Identification of the 6^+ and 8^+ Yrast States in ^{40}Ca

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The reaction ^{28}Si(^{14}N, $pn\gamma$)^{40}Ca has been used to populate high-spin states in ^{40}Ca, and levels at 6930 and 8098 keV are identified as the 6^+ and 8^+ yrast states. The results suggest the termination at spin 8 of the band based on the 3.35-MeV state. The previously identified level at 6930 keV is found to be a doublet.

The softness of the doubly magic ^{40}Ca nucleus to particle-hole excitations has been used to explain the nature of the first excited 0^+ state at 3.35 MeV, which is interpreted as the lowest member of a 4p-4h (four particle, four hole) prolate rotational band.[1] The experimental evidence for such a band is primarily the energies of the lowest 2^+ and 4^+ states, which fit reasonably well a $J(J+1)$ spacing from the excited 0^+ state, and the enhanced $E2$ transitions between these states.[2] It is of crucial importance for the understanding of the ^{40}Ca spectrum and hence of other f-p-shell nuclei to test this interpretation by locating the higher-spin members of this band. We have located two states which we suggest are the 6^+ and 8^+ yrast states. The location of the proposed 8^+ state and the small $E2$ enhancement of its decay to the proposed 6^+ state indicate that the rotational model ceases to be applicable at spin 8.

The "grazing-collision" picture of Klapdor *et al.*[3] suggested that ^{28}Si(^{14}N, $pn\gamma$)^{40}Ca at an incident laboratory energy of 30–40 MeV would feed high-spin states in ^{40}Ca. The experimental procedures were similar to those used in other heavy-ion reactions in this mass region.[4-6] We have measured γ-ray excitation functions and γ-ray angular distributions (which also permit observation of Doppler shifts). To identify ^{40}Ca γ rays, a γ-γ coincidence experiment was performed with a 35-MeV ^{14}N beam incident on a silicon chip. Ad-

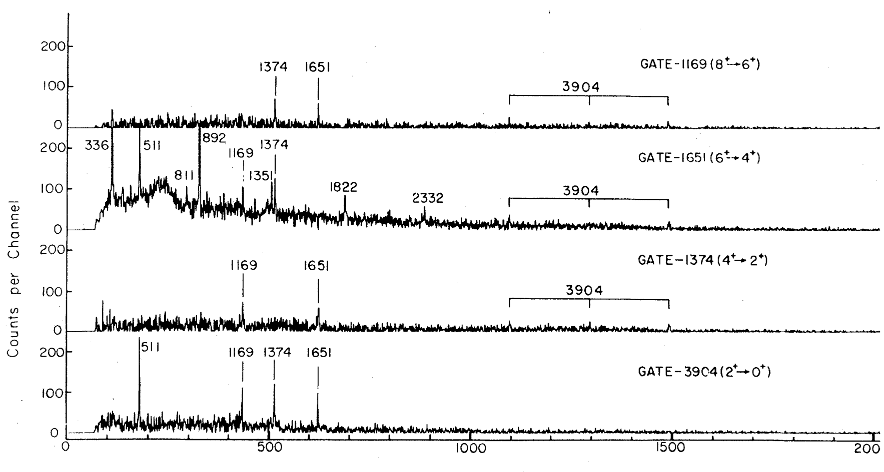

FIG. 1. γ-γ coincidence spectra. This is a sum of spectra observed in all three detectors. The spectrum gated by the 1651-keV γ ray shows additional lines attributed to ^{40}K (see text).

dress-recording techniques were used for coincidences between a Ge(Li) detector at $\pi/2$ and two at 0 and $-\pi/2$ with respect to the beam direction.

Figure 1 shows γ-γ coincidence spectra gated by windows set on γ rays connected with the prolate band. In addition to the known ^{40}Ca γ rays of 3904 and 1374 keV, two new γ rays are seen, at 1651 and 1169 keV. Figure 2 shows the proposed energy-level diagram. The γ-ray intensities indicated that there was about 30% side feeding into each level which permitted us to order the γ rays and place the energy levels unambiguously. The peaks in the spectrum gated by the 1651-keV γ ray other than those of ^{40}Ca are in coincidence with the 1651-keV γ ray of ^{40}K. The ^{40}Ca γ rays, including the 1169 keV, are not observed in a spectrum gated by the 892-keV γ ray which appears prominently in coincidence with the 1651-keV γ ray of ^{40}K.

