surprising is that in spite of the short mean free path, it would appear that much structure in the Bragg intensities can still be associated with details of the three-dimensional elastic band structure (see Refs. 3, 25, and, for example, M. P. Seah, Surface Sci. 17, 181 (1969)].

[25]R. M. Stern, J. J. Perry, and D. S. Boudreaux, Rev. Mod. Phys. 41, 275 (1969).

[26]K. Moliere and H. Wagenfeld, Z. Kristallogr. 110, 175 (1958).

[27]G. Lehmpfuhl and A. Reiszland, Z. Naturforsch. 23A, 544 (1968).

[28]E. G. McRae, J. Chem. Phys. 46, 3258 (1966).

[29]D. S. Boudreaux and V. Heine, Surface Sci. 8, 426 (1967).

[30]K. Kambe, Surface Sci. 20, 213 (1970).

[31]C. B. Duke and C. W. Tucker, Jr., Phys. Rev. Lett. 23, 1163 (1969).

[32]E. G. McRae and C. Caldwell, Surface Sci. 7, 41 (1967).

[33]S. Andersson, Surface Sci. 19, 21 (1970).

[34]S. Miyake and K. Hayakawa, Acta Crystallogr. A26, 60 (1970).

[35]S. Friedman and R. M. Stern, Surface Sci. 17, 214 (1969).

[36]A true resonance is predicted only for s-wave scatterers. The fact that surface-wave–related diffraction effects are sharp indicates that the wave field propagating in the surface plane is less strongly damped than normal. Such surface reflections should also be extremely sensitive to surface conditions (the presence of adsorbed atoms, etc.).

$E2$ Effective Charges of the $f_{7/2}$ Proton and Neutron Deduced from the Lifetimes of the 6^+ States in ^{50}Ti, ^{54}Fe, and ^{42}Ca

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The half-lives of the lowest 6^+ states in ^{50}Ti, ^{54}Fe, and ^{42}Ca have been measured to be 0.41 ± 0.02, 1.24 ± 0.04, and 5.52 ± 0.15 nsec, respectively. The deduced polarization charges $\delta e_{\rm eff}$ are around $0.65e$ both for the $f_{7/2}$ proton and neutron.

In the present note we report on measurements of the $E2$ transition probabilities between the lowest 6^+ and 4^+ states in ^{50}Ti ($Z=20+2$, $N=28$), in ^{54}Fe ($Z=28-2$, $N=28$), and in ^{42}Ca ($Z=20$, $N=20+2$) in order to discuss the $E2$ core polarization in the $0f$-$1p$ shell region. The main configuration of the above states is expected to be $(f_{7/2}{}^2)\pi$, $(f_{7/2}{}^{-2})\pi$, and $(f_{7/2}{}^2)\nu$, respectively. We can, therefore, deduce $E2$ effective charges both for proton and for neutron in the $f_{7/2}$ orbital without much ambiguity of the wave functions of the states involved. The same procedure was applied to the ^{208}Pb region,[1] and it was found that the effective charge deduced from the $I\to I-2$ $E2$ transition probabilities between the two-particle states is nearly the same as that deduced from the static quadrupole moment of the relevant single-particle state. In the present case we cannot make such a comparison because of no measured quadrupole moment either in ^{49}Sc, in ^{55}Co, or in ^{41}Ca, but we believe that the effective charges thus deduced should be the most reliable ones to be compared with the microscopic calculations[2,3] or with the macroscopic estimate[4] and to be used for shell-model calculations.

The relevant level schemes presently known[5-7] are shown in the insets of Figs. 1 and 2. The lifetimes of the 3197-keV 6^+ level in ^{50}Ti and the 2948-keV 6^+ level in ^{54}Fe were measured by the delayed-coincidence method in the decay of 1.7-min ^{50}Sc and the 1.5-min isomer of ^{54}Co, respectively. ^{50}Sc was produced in the reaction ^{50}Ti(n, p)^{50}Sc with 14-MeV neutrons from the neutron generator of the Electrotechnical Laboratory, Tanashi Branch (at the early stage of this experiment the neutron generator of the University of Tokyo was also used), and both β and γ rays were detected with plastic scintillators coupled with model 56 AVP phototubes. The ^{54}Co isomer was produced in the reaction ^{54}Fe(p,n)^{54}Co with 15-MeV protons from the Institute for Nuclear Study synchrocyclotron, and a $1\frac{1}{2}\times1\frac{1}{2}$-in. NaI(Tl) and a plastic scintillator were used to detect γ rays and positrons, respectively. In both cases the time distribution was measured with a time-to-amplitude converter system. The detailed ex-

