}\text{Ca}(p, p2n\gamma)^{46}\text{Ca}$. The result $\tau = 14.8 \pm 1.4$ ns is in excellent agreement with the present measurement.

III. ^{42}Ti 6_1^+ LIFETIME

The lifetime measurement for the 6_1^+ state in ^{42}Ti utilized a technique similar to that described in the previous section for ^{46}Ca . Two different reactions, $^{40}\text{Ca}(\alpha, 2n\gamma)^{42}\text{Ti}$ and $^{40}\text{Ca}(^3\text{He}, n\gamma)^{42}\text{Ti}$, were studied for the population of excited levels in ^{42}Ti . Excitation function with γ -ray singles spectra were measured during the bombardment of a natural Ca target (14-mg/cm² rolled metal foil) with α and ^3He particles in the energy range of $E_\alpha = 25$ –55 MeV and $E_{^3\text{He}} = 6$ –16 MeV, respectively. The reaction $^{40}\text{Ca}(\alpha, 2n\gamma)^{42}\text{Ti}$ was unsuccessful since γ lines^{9, 10} from ^{42}Ti were not observed in the γ -singles spectra with any significant intensity above the background. However, these γ lines were observed from the reaction $^{40}\text{Ca}(^3\text{He}, n\gamma)^{42}\text{Ti}$. From the excitation function measurement a beam energy of $E_{^3\text{He}} = 12$ MeV was chosen for the lifetime measurement.

Figure 4 shows the in-beam γ -ray spectrum measured during the bombardment of the Ca target with 12-MeV ^3He particles. The strongest lines in the spectrum originate from the reactions $^{40}\text{Ca}(^3\text{He}, p\gamma)^{42}\text{Sc}$ (with subsequent β decay to ^{42}Ca) and $^{40}\text{Ca}(^3\text{He}, 2p\gamma)^{41}\text{Ca}$. Recent information from the literature have been used to assign the transitions in ^{42}Sc (Ref. 11) and ^{41}Ca (Refs. 12 and 13). In addition to these nuclei there are several γ lines from the contaminant reaction $^{16}\text{O}(^3\text{He}, p\gamma)^{18}\text{F}$. Although they are relatively weak the 366-, 1120-, and 1555-keV γ rays, which have been previously assigned^{9, 10} to the decay cascade of the 3041-keV

