1^+ state in ^{44}Ca

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A 1^+ level at 5210 keV was observed in ^{44}Ca, using the (γ,γ') reaction. The measured $M1$ strength to the ground state was found to be small, $B(M1)\uparrow = 0.15 \pm 0.06\ \mu_N^2$, indicating that the $M1$ strength is probably spread over a wide excitation energy range. In addition, a mixed $E2$-$M1$ transition to an excited state was observed, and its $B(E2)\downarrow$ was determined to be $4.2 \pm 0.8\ e^2\,\mathrm{fm}^2$.

The current considerable interest in magnetic dipole excitations, both experimentally and theoretically, has yielded an extensive search for the location and strength of transitions from ground to $J = 1^+$ excited states in the Ca isotopes.[1–6] McGrory and Wildenthal[2] performed a calculation in a full fp-shell model space and predicted the $M1$ strength in ^{42,44,46,48}Ca isotopes to be located in the excitation energy region 10–11 MeV with total $\Sigma B(M1)$ varying from 1.86 μ_N^2 for ^{42}Ca to 8.96 μ_N^2 for ^{48}Ca. Experimentally, the $M1$ strength for ^{42,48}Ca isotopes was found to be located in the above predicted energy region in a single state and the $B(M1)$ strength was observed to be quenched by a factor of about 3 with respect to the theoretical predictions. No conclusive evidence for 1^+ states was found in ^{44}Ca (Refs. 1 and 5) in the excitation energy range 8–12 MeV. By applying the shell model for studying the level structure of ^{44}Ca allowing the four valence neutrons to populate the single particle orbitals $0f_{7/2}$, $0f_{5/2}$, $1p_{3/2}$, $1p_{1/2}$, it was shown[7,8] that 1^+ levels are expected in this isotope at an excitation energy of 4–5 MeV.

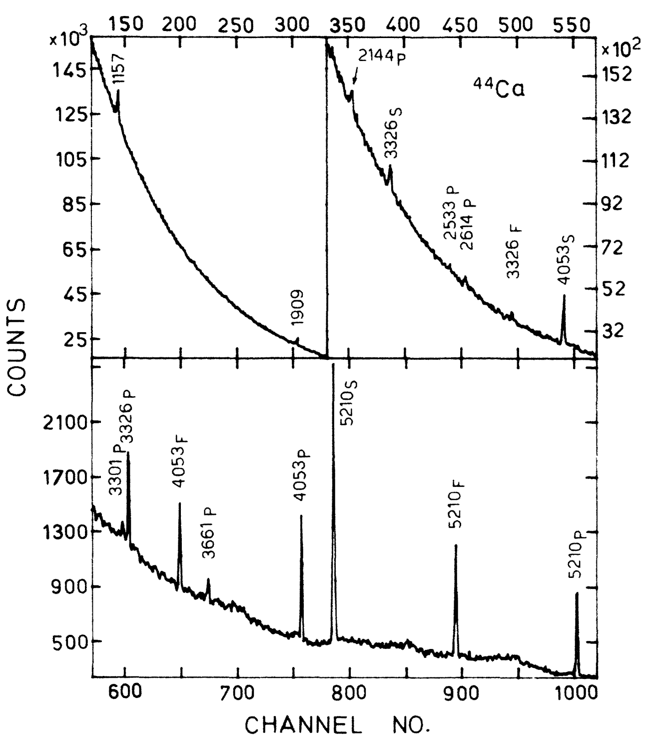

FIG. 1. The scattered spectrum from a ^{44}Ca target at 120° as measured with a 40 cm^3 Ge(Li) detector.

In the present work we report the observation of a 1^+ level in ^{44}Ca located at 5.21 MeV. Experimentally, we used the technique of random photoexcitation of nuclear levels via neutron capture gamma rays.[9,10]

The gamma source was obtained from the V(n,γ) reaction yielding monoenergetic photons in the energy range 4–7 MeV. The target consists of natural Ca, 4.86 g/cm^2 thick. The scattered photon spectrum was measured with a 40 cm^3 Ge(Li) detector. Figure 1 shows the scattered radiation spectrum from the Ca target obtained at 120° with respect to the photon beam direction. The spectrum contains a strong elastic gamma line at 5210 keV. All the other gamma lines (except the 3661 keV line) were identified to correspond to primary and secondary inelastic transitions from the 5210 keV level to low lying levels in ^{44}Ca. By considering the gamma line energies given in

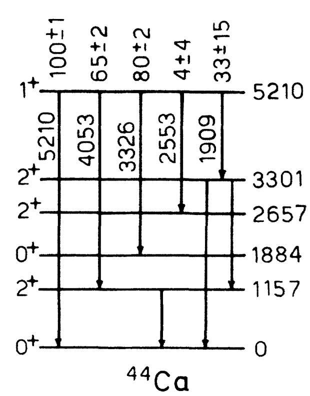

FIG. 2. Decay scheme of the 5210 keV resonance level in ^{44}Ca, showing the relative intensities for deexcitation to low lying levels.