The state we located at 6930 keV decays solely to the 4^+ state at 5278 keV, and in particular we do not observe a 3193-keV transition to the 3^- state at 3737 keV, either in singles (< 6%) or in coincidence with the 3737-keV γ ray. Tellez *et al.*[7] report 50% branches to the 3^- and 4^+ states from a level at 6928 keV. We conclude that there is a previously unresolved doublet near 6930 keV.[8]

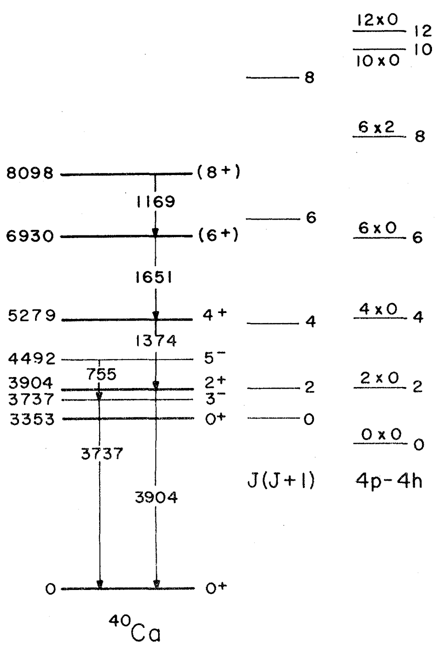

FIG. 2. Energy-level diagram showing those transitions seen in the reaction ^{28}Si(^{14}N, $pn\gamma$)^{40}Ca. Also shown is a $J(J+1)$ spectrum and a weak-coupling 4p-4h yrast spectrum obtained from the energy levels of ^{36}Ar and ^{44}Ti. In the latter, the notation $J_1 \times J_2$ on each level means (^{44}Ti; J_1) × (^{36}Ar; J_2). Note that the yrast levels are given by the ^{44}Ti levels except for the 8^+ state. The 4p-4h spectrum has been arbitrarily aligned to the experimental spectrum at the 2^+ state.

The assignment of 6^+ and 8^+ to the states at 6930[9] and 8098 keV is based on the following considerations. The angular distribution of the 1169-keV γ ray is consistent with a stretched $E2$ transition from a fairly well-aligned state (see Table I). Angular distributions were not obtained for the 1374- and 1651-keV γ rays because of interfering peaks in the spectra, but we have used the ratio method[11] of γ-γ coincidence intensities at angles of $\pi/2$ and 0 to confirm that transitions in the cascade are consistent with stretched $E2$ transitions. In Table II, the experimental ratio

$$R(\tfrac{1}{2}\pi, 0)_{\text{expt}} = \frac{W[\gamma_1(\frac{1}{2}\pi), \gamma_2(0)]}{W[\gamma_1(0), \gamma_2(\frac{1}{2}\pi)]}$$

is compared to the theoretical value for stretched $E2$ cascades. Although the statistical scatter is large, the results are consistent with the theoretical prediction and the average of all of them is quite close to 1. Furthermore, crossover transitions from the proposed 8^+ to 4^+, or proposed 6^+ to 2^+, are not seen (< 10%). Finally, there is the accumulating evidence that these sorts of heavy-ion reactions do produce preferentially yrast cascades in even nuclei in the f-p shell.[4-6]

We have looked for some evidence of a Doppler line shape on the 1169-keV γ ray. Although the observation is somewhat hampered by nearby γ rays, no evidence could be found for a Doppler-shifted component and conservatively we can say that the lifetime of the 8^+ state is longer than 3.0 psec [corresponding to $F(\tau) < 0.2$], assuming that feeding into the state is fairly prompt. As discussed below, the 8^+ state is fed apparently only by particle side feeding. The observation of a prominent Doppler-shifted component on the 3904-keV transition in singles suggests that side feeding is indeed prompt.

An analysis of the data of Fig. 1 indicates that a $10 \to 8$ transition from 300 keV to about 3 MeV is less than about 20% of the $8 \to 6$ transition. In the coincidence spectra the intensities of the members of the cascade above the gating γ ray decrease by only about 30% for each higher member, suggesting that a 10^+ state within a few MeV of the 8^+ should have been sufficiently populated to have been seen. (The maximum proton width of a 10^+ state ($l = 8$) is smaller than a 1-Weisskopf unit (W.u.) $E2$ width to the 8^+ state up to 11 MeV excitation.) From the grazing-collision pic-

TABLE I. γ-ray energies and angular distribution coefficients.