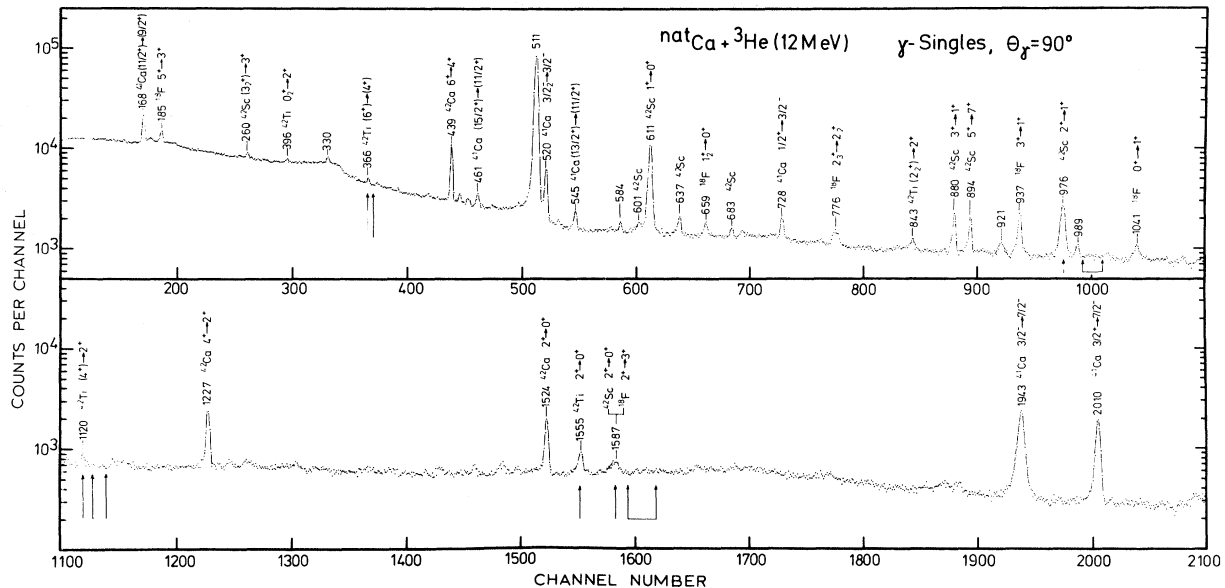


FIG. 4. In-beam γ -ray spectrum measured with a 32-cm³ Ge(Li) detector during the bombardment of a 14-mg/cm² thick metal Ca foil with 12-MeV ^3He particles. The assigned γ lines are from the reactions $^{40}\text{Ca}(\beta\text{He}, p\gamma)^{42}\text{Sc}$, $^{40}\text{Ca}(\beta\text{He}, 2p\gamma)^{41}\text{Ca}$, $^{40}\text{Ca}(\beta\text{He}, n\gamma)^{42}\text{Ti}$, and $^{16}\text{O}(\beta\text{He}, p\gamma)^{18}\text{F}$. The arrows in the γ -ray spectrum indicate the selected peaks and background regions to produce the time spectra shown in Fig. 5.

(6^+) state in ^{42}Ti (see Fig. 1) are also clearly observed. The spin sequence $6^+ \rightarrow 4^+ \rightarrow 2^+ \rightarrow 0^+$ is suggested by the comparison with other members of the $T=1$ triplet in ^{42}Sc and ^{42}Ca (Refs. 9 and 10). The Coulomb energy shift for these levels is in good agreement with the calculation of Bertsch.¹⁴ A recent distorted-wave Born-approximation (DWBA) analysis for the $^{40}\text{Ca}(\beta\text{He}, n)^{42}\text{Ti}$ reaction¹⁵ is consistent with an $L=6$ two-proton transfer to a state in ^{42}Ti at $E_x = 3.06 \pm 0.07$ MeV. A 6^+ assignment for the 3041-keV level is also supported by the results of the $^{40}\text{Ca}(^{12}\text{C}, ^{10}\text{Be})^{42}\text{Ti}$ two-proton transfer reaction experiment,¹⁶ in which a high-spin state was observed at 3.05 MeV. The observed absolute intensity of the 366-, 1120-, and 1555-keV γ rays in the present experiment was in the ratio 1 : 2 : 6.

Time spectra were taken for the three cascade transitions in ^{42}Ti as well as for several γ rays which were known to be prompt ($\tau < 1$ ps). The arrows in the spectrum shown in Fig. 4 indicate these γ rays as well as the regions near the peaks of interest which were used for background subtraction in the time spectra. In this experiment the subtraction of the background contribution in the time spectra is important since the peak to background ratio is small and several high energy γ rays (3201 and 3369 keV) from the competing reaction $^{40}\text{Ca}(\beta\text{He}, 2p\gamma)^{41}\text{Ca}$ are known to have delayed components with a mean lifetime of about 5 ns¹² and have Compton tails which extend down to the regions of interest. The normalization for

the background subtraction was obtained from the ratio of the summed counts in a flat delayed region of the time spectra (starting about 40 ns after the prompt peak) for the γ ray of interest and the respective γ -ray background region. The time spectra for the ^{42}Ti 1120- and 1555-keV γ rays and for the prompt ^{42}Sc 976-keV $2^+ \rightarrow 1^+$, ^{42}Sc 1587-keV $2^+ \rightarrow 0^+$, and ^{18}F 1587-keV $2^+ \rightarrow 3^+$ rays^{17, 18} are shown in Fig. 5. The natural beam burst width for the low energy ^3He beam was considerably worse compared to the 50-MeV α beam used in the ^{46}Ca measurement. This was probably due to instabilities of the rf, which was close to the lower limit available at the IPCR cyclotron. The total prompt time resolution which contains both contributions from the beam resolution and Ge(Li) detector resolution (pulse shape discrimination was not used) was about 6.3 ns. This prompt peak, see Fig. 5(c), is not pure Gaussian in shape due to the beam resolution.

