PHYSICAL REVIEW C VOLUME 13, NUMBER 2 FEBRUARY 1976

The $E0$-pair decay of the 0^+ second excited states in ^{42}Ca and ^{44}Ca

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(Received 28 August 1975)

The $E0$-pair decay branching ratio (Γ_π/Γ) for the 1.84-MeV (0^+) and 1.88-MeV (0^+) second excited states of ^{42}Ca and ^{44}Ca were measured. The states were excited by proton inelastic scattering. e^--e^+ pairs from the $E0$-decay were stopped in a carbon cylinder and the resulting annihilation radiation was detected in two NaI(Tl) detectors in triple coincidence with backscattered protons. The observed branching ratios are $(0.88\pm0.14)\times10^{-3}$ and $(2.05\pm0.17)\times10^{-2}$ for ^{44}Ca and ^{42}Ca, respectively, corresponding to monopole strengths of $\rho=0.30\pm0.10$ and $\rho=0.34\pm0.03$. These results are consistent with a theoretical description of these states which includes large admixtures of deformed state wave functions.

[NUCLEAR REACTIONS ^{42,44}Ca(p,p'), $E=4.40$ MeV; ^{42,44}Ca measured $E0$ branching ratio. Deduced $E0$ strength. Enriched targets.]

I. INTRODUCTION

The observed properties of the low-lying states of the calcium isotopes have led many authors[1-3] to a theoretical description which includes both core-excited deformed states and the usual shell model states. In particular for ^{42}Ca and ^{44}Ca, these interpretations predict significant proton particle-hole components in the wave functions of both ground and excited states. Such proton admixtures can, in these nuclei, lead to large monopole strengths for $0_2^+\to0_1^+$ transitions (Fig. 1); in the absence of proton core excitations, monopole transition strengths are identically zero. Previous measurements[4,5] in ^{42}Ca, although not in agreement with each other, show that the monopole strength is indeed large. Additional experimental evidence supports significant proton particle-hole components; the (t,p) cross sections to the 0_2^+ states in ^{42,44}Ca are small[6,7] and the $(d,{}^3\text{He})$ reaction on ^{44}Ca indicates that the $d_{3/2}$ proton orbits in the ground state of ^{44}Ca are only 50% occupied.[8]

The branching ratio for e^+-e^- pair decay has been remeasured for the 1.84-MeV (0^+) state of ^{42}Ca and measured for the 1.88-MeV (0^+) state of ^{44}Ca. The results are combined with lifetime measurements[10,11] to extract monopole matrix elements for comparison with model predictions and $E0$ decay rates in ^{40}Ca [18,19] and ^{48}Ca.[20]

II. EXPERIMENTAL PROCEDURE

A schematic diagram of the experimental arrangement and electronic configuration is shown in Fig. 2. The technique involved exciting levels by inelastic proton scattering and determining the fraction of pair decay by detecting the annihilation γ rays from decay positrons. Self-supporting 1-mg/cm^2 targets were prepared by evaporation of material enriched to 94% in either ^{42}Ca or ^{44}Ca and containing 5% ^{40}Ca and 1% ^{44}Ca or ^{42}Ca. The target was held in a carbon cylinder of sufficient size (8-mm radius by 25.4-mm length) to stop and annihilate pair decay positrons. The proton beam passed through a 6-mm-diam hole in the cylinder; protons scattered to a mean angle of 170° were detected in an annular surface barrier detector. A proton bombarding energy of 4.40 MeV, below the ^{44}Ca (p,n) ^{44}Sc threshold ($Q=-4.43$ MeV), provided sufficient excitation of the 0^+ states and eliminated background from the β^+ decay of ^{44}Sc. Two 12.7-cm-diam by 12.7-cm-long NaI(Tl) detectors were placed 20 cm from the target on opposite sides of the target chamber to observe the two 0.511-MeV γ rays from positron annihilation. A time-to-amplitude converter (TAC) was started by a timing signal from the proton counter and stopped by a signal derived from a fast overlap coincidence between the two γ-ray detectors. A resolving time of

