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Properties of the Low-Lying States of ^{48}Ca

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The energies, spins, decay modes, and lifetimes of the first three excited states of ^{48}Ca have been determined. The results are: 3.832 MeV (2^+), 0.053 ±0.024 psec; 4.284 MeV (0^+), 322 ±16 psec; and 4.507 MeV (3^-), $8.8^{+5.5}_{-2.8}$ psec.

In the shell-model sense, the nuclei ^{16}O, ^{40}Ca, and ^{48}Ca are doubly magic. In the case of ^{16}O and ^{40}Ca, one-particle–one-hole (1p-1h) states of positive parity involve promotion of particles across two or more subshells. Consequently, positive-parity multiparticle-multihole (np-nh) states lie below these 1p-1h states. The lowest positive parity levels of these nuclei exhibit collective characteristics and have been adequately described as combinations of 0p-0h and deformed 2p-2h, and as 4p-4h excitations.[1] Even negative-parity levels, which to first approximation can be 1p-1h states, exhibit decay properties which indicate the importance of collective effects.[2] An alternative description of ^{16}O,[3] involving a detailed microscopic shell-model calculation rather than a deformed basis description, successfully accounts for many of the observed properties and gives further indication of the np-nh nature of many of the states. Models[4,5] involving 1p-1h excitations in the $2s$-$1d$, $2p$-$1f$, and $1g_{9/2}$ shell-model configuration space have been applied to ^{48}Ca. The known spectrum of negative-parity levels can be successfully reproduced, but attempts to describe positive-parity levels in a like manner indicate, as in ^{16}O and ^{40}Ca, a more complicated structure.

The properties of excited states in ^{48}Ca have been investigated through (p,p'),[6] (α,α'),[7] (t,p),[8] and (e,e')[9] reactions. The inelastic α-particle and electron scattering work has determined $E2$ and $E3$ transition probabilities for the decay of the 2^+ and 3^- states to ground. Gorodetzky *et al.*[10] have measured the branching ratio of the 3^- state in a $(p,p'\gamma)$ experiment. This paper describes the results of $(p,p'\gamma)$ angular-correlation studies which unambiguously identify the spins of the 3.832- and 4.507-MeV levels as 2 and 3, respectively, and of Doppler-shift-attentuation measurements of the mean lifetimes of these states. In addition, the mean life of the 4.284-MeV state was measured by a delayed-coincidence technique; its spin and parity were assigned as 0^+ by the observation of an $E0$ pair decay to ground.

EXPERIMENTAL PROCEDURES

The levels of ^{48}Ca were excited via the (p,p') reaction at bombarding energies from 7 to 9 MeV. In all experiments, protons backscattered near 170° were detected in an annular surface-barrier detector. An 0.8-mg/cm^2 target of 97% enriched ^{48}Ca evaporated on a 10-μg/cm^2 carbon foil was used to obtain excitation functions to determine proton bombarding energies appropriate to maximum excitation of a given level. This target was also used for the angular-correlation and direct-timing experiments. A 2-mg/cm^2 self-supporting target was used for the Doppler-shift measurements. Details of the target chamber, counter geometry, and electronics have been published previously.[11]

The angular-correlation measurements were done in the standard method II geometry described by Litherland and Ferguson,[12] and were analyzed using the phase conventions of Rose and Brink.[13] γ rays in coincidence with backscattered particles were detected in a 3-in.-diam by 3-in.-long NaI(Tl) scintillation counter. For the Doppler-shift measurements, a 30-cm^3 coaxial Ge(Li) detector placed at 30 and 150° with respect to the beam was used to detect the γ rays. The formalism of Lindhard, Scharff, and Schiøtt for electronic and nuclear stopping powers[14] and of Blaugrund for large-angle scattering corrections[15] was used to extract the lifetimes from the measured Doppler shifts. An electronic slowing down time $\alpha = 1.65$ psec was extrapolated from experimental stopping-power data; this value is 20% smaller than the theoretical estimate.[14] Details of the technique have been presented by Bertin *et al.*[11]

In the delayed-coincidence measurement of the lifetime of the 4.284-MeV (0^+) level, a 1-in.-diam. by 1-in.-long NaI(Tl) crystal was used for γ-ray detection. The scintillator was mounted on an Amperex XP-1021 photomultiplier tube. The associated fast-electronics apparatus was identical to that used by MacDonald *et al.*[16] The 4.284-MeV state decays mainly to the 3.832-MeV (2^+) state which in turn decays to ground. As the latter transition is essentially prompt, a γ-ray-energy window covering the range 3 to 4 MeV was set, and time spectra were taken for protons populating the 0^+ state (delayed) and the 2^+ state (prompt). A full width at half maximum of typically 540 psec was obtained for the prompt-time distribution.

