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MEASUREMENT OF THE MEAN LIFE OF THE 4.49-MeV (5^-) STATE OF ^{40}Ca. EFFECTS OF DEFORMED COMPONENTS ON THE LIFETIMES OF THE ODD-PARITY STATES

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We have measured a mean life of 392 ± 12 psec for the 4.49-MeV (5^-) state of ^{40}Ca, corresponding to an $E2$ transition strength of 1.04 ± 0.03 Weisskopf units which is considerably stronger than that predicted by a one-particle, one-hole description of the states. However, this $E2$ decay rate and those of eight other $E2$ transitions between odd-parity states can be understood when the states are described as admixtures of deformed and spherical wave functions.

The low-lying negative-parity states of ^{40}Ca are described by Gerace and Green[1] as combinations of random phase approximation (RPA) states and three-particle, three-hole (3p-3h) deformed states. In particular, the 3.74- (3_1^-) and 4.49-MeV (5_1^-) states are described as largely RPA states, each having of the order of 5% 3p-3h deformed component. Other authors[2,3] describe the odd-parity spectrum as RPA states and obtain good agreement (as do Gerace and Green) for $E3$ and $E5$ transition rates of the 3_1^- and 5_1^- states to the ground state. These rates are not sensitive to the deformed component of the excited-state wave functions. However, small admixtures of deformed-state components may contribute significantly to transition rates between excited negative-parity levels. This Letter reports the measurement of the lifetime of the 4.49-MeV (5_1^-) state, the decay of which reflects deformed-state admixtures.

The lifetime of the 4.49-MeV (5_1^-) state was measured by exciting the state via the $(p, p'\gamma)$ reaction at a bombarding energy of 7.73 MeV and recording particle-gamma delayed-coincidence time spectra. Protons were detected by a 300-μ depletion depth annular surface-barrier detector subtending an average angle $\langle\theta\rangle = 170°$ with respect to the beam. Gamma rays were detected at 45° with respect to the beam in a 1-in.-diam by 1-in.-long NaI(Tl) crystal mounted on an Amperex XP-1021 photomultiplier. Signals from the particle detector were sent into a fast voltage preamplifier,[4] as well as into a slow charge-sensitive preamplifier. The fast particle signal and the anode pulse from the photomultiplier were sent into fast discriminators which provided input timing signals for a time-to-amplitude converter (TAC). TAC spectra, gated by particles and gamma rays of selected energy, were recorded in 1024-channel memory subgroups of the Rutgers-Bell SDS-910 on-line computer.

The 4.49-MeV (5_1^-) state decays 100% via a 0.75-MeV gamma ray to the 3.74-MeV (3_1^-) state which in turn decays to ground. The mean life of the 3_1^- state, 85 ± 21 psec,[5] is short enough to allow a determination of the lifetime of the 5_1^- state by observing only the 3.74-MeV high-energy gamma ray of the cascade $5_1^- \rightarrow 3_1^- \rightarrow 0$. This technique enables "prompt" and "delayed" time spectra to be accumulated concurrently and with the same gamma-ray energy window by gating the TAC spectrum with the inelastic protons exciting both the 3_1^- ("prompt") and the 5_1^- ("delayed") states. It further results in better time resolution than could be obtained by observing the 0.75-MeV gamma ray directly.

Figure 1 shows time spectra gated by protons exciting the 5_1^- and 3_1^- levels. In both cases, the gamma-ray energy windows covered a range from 3.0 to 4.0 MeV. The width of the "prompt" time peak is 460 psec and was observed to be only slightly broader than a similar time spectrum obtained by gating the TAC spectrum with protons from the 3.90-MeV (2^+) state, which is truly prompt. Analysis of the slope of the 5_1^- delayed-coincidence curve yields a mean life $\tau = 392 \pm 12$ psec. The portion of the decay curve from which the slope was extracted is indicated on Fig. 1 and was chosen to eliminate effects due to the finite system time resolution and the finite lifetime of the 3_1^- intermediate state. The observed lifetime corresponds to a transition strength $|M|^2 = 1.04 \pm 0.03$ Weisskopf units or