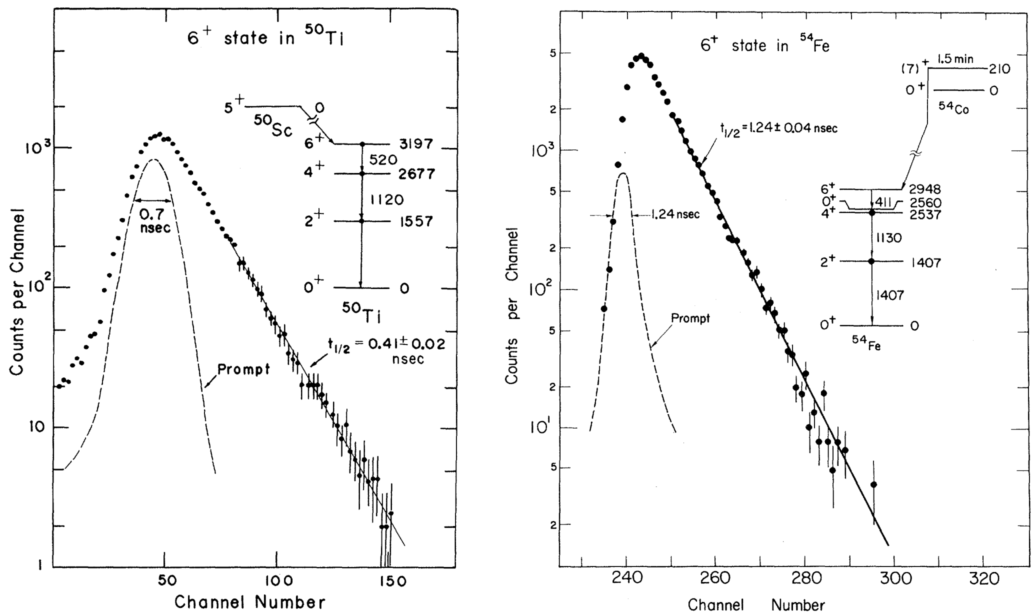

FIG. 1. β^--γ and β^+-γ delayed coincidence curves in the decay of the 1.7-min ^{50}Sc and the 1.5-min ^{54}Co isomer, respectively. The decay schemes from Refs. 5, 6, and 7 are also shown. The three γ rays in cascade showed the same time distribution, indicating that the 6^+ states have half-lives of 0.41 ± 0.02 nsec for ^{50}Ti and 1.28 ± 0.04 nsec for ^{54}Fe, respectively.

perimental procedure will be described elsewhere. The measured half lives are 0.41 ± 0.02 nsec for the 6^+ state in ^{50}Ti and 1.24 ± 0.04 nsec for that of ^{54}Fe (see Fig. 1).

The lifetime of the 6^+ state in ^{42}Ca has been recently reported by other authors,[8,9] but a large discrepancy still exists. In the present work the 6^+ state was excited by the reaction ^{40}Ca(α, 2p)^{42}Ca with 25-MeV α particles from the cyclotron at the Institute of Physical and Chemical Research, and the time analysis of the γ rays was carried out by using the natural beam bursts of a 132-nsec interval in the same way as described in Yamazaki and Ewan[10] [in the present case NaI(Tl) counter was used]. The half-life of the 6^+ state of ^{42}Ca has been determined to be 5.52 $\pm$0.15 nsec (see Fig. 2), which is in good agreement with the value obtained by Mendelson and Carpenter.[9]

The experimental $B(E2)$ values of the observed $6^+\to4^+$ transitions obtained are

$$^{50}\text{Ti}:\ (36.3\pm1.8)e^2\ \text{fm}^4,$$
$$^{54}\text{Fe}:\ (38.9\pm1.3)e^2\ \text{fm}^4,$$
$$^{42}\text{Ca}:\ (6.28\pm0.17)e^2\ \text{fm}^4.$$