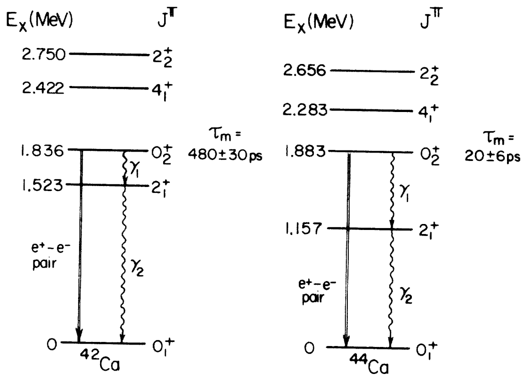

FIG. 1. Energy level diagrams of the low-lying states in ^{42}Ca and ^{44}Ca.

about 10 ns full width at half maximum and a true to random coincidence ratio of 100 : 1 was obtained. γ-ray and particle-energy spectra were gated by appropriate slow coincidence conditions and routed into separate memory subgroups of a Sigma-2 computer. Pair decay fractions were deduced either from particle spectra gated by annihilation radiation in the two NaI(Tl) detectors or from γ-ray spectra in one detector gated by 511-keV radiation in the other crystal and particles of appropriate energy. The observed positron yields were corrected for external pair production from the γ decay of the 2_1^+ states (see Fig. 1) by measuring the positron yields in coincidence with protons exciting those states. The positron detection efficiency was measured using a ^{90}Zr target and observing the pair decay of the 1.761-MeV 0^+ first excited state. Using the published[9] value for the ratio of internal conversion to pair decay $K/\pi = 2.38 \pm 0.08$, an efficiency of $(\epsilon\Omega)_\pi = (5.29 \pm 0.19)\times 10^{-3}$ was obtained, in good agreement with estimates based on detector geometry. Finally, the observed number of 0.511-MeV γ rays was corrected for randoms and Comptons from the γ-γ cascade.

III. RESULTS

Coincidence spectra with random coincidence events subtracted are shown in Fig. 3. The 0.726- and 1.157-MeV peaks in the ^{44}Ca spectrum and the 0.313-MeV peak in the ^{42}Ca spectrum for the 0^+ states arise from the real triple coincidences of the cascade γ transitions. The resulting numbers N_{511} were divided by the number of protons N_p feeding the 0_2^+ states, and these relative branching ratios were further divided by the absolute efficiency to give the branching ratios shown in Table I, i.e.,

$$B = \Gamma_\pi/\Gamma = [1/(\epsilon\Omega)_\pi](N_{511}/N_p).$$

An additional correction is necessary because of the 1% ^{42}Ca impurity present in the ^{44}Ca target. The protons populating the two 0^+ states in ^{44}Ca and ^{42}Ca are unresolved in the particle spectrum. Since both 0^+ states are equally strongly excited, a contribution of 2×10^{-4} to the branching ratio of ^{44}Ca due to the ^{42}Ca impurity can be calculated from the ^{42}Ca measurements. In the case of ^{42}Ca, a similar correction is approximately 10^{-5} and is negligible.

The pair decay rates may now be computed from these branching ratios and the previously measured[10,11] lifetimes and are shown in Table I. Church and Weneser[12] have shown that the pair decay rate can be written as

$$W_\pi = \Omega_\pi \rho^2,$$

where Ω_π is an electronic factor. The $E0$ strength ρ is given by $\rho = (1/R^2)\int \psi_f^* \sum_p r_p^2 \psi_i d^3r$, where the sum is over protons only. ψ_i and ψ_f are the initial and final nuclear wave functions, and R is the nuclear radius. The Ω_π were calculated using expressions given in Refs. 12–14, including finite nuclear size and Coulomb screening effects as suggested by Durand[15] and Bahcall.[16] Wilkinson[17] has proposed a single particle estimate for $E0$ moments $|M_\pi^{sp}| = 0.65A^{2/3}$ fm^2. In Table I the values for the $E0$ strengths are also expressed in terms of the Wilkinson unit and labeled ρ^{sp}.