A lifetime could not be extracted for the ^{42}Ti 366-keV transition due to the very small peak to background ratio and the lack of a prompt γ ray with a similar energy for comparison. The other two γ rays of ^{42}Ti show an exponential tail beyond that observed for the prompt γ rays. The solid curves in the delayed part are the results of a χ^2 fit with a constant plus exponential. The extracted lifetimes are due to delayed feeding of the 2675-keV level, since the 1120-keV γ ray has some prompt component. Thus, these lifetimes are attributed to the 3041-keV (6^+) level. Due to the

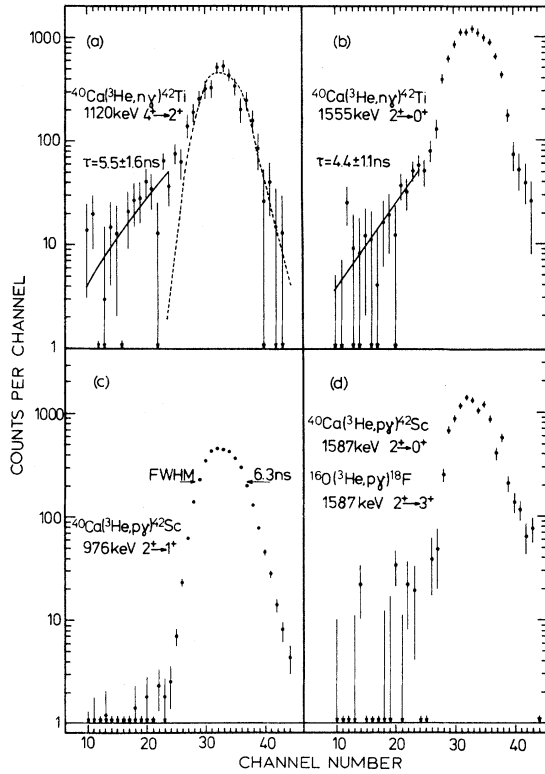


FIG. 5. Time spectra measured for relevant delayed and prompt γ -ray transitions from the spectrum shown in Fig. 4. Since the statistics were rather poor the two time distributions of each transition (compare Fig. 3) have been added. A normalized background time spectrum region has been subtracted from each spectrum. The extracted lifetimes are the result of a χ^2 fit with a constant plus exponential.

small peak to background ratios the extracted lifetimes are rather sensitive to the background subtraction, which resulted in an additional ± 1 -ns uncertainty of the fitted lifetimes. Therefore, the final value of the mean lifetime of the 3041-keV level is given by

$$\tau(6^+ \text{ } ^{42}\text{Ti}) = 5 \pm 2 \text{ ns.}$$

The present result is in disagreement with a previous measurement by Cox *et al.*,¹⁰ who report a lifetime of $\tau = 26 \pm 5$ ns. The result of Cox *et al.* was obtained with the $^{40}\text{Ca}(^3\text{He}, n\gamma)^{42}\text{Ti}$ reaction with an 8-MeV ^3He beam using time spectra obtained in an n - γ coincidence. The time spectrum of the 366-keV γ ray was analyzed assuming a prompt resolution estimated by the 1555-keV γ ray. If their prompt resolution was much energy dependent, an erroneous lifetime could have been obtained, which may explain the above disagreement. Another reported lifetime measurement which was attributed to the ^{42}Ti 6^+ level was later

found to originate from a transition (460 keV) in ^{41}Ca (Ref. 19).

IV. DISCUSSION

Table I summarizes the present experimental information on $E2$ -decay properties of the 2^+ , 4^+ , and 6^+ states in $(1f_{7/2})^{\pm 2}$ nuclei. In order to compare the experimental data on the basis of the effective charge concept the additional charge $\delta e = e_{\text{eff}} - 1$ for protons and $\delta e = e_{\text{eff}}$ for neutrons are given in the last column of Table I. The effective charge e_{eff} has been extracted from the experimental $B(E2)$ values with the assumption of pure $(1f_{7/2})^{\pm 2}$ configurations through the relation

$$B(E2, J \rightarrow J')_{\text{exp}} = S [J(f_{7/2}^2) - J'(f_{7/2}^2)] \times \frac{e_{\text{eff}}^2}{4\pi} |\langle f_{7/2} | r^2 | f_{7/2} \rangle|^2.$$