The branching ratio for the monopole pair decay of the 4.284-MeV (0^+) state was measured using, as a target holder, an aluminum cylinder of radius 8 mm with a 6-mm-diam. channel for beam transmission. Positrons from the monopole decay were stopped in the cylinder. The resulting annihilation radiation and other decay γ rays were detected in a 3-in. by 3-in. NaI(Tl) crystal in coincidence with back-scattered protons exciting the 0^+ state.

RESULTS

3.832-MeV Level

This level was excited at a proton bombarding energy of 7.60 MeV. The particle-γ angular correlation obtained at this energy results in an unambiguous assignment of spin 2 to the state. Ge(Li) γ-ray spectra, taken at 30 and 150°, yield a Doppler shift of (26.9 ± 0.8) keV for the 3.832-MeV γ ray. This shift corresponds to an attenuation factor $F(\tau) = 0.93 \pm 0.03$ and a mean lifetime $\tau = 53 \pm 24$ fsec. The error includes the statistical error in the measured Doppler shift and the effect of a possible ±15% uncertainty in the stopping-power expressions used to calculate the $F(\tau)$ curve.[11]

4.284-MeV Level

The 4.284-MeV level was observed to decay via a 451.9 ± 0.5-keV γ-ray transition to the 3.832-MeV (2^+) state and by internal pair creation to the ground state. The existence of the latter decay mode is the basis for an assignment of $J^\pi = 0^+$ to this level. Figure 1 shows γ-ray spectra obtained in coincidence with protons populating the 0^+ states at 4.284 and 3.353 MeV in ^{48}Ca and ^{40}Ca, respectively. The spectrum obtained from the latter state, which deexcites entirely by pair decay, was used to determine the positron detection efficiency for the target holder described above. The decomposition of the ^{48}Ca spectrum into peaks at 0.452 and 0.511 MeV is indicated in Fig. 1. The 0.511-MeV peak is due to both the internal pair decay of the 0^+ state and external pair formation from the high-energy γ ray of the dominant 4.284-MeV (0^+) → 3.832-MeV (2^+) → 0 (0^+) cascade decay. The contribution to the 0.511-MeV peak due to external pair formation was determined by accumulating a γ-ray spectrum in coincidence with protons exciting the 3.832-MeV state, normalized to the same number of 3.832-MeV γ rays as seen in the 4.284-MeV state decay. The $E0$ crossover decay was determined to be $(22.5 \pm 0.8)\%$. The mean lifetime of this level was extracted from the proton-γ-ray time spectra shown in Fig. 2; a mean life $\tau = 322 \pm 16$ psec was obtained from the slope of the delayed curve.