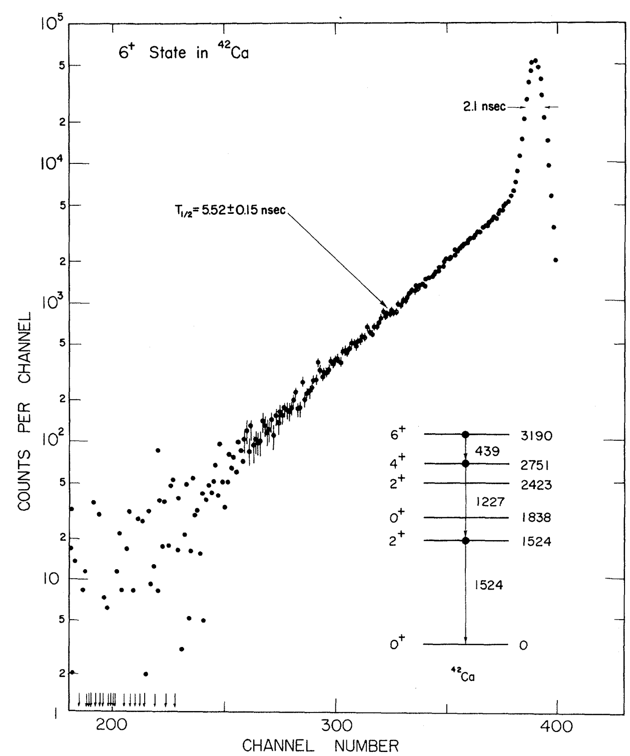

FIG. 2. A time distribution of the 439-keV $6^+\to4^+$ γ ray in the reaction ^{40}Ca(α, 2p)^{42}Ca at $E_\alpha = 25$ MeV, taken with a NaI(Tl) scintillator coupled with a model 56 AVP phototube in natural beam bursts of a 132 nsec interval from the Institute for Physical and Chemical Research cyclotron. The long-lived component from the decay of the 1-min ^{42}Sc has been subtracted. The prompt component is due to the Compton background from higher energy γ rays, indicating that the beam width (full width at half-maximum) is around 2 nsec.

The deduction of effective charges from $B(E2, 6^+ \to 4^+)$ requires good knowledge of the wave functions of the relevant states. The level structure of ^{42}Ca and ^{50}Ti has been studied by many authors,[11-18] and it is generally supported that both the 4^+ and 6^+ states in question are well described by two-particle configurations within the f-p shell. Although a considerably large admixture of deformed states such as 4-particle, 2-hole type is necessary to obtain overall agreement of energy spectra and transition rates in ^{42}Ca,[13,18] it was found that such a mixing to the 4^+ and 6^+ states brought too large $B(E2, 6^+ \to 4^+)$.[18] A question concerning consistent treatment of ^{42}Ca states still remains. In ^{50}Ti the mixing of the deformed states is expected to be very small because of blocking of core excitation due to the completely filled nature of the $0f_{7/2}$ neutron shell. To avoid complexity, therefore, we take the following two-particle configurations for the 4^+ and 6^+ states in ^{42}Ca as well as in ^{50}Ti:

$$|6^+\rangle = a|f_{7/2}^2\rangle + b|f_{7/2}f_{5/2}\rangle,$$

$$|4^+\rangle = a'|f_{7/2}^2\rangle + b'|f_{7/2}p_{3/2}\rangle + c'|f_{7/2}f_{5/2}\rangle + d'|f_{7/2}p_{1/2}\rangle.$$

Aside from the main contribution of the $(f_{7/2}^2)6^+ \to (f_{7/2}^2)4^+$ type, only one major correction to $B(E2)$ arises from the $f_{7/2}p_{3/2}$ configuration. We thus have

$$B(E2,\ 6^+ \to 4^+) \approx aa' \times 0.433(e_{\rm eff}^2/4\pi)|\langle f_{7/2}|r^2|f_{7/2}\rangle|^2[1-1.89(b'/a')(\langle p_{3/2}|r^2|f_{7/2}\rangle/\langle f_{7/2}|r^2|f_{7/2}\rangle)]^2,$$

where $e_{\rm eff}$ represents an effective charge, i.e., a true charge plus a polarization charge ($\delta e_{\rm eff}$).