Here, the statistical factor S is given by 0.952, 0.950, and 0.433 for the $2^+ \rightarrow 0^+$, $4^+ \rightarrow 2^+$, and $6^+ \rightarrow 4^+$ transitions, respectively. The radial matrix element has been calculated from harmonic oscillator radial wave functions with the relation

$$\langle f_{7/2} | r^2 | f_{7/2} \rangle = \frac{9}{2} \frac{\hbar}{m\omega} = 4.55 A^{1/3} \text{ fm}^2$$

assuming $\hbar\omega = 41 A^{-1/3}$ MeV.

Due to the truncation of the shell model space to $(1f_{7/2})^{\pm 2}$ configurations, the additional charges in Table I exhibit the effect of three main contributions¹¹ to the effective $E2$ operator: (i) $\Delta N = 0$ particle excitations from the $1f_{7/2}$ orbital to other $1f$ - $2p$ orbitals. (ii) $\Delta N = 1$ two-particle excitations from $2s$ - $1d$ to $1f$ - $2p$ orbitals. (iii) $\Delta N = 2$ single-particle excitations from $2s$ - $1d$ to $3s$ - $2d$ - $1g$ and from $1p$ to $1f$ - $2p$ orbitals. Here, $N = 2(n-1) + l$ labels the major oscillator shells. There is considerable interest to extract the last ($\Delta N = 2$) contribution, usually referred to as the polarization charge, from the measured $B(E2)$ values, since a reliable value can give information about the isoscalar and isovector part of the effective $E2$ operator and its connection to the giant quadrupole resonance. To isolate the $\Delta N = 2$ core polarization one has to take into account explicitly the configuration admixtures of type (i) and (ii) in the calculation of the theoretical $B(E2)$ values. A detailed discussion of this procedure for several nuclei in the $1f_{7/2}$ shell can be found in the work of Brown *et al.*¹¹ In the following the consistency of the ^{42}Ti and ^{46}Ca effective charges will be discussed and compared with effective charges for other $1f_{7/2}$ nuclei.

A recent shell model calculation by Ogawa,²⁰ who used $(f_{7/2} p_{3/2})^2$ and $(f_{7/2} p_{3/2})^6$ neutron configurations for ^{42}Ca and ^{46}Ca and the effective

interactions from Federmann and Pittel²¹ results in a remarkably constant neutron effective charge for the $6^+ \rightarrow 4^+$ transitions. Using the same $\hbar\omega = 41A^{-1/3}$ MeV as in Table I for the radial matrix elements, one obtains $e_{\text{eff}}(6^+ \rightarrow 4^+) = (0.69 \pm 0.01)e$ and $(0.68 \pm 0.02)e$ for ^{42}Ca and ^{46}Ca , respectively. On the other hand, the effective charges for the $2^+ \rightarrow 0^+$ transitions using the $(f_{7/2}p_{3/2})^n$ wave functions²⁰ are $e_{\text{eff}}(2^+ \rightarrow 0^+) = (1.91 \pm 0.02)e$ and $(1.10 \pm 0.07)e$ for ^{42}Ca and ^{46}Ca , respectively, which indicates that other configurations of type (ii) involving core deformed components are more important in ^{42}Ca than in ^{46}Ca . Unfortunately, for a complete comparison between ^{42}Ca and ^{46}Ca , the experimental results on the 2^+ lifetime in ^{46}Ca are somewhat inconsistent and no measurement has been reported for the 4^+ lifetime. The inclusion of detailed wave functions involving $(fp)^2 + (sd)^{-2}(fp)^4$ configurations in ^{42}Ca by the procedure used by Flowers and Skouras²² reduces the extracted effective charges for the $2^+ \rightarrow 0^+$ transition.¹¹ However, these extended wave functions also reduce the ^{42}Ca $6^+ \rightarrow 4^+$ effective charge, which makes the comparison with ^{46}Ca worse and thus suggests that the procedure of Flowers and Skouras overestimates the deformed admixtures in the high-spin 4^+ or 6^+ states of ^{42}Ca . The effective charges for the ^{42}Ca and ^{46}Ca $6^+ \rightarrow 4^+$ transitions using the $(f_{7/2}p_{3/2})^n$ wave functions are also in good agreement with the analysis of Towsley, Cline, and Horoshko²³ for the $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ transitions in ^{42}Ca . By analyzing the $E2$ transitions for both the ground state band and the excited deformed band, they obtain $e_{\text{eff}} = 0.65 \pm 0.04e$.