$$B(E2; 5_1^- \rightarrow 3_1^-) = (8.4 \pm 0.3)e^2\ \mathrm{fm}^4.$$

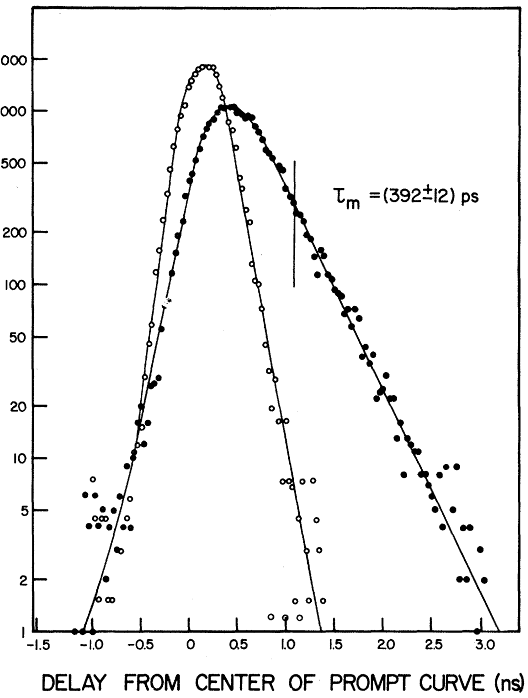

FIG. 1. Proton-gamma time coincidence spectra gated by protons exciting the 5_1^- ("delayed") and the 3_1^- ("prompt") levels and gamma rays in the range of 3.0 to 4.0 MeV.

Dieperink, Leenhouts, and Brussaard,[2] using RPA wave function, have calculated a 5_1^- state lifetime of 19 nsec. The mean life was recalculated using the vave functions of Ref. 2, an effective charge[6] $e_n + e_p = 2e$, and a value of oscillator parameter chosen to fit the size of ^{40}Ca, $(m\omega/h)^{1/2} = 0.498$. Table I shows the result of this calculation together with those obtained with the RPA wave functions of Gerace and Green[1] and Gillet and Sanderson[3] and the same effective charge. In addition, the lifetime has been calculated by assuming that the 5_1^- and 3_1^- states are simply a $(d_{3/2}^{-1}, f_{7/2})$ p-h configuration. In all lifetime calculations experimental level energies were used. The calculations fail to reproduce the observed transition strength. A recent calculation by Poletti et al.,[7] who consider these states as simple $(d_{3/2}^{-1}, f_{7/2})$ configurations and include an effective charge of $e_n + e_p = 2e$, underestimates the $5_1^- \rightarrow 3_1^-$ transition strength by a factor of 3. None of these calculations includes deformed-state admixtures in the wave functions of the states.

Table I. Comparison of experimental and theoretical strengths of the $5_1^- \to 3_1^-$ transition in ^{40}Ca.[a]

Lifetime (nsec)	$B(E2; 5_1^- \to 3_1^-)$ (e^2 fm^4)	Reference
0.392 ± 0.012	8.4 ± 0.3	Present experiment
0.62 ± 0.14	5.5 ± 1.4	Present calculation
2.0	1.7	Dieperink, Leenhouts, and Brussaard[a]
15	0.23	Gillet and Sanderson[b]
1.1	3.1	Gerace and Green[c]
1.4	2.6	$(d_{3/2}^{-1}, f_{7/2})$
1.1	3.1	Poletti et al.[d]

[a] Ref. 2. Recalculated, as discussed in the text.
[b] Ref. 3.
[c] Ref. 1.
[d] Ref. 6.

Gerace and Green[1] do not calculate the deformed-component contribution to the $5_1^- \to 3_1^-$ transition rate. In their model, these states possess 4.7 and 6.8% 3p-3h deformed component, respectively; the largest amount of 3^- deformed component (56%) is found in the wave function of the 6.28-MeV (3_2^-) state. This state decays to the 5_1^- state via a strong E_2 transition. A weighted average of recent lifetime and branching-ratio measurements[7-10] yields $B(E2; 3_2^- \to 5_1^-) = (72 \pm 18)e^2$ fm^4. In the SU(3) limit, Gerace and Green[1] calculate a $B(E2)$ for this transition of (80 to 89)e^2 fm^4, which is in good agreement with the observed value. However, Dieperink, Leenhouts, and Brussard,[2] considering these as pure RPA states, predict a $3_2^- \to 5_1^-$ rate which is an order of magnitude too low. The $E2$ decay scheme of the low-lying odd-parity states can be explained with a combination of spherical (utilizing an effective charge[6]) and deformed mechanisms.[11] In particular, the $3_2^- \to 5_1^-$ decay rate was calculated assuming the band strength necessary to complement the spherical component to yield the experimental value. In fact, this band strength is not a free parameter, as it corresponds to a deformation parameter β which must be consistent with those of the even-parity states.[12] This condition was satisfied in this case. Once the strength of the band is determined, it is easy to evaluate the deformed amplitude for the $5_1^- \to 3_1^-$ decay in terms of the ratio

$$\left[\frac{B(E2; 5_1^- \to 3_1^-)}{B(E2; 3_2^- \to 5_1^-)}\right]^{1/2} = \left[\frac{C_{\mathrm{def}}(3_1^-)}{C_{\mathrm{def}}(3_2^-)}\right]^{1/2} \times \frac{(5210|31)}{(3210|51)},$$

where $C_{\mathrm{def}}(X)$ is the percentage of deformed component in state X and where the Clebsch-Gordan coefficients relate in-band transition amplitudes for a $K = 1$ band. Thus, a $B(E2)$ value for the $5_1^- \to 3_1^-$ decay of $7.6e^2$ fm^4 is obtained. This rate arises from a coherent combination of spherical and deformed components and is in good agreement with our measured value of $(8.4 \pm 0.3)e^2$ fm^4.