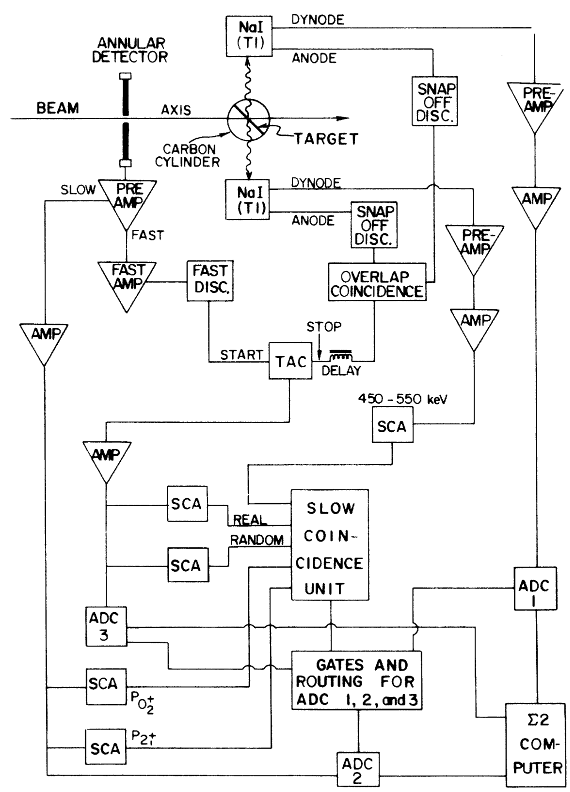

FIG. 2. A schematic diagram of the experimental arrangement and the electronic circuitry.

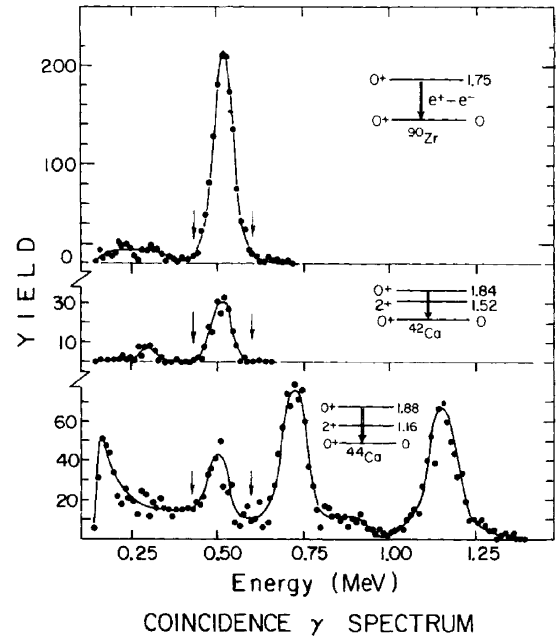

FIG. 3. Coincidence γ-ray spectra obtained from ^{44}Ca, ^{42}Ca, and ^{90}Zr.

IV. DISCUSSION

The experimental situation with regard to ^{42}Ca now appears to be well established. The ρ value given by Benczer-Koller, Nessin, and Kruse[4] was deduced from measurements of the ratio of pair to K conversion electrons (π/K) and of the ratio of cascade to crossover conversion electrons $\alpha_K(0.313\text{ MeV}, E2)/\alpha_K(1.836\text{ MeV}, E0)$ together with a theoretical value for $\alpha_K(0.313\text{ MeV}, E2)$. The large size of the ρ value is due mainly to the magnitude of the π/K ratio ($\pi/K = 9.0 \pm 1.8$) which is significantly larger than present theoretical estimates ($\pi/K = 6.9$). One possible explanation for the discrepancy in the experimental π/K ratio is that no correction was made for external pairs from the 1.523-MeV $2_1^+ \to 0_1^+$ transition. The more recent determination of Belyaev, Vasilenko, and Kaminker[5] takes into account external pairs. The present measurement is subject to fewer corrections since the partial decay width is directly measured and agrees well with the results of Belyaev *et al.*[5]