Since in the case of ^{54}Fe many configurations are required and no reliable calculation is available, we do not attempt to deduce the effective charge using configuration mixing. We would like, however, to stress the excellent agreement of $B(E2,\ 6^+ \to 4^+)_{\rm exp}$ between ^{50}Ti and ^{54}Fe, as is predicted by the shell-model description with pure $f_{7/2}^2$ and $f_{7/2}^{-2}$ configurations. It seems to give strong support to our treatment of ^{50}Ti states.

In the above expressions we assume a common effective charge associated with both $f_{7/2}$ and $p_{3/2}$ orbitals (this assumption affects only the correction term in the brackets). Although mixing terms from neutron excitation are necessary for ^{50}Ti, we neglect it for simplicity. It may be justified because $e_{\rm eff}$ for the neutron is about two times smaller than that for the proton. The relevant radial integrals for ^{42}Ca are estimated to be

$$\langle f_{7/2}|r^2|f_{7/2}\rangle = 15.3 \text{ fm}^2$$

and

$$\langle p_{3/2}|r^2|f_{7/2}\rangle = -12.2 \text{ fm}^2$$

from the wave functions calculated by Kanestrøm and Koren[16] with the Woods-Saxon potential (WS). As to ^{50}Ti, no specific calculation is available, but we use the same radial integrals corrected by the $A^{1/3}$ dependence. We also used values calculated from the harmonic oscillator (HO) wave functions with $\nu = 0.96A^{-1/3}$ fm^{-2}.

Figure 3 summarizes the present results. The polarization charge, $\delta e_{\rm eff}$, is plotted versus the mixing amplitude of the $f_{7/2}p_{3/2}$ configuration. The values of the mixing amplitude (b') calculated by several authors[11,14,16,17] are also indicated (for consistency with our treatment we adopt only those determined without mixing of the deformed states). In ^{50}Ti Kuo and Brown have calculated b' to be 0.10, from which we obtain

$$\delta e_{\rm eff}(P) = 0.74 \text{ for WS},$$
$$= 0.62 \text{ for HO}.$$

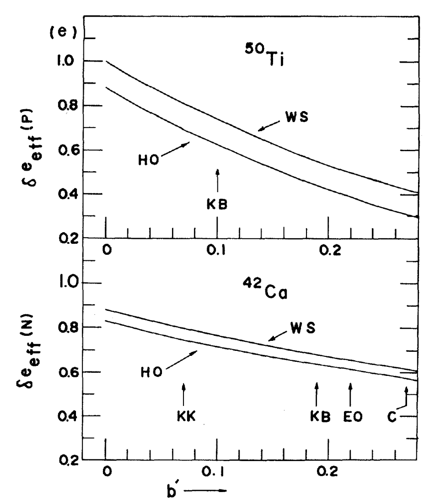

FIG. 3. The effective charge $\delta e_{\rm eff}$ versus the mixing amplitude b' of the $f_{7/2}p_{3/2}$ configuration for two different radial integrals calculated with the Woods-Saxon (WS) and the harmonic oscillator (HO) wave functions (see text). Values of the mixing amplitude calculated in Refs. 11, 14, 16, and 17 are indicated by arrows: EO (Ref. 11); KB (Ref. 14); KK (Ref. 16); and C (Ref. 17).

In the case of ^{42}Ca most of the calculated values of b' fall between 0.19 and 0.27, yielding

$$\delta e_{\rm eff}(N) = 0.69\text{-}0.63 \text{ for WS},$$
$$= 0.64\text{-}0.59 \text{ for HO}.$$

According to Bohr and Mottelson,[4] the polarization charge deduced here should be considered to originate not only from high-energy ($\sim 2\hbar\omega$) $E2$ excitations of the core but also from low-energy 0^+ (ground) $\rightarrow 2^+$ transitions. The latter part, being the surface oscillation of the core, is essentially isoscalar and may depend strongly on the core property. However, there seems not much difference between ^{40}Ca and ^{48}Ca, because the 0^+(gnd) $\rightarrow 2^+$(1st) excitation, which gives the largest contribution to $\delta e_{\rm eff}$, has almost the same energy and $B(E2)$, yielding $\delta e_{\rm eff} \approx 0.2e$ in both the nuclei.