A similar situation obtains for the decay of the 6.026-MeV (2_1^-) state[7,13] to the 3_1^- state. The $E2$ component of this transition has a strength of $(37 \pm 5)e^2$ fm^4. RPA calculations[2] predict a much smaller $B(E2)$ for this transition as well as an $M2$ transition to ground which has not been observed experimentally. Poletti et al.[7] underestimate the $E2$ strength by a factor of 3, while overestimating the $M1$ strength by a factor of 6. Once again the presence of 3p-3h deformed components is indicated in the radiative decay prop-

Table II. Strengths of $E2$ transitions between negative-parity levels of ^{40}Ca. The experimental values are a weighted average of the data of Refs. 7-10. The present calculation includes spherical (SPEII set of Ref. 1) and deformed (3p-3h) contributions to the transition strengths.[a]

Transition (Deformed-component intensity[a])	$B(E2)$ (e^2 fm^4) Experiment	Present calculation
$5_1^-(4.7\%) \to 3_1^-(6.25\%)$	8.4 ± 0.3	7.6
$4_1^-(0.81\%) \to 3_1^-(6.25\%)$	1.9 ± 0.8	2.5
$4_1^-(0.81\%) \to 5_1^-(4.7\%)$	48 ± 23	53.6
$1_1^-(96\%) \to 3_1^-(6.25\%)$	< 25	22.0
$2_1^-(67\%) \to 3_1^-(6.25\%)$	37 ± 5	34.9
$3_2^-(56\%) \to 3_1^-(6.25\%)$	< 1	0.84
$3_2^-(56\%) \to 5_1^-(4.7\%)$	72 ± 18	72.0
$3_3^-(0\%) \to 3_1^-(6.25\%)$	10.6 ± 3.6	4.0
$3_3^-(0\%) \to 5_1^-(4.7\%)$	4.1 ± 2	4.7

[a] Ref. 1.

erties of the 2_1^- level [as well as in the stripping strength of the reaction[14,15] $^{39}\mathrm{K}(^3\mathrm{He},d)^{40}\mathrm{Ca}$]. Gerace and Green[1] quote a value of 67% deformed-state admixture in the 2_1^--state wave function. Using this value, the deformed transition amplitude of the $2_1^- \rightarrow 3_1^-$ decay can be calculated in terms of that for the $3_2^- \rightarrow 5_1^-$ decay in a manner similar to that used above for the decay of the 5_1^- state. A coherent combination of spherical and deformed amplitudes yields $B(E2; 2_1^- \rightarrow 3_1^-) = 34.9e^2\ \mathrm{fm}^4$.

The strengths of the three transitions $3_2^- \rightarrow 5_1^-$, $5_1^- \rightarrow 3_1^-$, and $2_1^- \rightarrow 3_1^-$ are all underestimated in p-h calculations. Actually, the experimental strengths are consistent with those calculated with the inclusion of spherical and deformed-component admixtures. The results of such a calculation for these and six other transitions between negative-parity levels are summarized in Table II. The calculated transition strengths are in excellent agreement with experiment, which demonstrates the interplay of spherical and deformed components in the $E2$ rates.

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GALACTIC LINE EMISSION FROM 1 TO 10 keV

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We calculate the flux of x rays produced by low-energy cosmic-ray nuclei in H I regions. We consider electron capture to excited states by cosmic-ray nuclei of heavy elements, followed by cascades down to the ground state. It is found that the electron-capture processes may yield appreciable line intensities in the range 1-10 keV in the galactic plane.

Hayakawa[1] originally suggested that low-energy cosmic rays (in the range 1-100 MeV) may be an important heat source in the interstellar medium. Cosmic-ray heating has been extensively studied by Hayakawa, Nishimura, and Takayanagi[2] and more recently by Pikel'ner,[3] Balasubrahmanyan *et al.*,[4] and Spitzer and Tomasko,[5] who find substantial agreement with the observed properties of the interstellar medium. However, this is at best an indirect argument for the presence of subcosmic rays. Indeed the observed diffuse soft x-ray flux may be of comparable significance as a heating mechanism.[6] In order to distinguish between heating by subcosmic rays and other possible mechanisms, it is clearly of great importance to attempt to observe low-energy cosmic rays. Direct observations at low energies are unreliable because of the substantial degree of solar modulation.[7]

A more promising approach is to investigate the interactions of low-energy cosmic rays with H I regions. Observations yield an upper limit on