If the 0_1^+ and 0_2^+ states were pure two particle or four particle neutron states as they would be in the shell model, then ρ would vanish. ρ values comparable to those measured can only arise from significant core-excited proton components, since the operator $r_p{}^2$ in the definition of ρ is a one-body operator which operates exclusively on protons. Theoretical models for ^{42}Ca and ^{44}Ca have been proposed by Gerace and Green,[1] Flowers and Skouras,[2] Skouras,[3] and McCullen and Donahue.[11] These models all have the general form

$$\psi_{0_1^+} = \alpha|np\rangle + \beta|(n+2)\text{p-2h}\rangle_{\text{def}},$$

$$\psi_{0_1^+} = -\beta|np\rangle + \alpha|(n+2)\text{p-2h}\rangle_{\text{def}},$$

where $n = 2, 4$. The $|np\rangle$ component represents the 2 or 4 excess neutrons placed in the f-p shell, and the $|(n+2)\text{p-2h}\rangle_{\text{def}}$ component represents the same neutrons coupled to the 2p-2h proton core deformed state. In these models the evaluation of ρ reduces to

$$\rho = (1/R^2)\alpha\beta\langle r^2\rangle_{\text{def}} C,$$

where C is the Clebsch-Gordan coefficient which represents the proton fraction of the deformed component ($C = \frac{3}{4}$ for ^{42}Ca and $C = 0.68$ for ^{44}Ca). The results of calculations based on the various models are shown in Table I. In the case of ^{42}Ca, the model of Flowers and Skouras features a larger configuration space than that of Gerace and Green but gives no better agreement with experiment. The good agreement among all the various theoretical models and experiment is further evidence

TABLE I. Summary of the monopole pair decay branching ratios and monopole strengths (experimental and theoretical) for the 0^+ second excited states in ^{42}Ca and ^{44}Ca.

Nucleus	E_x (MeV)	τ_m (ps)	Ω_π (sec^{-1})	Γ_π/Γ	ρ (exp)	ρ^{sp} [a]	ρ (theory)
^{42}Ca	1.836	480 ± 30 [b]	3.75×10^8	$(2.05\pm0.17)10^{-2}$ [c]	0.34 ± 0.03 [c] 0.41 ± 0.04 [e] 0.282 ± 0.015 [g]	0.89 ± 0.09	0.32 [d] 0.24 [f]
^{44}Ca	1.883	20 ± 6 [h]	4.72×10^8	$(8.8\pm1.4)10^{-4}$	0.30 ± 0.10 [c]	0.78 ± 0.26	0.31 [i]

[a] ρ expressed in Wilkinson single particle units, Ref. 17.
[b] Reference 10.
[c] This work.
[d] Derived from Ref. 1.
[e] Reference 4.
[f] Derived from Ref. 2.
[g] Reference 5.
[h] Reference 11.
[i] Derived from Ref. 11.

for the necessity of mixing a low-lying deformed state with the usual shell model states.

The results of the present work can be combined with previous measurements of $E0$ strengths in ^{40}Ca [18,19] and ^{48}Ca [20] in order to illustrate the changes in the amount of proton core excitation which occur as neutrons are added to the $f_{7/2}$ shell. Although it is doubly magic, ^{40}Ca is well described by models which include proton excitations, and the $E0$ strength for $0_2^+ \to 0_1^+$ is $\rho = 0.16$. In ^{42,44}Ca the valence neutrons appear to break up the core even more and large ρ values are found (0.34 and 0.30). ^{48}Ca appears to be a good closed shell model nucleus and the $0_2^+ \to 0_1^+$ transition is indeed weak ($\rho = 0.08$).

We would like to thank Dr. P. Goode and Dr. L. Zamick for their assistance in the calculation of the ρ values. We would also like to thank R. Klein for preparing the targets.

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†Work supported in part by the National Science Foundation.

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