Both the present and previous result for the ^{42}Ti (6_1^+) \rightarrow (4_1^+) transition, which are inconsistent with each other are given in Table I. Compared with other proton effective charges in Table I the negative additional charge needed to explain the previous ^{42}Ti lifetime measurement of $\tau = 26 \pm 5$ ns is anomalous. Also it would be very difficult to explain this anomaly using more refined wave functions. The effective charge needed for the present measurement ($\tau = 5 \pm 2$ ns) is more reasonable and will be discussed further.

With the $(f_{7/2}p_{3/2})^2$ shell model calculation of Ogawa the additional charge needed for the ^{42}Ti $6^+ \rightarrow 4^+$ transition (with the present lifetime result) is $\delta e = 0.36_{-0.20}^{+0.38}e$. This can be compared to a previous analysis of the $5^+ \rightarrow 7^+$ ^{42}Sc transition

probability with $(fp)^2$ wave functions in which an additional proton charge of $\delta e = -(0.04 \pm 0.16)e$ was needed.¹¹ Although the errors are large, the additional proton charge seems to be larger in ^{42}Ti than in ^{42}Sc . A possible explanation for this is that the radial wave functions are larger in ^{42}Ti than in ^{42}Sc due to the smaller relative binding energies of the ^{42}Ti states; the 6_1^+ state in ^{42}Ti is bound by only 0.5 MeV relative to ^{40}Ca . This indicates that in order to extract a reliable proton polarization charge for nuclei near ^{40}Ca it would be necessary to use more realistic single particle wave functions in cases with small binding energies.

It would be interesting to compare the present result for ^{42}Ti with the proton effective charges for ^{50}Ti and ^{54}Fe using $(fp)^n$ wave functions. However, the results of an exact $(fp)^n$ calculation for these nuclei is not available. This is not as simple as for the Ca isotopes, since one has to consider the excitation of both protons and neutrons in order to obtain wavefunctions of good isospin.²⁴

From the present data on $(1f_{7/2})^{+2}$ nuclei as discussed above we conclude that the independence of the effective charges on the number of valence particles (additivity) is well established from the $6^+ \rightarrow 4^+$ transitions in both $(\nu f_{7/2})^{+2}$ and $(\pi f_{7/2})^{+2}$ nuclei with the exception of ^{42}Ti . The extracted value $e_{\text{eff}} = 0.68e$ using $(f_{7/2}p_{3/2})^6$ wave functions²⁰ for the $6^+ \rightarrow 4^+$ transition in ^{46}Ca should be very near to the neutron polarization charge in this mass region. It is interesting to note that this value is close to the macroscopic estimate of Bohr and Mottelson²⁵ $e_{\text{pol}} = (Z/A - 0.32[(N-Z)/A] + \{0.32 - 0.32[(N-Z)/A]\} \times \tau_z)e$, which for ^{46}Ca leads to the value $e_{\text{pol}}(\text{neutron}) = 0.67e$. Any further conclusion concerning the proton polarization charge depends on a more precise measurement of the ^{42}Ti 6^+ lifetime and on theoretical calculations using more detailed wave functions for the $N=28$ isotones.

We should like to thank Dr. K. Ogawa for valuable theoretical discussions. B.A.B. and W.K. acknowledge a fellowship from the Japan Society for the Promotion of Science. Three of us (B.A.B., W.K., and G.D.S.) wish to express their gratitude to Professor A. Arima, Professor K. Nakai, Professor T. Yamazaki, and Dr. H. Kamitsubo for their great hospitality during the authors' stay in Japan.

*Present address: Physics Department, Technische Universität München, D-8046 Garching, Germany.