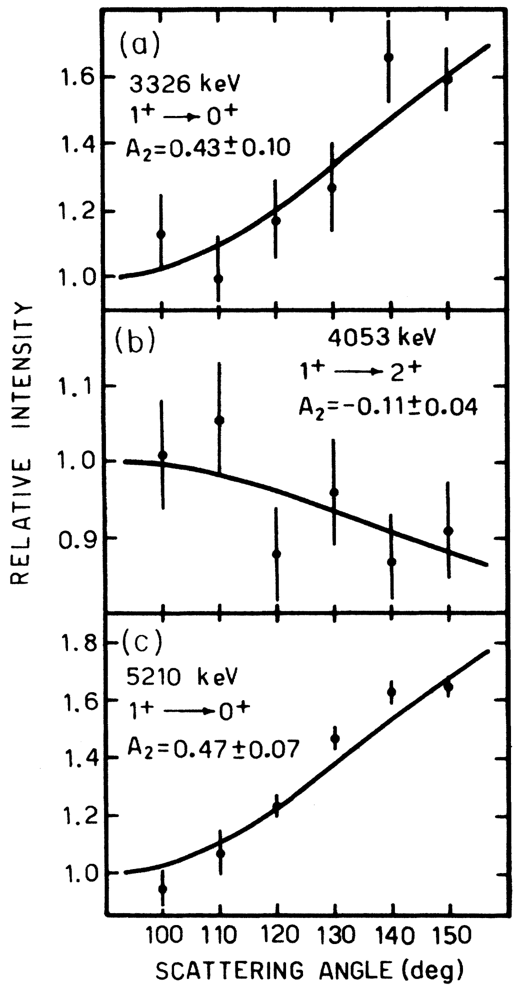

FIG. 3. Angular distributions of the elastic and some inelastic transitions deexciting the 5210 keV level in ^{44}Ca. The solid lines have the form $W(\theta)=1+A_2P_2(\cos\theta)$ and are least-square fits to the experimental data.

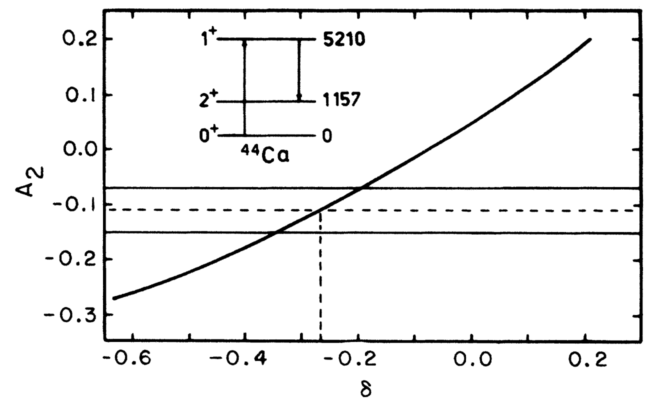

FIG. 4. A plot of the angular distribution coefficient A_2 as a function of the mixing amplitude δ for the spin sequence 0(1)1(1,2)2.

Fig. 1 in conjunction with known low lying levels of ^{44}Ca,[11] the decay scheme of the 5210 keV resonance level was constructed as shown in Fig. 2. The spin and parity of the resonance level were determined by measuring: (1) angular distributions of the elastic and inelastic transitions, and (2) the polarization of the elastically scattered photons using a Compton polarimeter.[12] Figure 3 shows the angular distributions of the 5210, 4053, and 3325 keV transitions that were measured at six angles between 100° and 150°. The A_2 coefficients were extracted by fitting the experimental results to the function $W(\theta)=1+A_2P_2(\cos\theta)$. Table I summarizes the experimental results concerning the angular distributions and polarization measurements. The A_2 values measured for the 5210 and 3326 keV transitions assign the spin $J=1$ for the 5210 keV level. The result of the polarization measurement was $N_{\parallel}/N_{\perp}=0.84\pm0.13$, where $N_{\parallel}$ and $N_{\perp}$ are the number of Compton gamma rays scattered in the resonance scattering plane and perpendicular to it, respectively. It indicates that the 5210 keV transition is $M1$, implying that the parity of the 5210 keV level is positive. The measured value $A_2=-0.11$ for the 4053 keV transition from the 1^+ resonance level to the 2^+ level indicates that this transition has a mixed multipolarity $E2/M1$. The mixing amplitude δ was deduced as shown in Fig. 4, yielding the value $\delta=-0.27\pm0.08$.