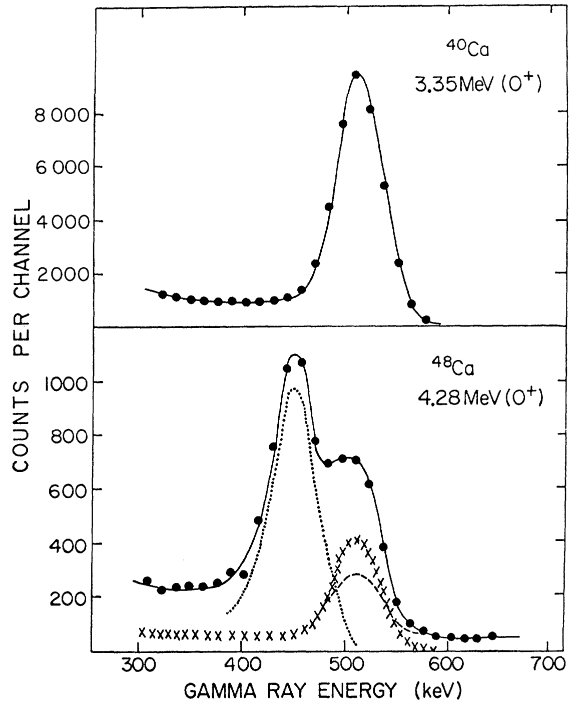

FIG. 1. Gamma-ray spectra in coincidence with protons inelastically scattered from 0^+ states of ^{40}Ca and ^{48}Ca. The dashed line is the contribution to the 0.511-MeV peak from external pair production of the 3.832-MeV cascade γ ray. The dotted curve shows the 0.452-MeV γ ray; the crossed curve represents the contribution to the 0.511-MeV peak from the internal pair decay of the 0^+ state.

4.507-MeV Level

This level decays $(27 \pm 2)\%$ via a crossover transition to the ground state and $(73 \pm 2)\%$ via a cascade 674.5 ± 0.4-keV γ-ray transition to the 3.832-MeV (2^+) state. A simultaneous fit to the three-particle γ-ray angular correlations results in an assignment of $J = 3$ to this level and a quadrupole/dipole mixing ratio $\delta = 0.00 \pm 0.03$ for the cascade transition. Measurement of the Doppler shift of the 0.675-MeV γ ray yields an attenuation factor $F(\tau)$

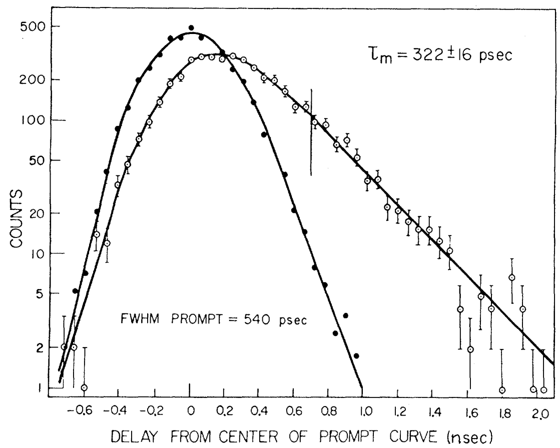

FIG. 2. Prompt and delayed time spectra as gated by protons exciting the 3.832-MeV (2^+) and 4.284-MeV (0^+) states, respectively.

$= 0.050 \pm 0.018$ corresponding to a mean life $\tau = 8.8^{+5.5}_{-2.8}$ psec.

DISCUSSION

Table I summarizes the spectroscopic information obtained for the first three excited states of ^{48}Ca. The spin assignments are in agreement with those from previous reaction studies[6-10] as are the present parity assignments which result from consideration of transition strengths. Positive parity is indicated for the 3.832- and 4.284-MeV levels as negative-parity assignments would result in unreasonably strong $M2$ transition strengths. Similarly, the 4.507-MeV level is assigned negative parity on the basis of the observed strength of the octopole ground-state transition.

Lifetimes of the 2^+ and 3^- states obtained in the present measurements show good agreement with those extracted from recent inelastic electron scattering experiments,[9] $|M|_{E2}{}^2 = 1.7 \pm 0.2$ Weisskopf units (W.u.) and $|M|_{E3}{}^2 = 6.8 \pm 1.0$ W.u. The present 4.507-MeV (3^-)→ 0 (0^+) transition strength is consistent with that obtained from inelastic α-particle[7] ($|M|_{E3}{}^2 = 8.0 \pm 1.2$ W.u.) and proton[6] ($|M|_{E3}{}^2 = 10.25$ W.u.) scattering data. However, the present 3.832-MeV (2^+)→ 0 (0^+) transition strength is in marked disagreement with that extracted from the (α, α')[7] ($|M|_{E2}{}^2 = 4.9 \pm 0.8$ W.u.) and (p,p')[6] ($|M|_{E2}{}^2 = 7.7$ W.u.) data. Similar discrepancies exist for transitions in ^{40}Ca[15] and ^{58}Ni.[10] The decay mode of the 4.507-MeV (3^-) state obtained in the present experiment (the table) is in only fair agreement with previously published work which gave crossover decays of 15%[10] and 20%.[6] The discrepancy may well be due to angular-distribution effects in the previous work.