†Present address: State University of New York, Stony Brook, New York 11794.

‡Alfred P. Sloan Research Fellow and Visiting Scientist of NSF U.S.-Japan Program. On leave from State University of New York, Stony Brook, New York.

§Present address: Department de Physique Nucleaire,

- C.E.N. Saclay, 911-0 Gif-sur-Yvette, France.
- ¹T. Nomura, C. Gil, H. Saito, T. Yamazaki, and M. Ishihara, *Phys. Rev. Lett.* 25, 1342 (1970).
- ²G. Fortuna, Ph.D. thesis, University of Padova, Italy, 1973 (unpublished).
- ³S. A. Anderson, O. Hansen, L. Vistisen, R. Chapman, and S. Hinds, *Nucl. Phys.* A125, 65 (1969).
- ⁴W. W. Daehnick and R. Sherr, *Phys. Rev. C* 7, 150 (1973).
- ⁵G. M. Crawley, P. S. Miller, G. J. Igo, and J. Kulleck, *Phys. Rev. C* 8, 574 (1973).
- ⁶W. W. Daehnick and M. J. Spisak, *Phys. Rev. C* 7, 2593 (1973).
- ⁷P. G. Bizzeti, P. R. Maurenzig, G. Poggi, and G. Lo Bianco, *Nuovo Cimento Lett.* 12, 53 (1975).
- ⁸W. Kutschera, G. D. Sprouse, H. Ikezoe, Y. Yamazaki, and T. Nomura, in *Proceedings of the International Conference on Gamma-Ray Transition Probabilities, Delhi, 1974* (to be published).
- ⁹R. Hartmann, H. Grawe, and K. Kändler, *Nucl. Phys.* A203, 401 (1973).
- ¹⁰A. J. Cox, J. M. G. Caraca, B. Schlenk, R. D. Gill, and H. J. Rose, *Nucl. Phys.* A217, 400 (1973).
- ¹¹B. A. Brown, D. B. Fossan, J. M. McDonald, and K. A. Snover, *Phys. Rev. C* 9, 1033 (1974).
- ¹²P. Gorodetzky, J. J. Kolata, J. W. Olness, A. R. Poletti, and E. K. Warburton, *Phys. Rev. Lett.* 31, 1067 (1973).
- ¹³N. G. Alenius, Ö. Skeppstedt, and E. Wallander, *Nuovo Cimento Lett.* 11, 617 (1974).
- ¹⁴G. F. Bertsch, *Phys. Rev.* 174, 1313 (1968).
- ¹⁵W. P. Alford, R. A. Lindgren, D. Elmore, and R. N. Boyd, *Phys. Rev. C* 10, 1013 (1974).
- ¹⁶D. K. Scott, P. N. Hudson, P. S. Fisher, C. U. Cardinal, N. Anyas-Weiss, A. D. Panagiotou, P. J. Ellis, and B. Buck, *Phys. Rev. Lett.* 28, 1659 (1972).
- ¹⁷P. M. Endt and C. Van Der Leun, *Nucl. Phys.* A214, 1 (1973).
- ¹⁸F. Ajzenberg-Selove, *Nucl. Phys.* A166, 1 (1971).
- ¹⁹H. J. Kim *et al.*, *Bull. Am. Phys. Soc.* 17, 932 (1972).
- ²⁰K. Ogawa, Institute for Nuclear Study, Tokyo (private communication).
- ²¹P. Federmann and S. Pittel, *Nucl. Phys.* A155, 161 (1970).
- ²²B. H. Flowers and L. D. Skouras, *Nucl. Phys.* A136, 35 (1969).
- ²³C. W. Towsley, D. Cline, and R. N. Horoshko, *Nucl. Phys.* A204, 574 (1973).
- ²⁴E. Osnes, in *Proceedings of the Topical Conference on the Structure of $I_{f_{7/2}}$ Nuclei, Padova, 1971*, edited by R. A. Ricci (Editrice Compositore, Bologna, 1971), p. 79.
- ²⁵A. Bohr and B. Mottelson, *Nuclear Structure* (Benjamin, New York, to be published), Vol. II, Chap. 6.