The present analysis, therefore, leads to a remarkable fact that $\delta e_{\rm eff}$ from the former origin has nearly the same value for both the $f_{7/2}$ proton and neutron. In other words, if one expresses the polarization charge of high-energy origin by $\delta e_{\rm eff}$ (high-energy origin) $= e_{\rm eff}^{(0)} + e_{\rm eff}^{(1)} + e_{\rm eff}\tau_z$, where $\tau_z = +1$ for neutron and -1 for proton, then our experiment shows a very small isovector part $|e_{\rm eff}^{(1)}| \lesssim 0.05e$, while $e_{\rm eff}^{(0)} = 0.4\text{-}0.5$. This is contrary to the theoretical expectation[2-4] that an extra neutron excites core protons more strongly than an extra proton does due to the $T = 0$ component in the p-n interaction. The first-order perturbation calculation of Siegel and Zamick[3] showed that $e_{\rm eff}^{(1)} \sim 0.2e$. The macroscopic estimate of Bohr and Mottelson[4] gives also $e_{\rm eff}^{(1)} \approx 0.3e$.

The present experiment may infer that the $T = 0$ $E2$ giant resonance state might lie lower than the $T = 1$ state so that the former might play a leading role in the low-energy $E2$ transitions.[19] It is to be noted, however, that $\delta e_{\rm eff}(p)$ is rather sensitive to the choice of b'. Clearly, more information on this mixing amplitude is desired. It must be also of interest to deduce $\delta e_{\rm eff}(p)$ from reliable wave functions of the ^{54}Fe states.

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[1] T. Yamazaki, *Proceedings of the International School of Physics "Enrico Fermi," Varenna, 1967, Course XL,* edited by M. Jean and R. A. Ricci (Academic, New York, 1969), p. 791; M. Ishihara, Y. Gono, K. Ishii, M. Sakai, and T. Yamazaki, Phys. Rev. Lett. 21, 1814 (1968).

[2] H. Horie and A. Arima, Phys. Rev. 99, 778 (1955); H. Noya, A. Arima, and H. Horie, Progr. Theor. Phys., Suppl. 8, 33 (1958).

[3] S. Siegel and L. Zamick, Phys. Lett. 28B, 450 (1969), and Phys. Rev. 177, 1534 (1969).

[4] A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, 1969), Vol. I, and to be published.

[5] D. Wegener, Z. Phys. 198, 251 (1967).

[6] G. Chilosi, P. Guzzocrea, G. B. Vingiani, R. A. Ricci, and H. Morinaga, Nuovo Cimento 27, 86 (1963); C. Gil, unpublished.

[7] P. M. Endt and C. van der Leun, Nucl. Phys. A105, 1 (1967).

[8] R. Hartmann, K. P. Lieb, and H. Röpke, Nucl. Phys. A123, 437 (1969).

[9] R. A. Mendelson and R. T. Carpenter, Phys. Rev. 181, 1552 (1969).

[10] T. Yamazaki and G. T. Ewan, Phys. Lett. 24B, 278 (1967), and Nucl. Instrum. Methods 62, 101 (1968).

[11] T. Engeland and E. Osnes, Phys. Lett. 20, 424 (1966).

[12] P. Federman and I. Talmi, Phys. Lett. 22, 469 (1966).

[13] W. J. Gerace and A. M. Green, Nucl. Phys. A93, 110 (1967).

[14] T. T. S. Kuo and G. E. Brown, Nucl. Phys. A114, 241 (1969).

[15] H. W. Barz, K. Hehl, C. Riedel, and R. A. Broglia, Nucl. Phys. A126, 577 (1969).

[16] I. Kanestrøm and H. Koren, Nucl. Phys. A130, 527 (1969).

[17] D. M. Clement, Nucl. Phys. A132, 49 (1969).

[18] B. H. Flowers and L. D. Skouras, Nucl. Phys. A136, 353 (1969).

[19] S. Fallieros and R. A. Ferrell, Phys. Rev. 116, 660 (1959); Y. Suzuki and A. Arima, in Proceedings of the Symposium on Electron Scattering, Tokai, Japan, 1970 (to be published).