The radiative width of the 5210 keV level was determined by measuring: (1) the absolute elastic scattering cross section σ_r, (2) the ratio R_T of the scattering cross section at $T=78$ °K and $T=293$ °K, (3) the nuclear self-absorption ratio R, and (4) the ground state branching ratio Γ_0/Γ. The results are given in Table II. Details of such measurements were published elsewhere.[9,10]

The $M1$ strength for the transition from the ground state to the 5210 keV level was obtained from the results

TABLE I. Measured angular distribution coefficients A_2, the ratio $N_{\parallel}/N_{\perp}$, the multipolarities, and mixing amplitude of the transitions from the 5210 keV resonance level to the g.s. and low lying excited states in ^{44}Ca.

Transition (keV)	Spin sequence	A_2	$N_{\parallel}/N_{\perp}$	Multipolarity	Mixing amplitude δ
5210	$1^+\text{-}0^+_{\text{g.s.}}$	0.47±0.07	0.84±0.13	$M1$	
4053	$1^+\text{-}2^+_1$	−0.11±0.04		$E2/M1$	−0.27±0.08
3326	$1^+\text{-}0^+_1$	0.43±0.10		$M1$	

TABLE II. Measured values of the temperature variation ratio R_T, the self-absorption ratio R, the scattering cross section σ_r, the branching ratio Γ_0/Γ, and the total width Γ of the 1^+ 5210 keV level in ^{44}Ca.

R_T	R	σ_r (mb)	Γ_0/Γ	Γ (meV)	Γ_0 (meV)
1.10±0.07	0.014±0.006	606±240	0.35±0.04	228±40	80±30

given in Table II. The value is $B(M1)\uparrow = 0.15 \pm 0.06\ \mu_N^2$. This value for the $M1$ strength in ^{44}Ca is small compared to the experimental $M1$ strength in ^{42}Ca and ^{48}Ca (0.59 μ_N^2, 4.0 μ_N^2, respectively[1]) and to the predicted value of McGrory *et al.*[2] for ^{44}Ca.

The 5210 keV level is at a much lower excitation energy than observed and predicted by Refs. 1 and 2, but within reasonable agreement with the shell model calculations of Fu *et al.*,[7] and Federman and Pittel.[8] The relatively low value of $B(M1)$ strongly indicates that the $M1$ strength in ^{44}Ca is highly fragmented and spread over a wide energy excitation range, as also suggested by Richter.[5]

From the measured mixing amplitude of the 4053 keV transition, the $E2$ width obtained was $\Gamma = 3.8$ meV, which corresponds to $B(E2)\downarrow = 4.2 \pm 0.8\ e^2\ \text{fm}^2$ where $B(E2)\downarrow$ is given by[13]

$$B(E2)\downarrow = 1.22 \times 10^6 \Gamma(E2)/E^5 \ .$$

This $B(E2)\downarrow$ value is very close to the average over 11 $E2$ ground state transitions from levels in the excitation region 3.9–10 MeV observed in the neighboring ^{40}Ca isotope.[14] This average value was found to be 5.8 e^2 fm^2. It is also of interest to note that this $E2$ transition has $k_{E2} = (4.5 \pm 0.8) \times 10^{-14}$ MeV^{-5}, where k_{E2} is defined by

$$k_{E2} = \Gamma(E2)/(E^5 \times D \times A^{4/3}) \ .$$

We used $D = 0.5$ MeV for the spacing between 1^+ levels at 5 MeV excitation energy. This value was extracted from the table given by Lynn[15] and corrected for excitation energy and spin dependence using the relation of Maruyama,[16] with a level density parameter $a = 11$ MeV^{-1}. The k_{E2} value is very close to k_{E2}'s reported in a previous work[10] for ^{141}Pr and ^{205}Tl, and from (n,γ) experiments in Er, Gd, Pd, and Ho.[17] This fact indicates independence of high energy (5–8 MeV) $E2$ transition strength on mass number.

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