The 3.832-MeV (2_1^+)→ 0-MeV (0^+) transition strength is compatible with essentially a 1p-1h description of the 2_1^+ state. It further appears that neither the $E1$ nor the $E3$ decay of the 4.507-MeV (3^-) state provide much insight as to the structure of these states, as their decay strengths are compatible with a number of models. Indeed, Jaffrin and Ripka,[4] assuming a closed-shell core for ^{48}Ca in which pairing correlations play a small role, have calculated $E3$ transition probabilities with various models (Tamm-Dancoff and random-phase approximations and restricted configuration space) and for different forces. They obtain reduced $E3$ transition rates between 4.5 and 9.75 W.u., in fairly good agreement with experiment. Blomqvist and Kuo[5] have also calculated the energies and transition probabilities of odd-parity states in ^{40}Ca and ^{48}Ca, using the Hamada-Johnston interaction with and without the inclusion of core polarization. They find that core-deformation components are essential to predict the ^{40}Ca experimental level energies, but are not as crucial for agreement with the ^{48}Ca low-lying states.

The decay of the 4.284-MeV (0_1^+) state, however, seems more interesting. The $E2$ decay strength to the 2_1^+ state implies reasonable overlap of wave-function components for the two states, whereas the monopole pair decay to ground is relatively weak. The monopole "strength parameter" ρ[17] is smaller in ^{48}Ca ($\rho = 0.084$) than in ^{40}Ca ($\rho = 0.16$), and both are much smaller than in ^{42}Ca ($\rho = 0.41$). The wave function of the 0^+ state involves at least two-particle–two-hole excitations. Thus, the 0^+-state decay mode may indicate mixing of n-particle–n-hole amplitudes in wave functions of the low-lying levels.

TABLE I. Summary of the spectroscopic data for the first three excited states of ^{48}Ca. The uncertainty in excitation energy is 2 keV in each case.

Level energy (MeV)	J^π	Decay mode %	To	τ_m (psec)	σL	$\lvert M \rvert^2$ (W. u.)
3.832	2^+	100	0	0.053 ± 0.024	$E2$	1.8 ± 0.8
4.284	0^+	77.5 ± 0.81	3.832	322 ± 16	$E2$	9.8 ± 0.5
		22.5 ± 0.8	0		$E0$	$(\rho = 0.084)$
4.507	3^-	73 ± 2	3.832	$8.8^{+5.5}_{-2.8}$	$E1$	$(2.0^{+1.2}_{-0.6}) \times 10^{-4}$
		27 ± 2	0		$E3$	$10.1^{+6.3}_{-3.3}$

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Effect of Dynamical Deformation in Elastic Electron Scattering on the Charge Distributions of the Calcium Isotopes

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The presence of dynamical deformations in the ground-state charge distributions of the calcium isotopes provides a basis for understanding two well-known but very different effects observed in elastic electron scattering from these isotopes.

The first, seen at low momentum transfer, is the anomalous isotope dependence of the nuclear charge radius. It is shown that there is a deformation-dependent contribution to the rms radius, whose magnitude can be obtained from inelastic electron and α-particle scattering via a sum rule and which leads to a prediction of the isotopic dependence in substantial agreement with experiment.

The second observed effect, visible at high momentum transfer, is the appearance of oscillations in the ^{40}Ca and ^{48}Ca charge distributions, as revealed by fits to the elastic electron scattering data at 750 MeV. It is shown that an additional contribution of dynamical deformations to monopole elastic electron scattering, observable only at high momentum transfer, may be interpreted as due to an effective spherically symmetric "modulating charge" distribution superimposed upon the smoothly varying distribution obtained at lower energies. This modulating charge is calculated explicitly and exhibits an oscillatory behavior.

I. INTRODUCTION

In a previous paper[1] we developed a general phenomenological theory for the calculation of both elastic and inelastic transverse and longitudinal form factors for electron scattering from deformed nulcei. It is our purpose in this paper to concentrate on the effect of the presence of dynamical deformations on the Coulomb elastic monopole form factor, and the resultant consequences for