E_γ [a] (keV)	Energy (J^π) [b] Initial state	Final state	Angular distribution coefficients a_2	a_4	a_2 [c]	Multi-polarity
1168.7± 0.3	8098.2(8^+)	6929.5(6^+)	0.29± 0.07	−0.01± 0.08	0.68	$E2$
1651.0± 0.5	6929.5(6^+)	5278.5(4^+)				
1374.3± 0.3	5278.5(4^+)	3904.2(2^+)				
3904.0± 0.3	3904.2(2^+)	0(0^+)	0.15± 0.04	−0.10± 0.05	0.21	$E2$
754.7 [d]	4491.5(5^-)	3736.8(3^-)	0.217± 0.005 [e]	−0.106± 0.006	0.46	$E2$
3736.6 [d]	3736.8(3^-)	0(0^+)	0.34± 0.02	0.005± 0.018	0.34	$E3$

[a]Observed γ-ray energy, using a quadratic energy calibration curve fit to five known γ-ray energies (Ref. 10).
[b]Corrected for recoil following γ emission.
[c]Ratio of experimental a_2 to theoretical a_2 for stretched transition from fully aligned state.
[d]Energy taken from Ref. 10.
[e]Probably contaminated with a 757-keV transition in ^{39}K.

ture of Klapdor *et al.*[3] there appears no reason why there should not be appreciable feeding of a 10^+ state up to 11 MeV.

The above evidence suggests that we may be seeing the termination of this rotational band in ^{40}Ca. This is emphasized in Fig. 2 where the experimental energy levels are compared to the rigid-rotor prediction of a $J(J+1)$ spacing and to a 4p-4h weak-coupling picture where the energy levels of ^{36}Ar and ^{44}Ti with no particle-hole interaction are used to predict the yrast states (see caption Fig. 2). Neither picture predicts the considerably reduced spacing between the 6^+ and 8^+ states. A dramatically reduced spacing at the top of the yrast band is a common feature[4-6,12] in $(f_{7/2})^{2n}$ nuclei (n an integer). From the lower limit on the lifetime of the 8^+ state the upper limit on the $B(E2;\ 8\rightarrow 6)$ value is $120e^2$ fm^4 (<15 W.u.), much smaller than expected from $B(E2)$ values of the $4\rightarrow 2$ and $2\rightarrow 0$ transitions in the band[2,13] which have enhancements of 65 and 30 W.u. The termination of the band at 8^+ suggests perhaps that 2p-2h configurations, for which 8 is the maximum spin,[14] are dominant components in the high-spin states.

We should like to remark briefly that γ rays from the 3^- and 5^- states shown in Fig. 2 are also quite prominent, but that the 4^- state at 5614 keV is only weakly fed, if at all. No other ^{40}Ca γ rays were observed in coincidence with the 3737- and 755-keV γ rays, and termination of the negative-parity band at spin 5 is consistent with a predominant 1p-1h picture for it. The angular distribution coefficients and the γ-γ coincidence ratios for these γ rays are shown in Tables I and II.

In conclusion, it appears that the picture of a prolate rotational band based on the 3353-keV state, microscopically of a 4p-4h character, while useful for the states up to spin 4, and perhaps 6, is inappropriate for higher states. The evidence is that the band terminates at spin 8.

TABLE II. γ-γ coincidence ratios. The average $R(\frac{1}{2}\pi, 0)_{\rm expt}$ for the first three rows is 0.94± 0.16.

γ_1 (keV)	γ_2 (keV)	$R(\frac{1}{2}\pi, 0)_{\rm expt}$	$R(\frac{1}{2}\pi, 0)_{\rm theor}$	Assumed transition
1169	1651	0.84±0.27	1.0	$8\rightarrow 6\rightarrow 4$
1651	1374	0.82±0.24	1.0	$6\rightarrow 4\rightarrow 2$
1169	1374	1.45±0.39	1.0	$8\rightarrow 6\ (\rightarrow)\ 4\rightarrow 2$
755	3737	1.29±0.15	1.14 [a]	$5\rightarrow 3\rightarrow 0$

[a]Calculated assuming a Gaussian substate population with $\sigma=2.5$ consistent with $\alpha_2=0.46$.

[1]W. J. Gerace and A. M. Green, Nucl. Phys. A93, 110 (1967).
[2]Jack R. MacDonald, D. H. Wilkinson, and D. E. Alburger, Phys. Rev. C 3, 219 (1971).
[3]H. V. Klapdor *et al.*, Phys. Lett. 49B, 431 (1974); H. V. Klapdor *et al.*, Max-Planck-Institut fur Kernphysik, Heidelberg, Report No. MPI H-1974-V29 (to be published); H. V. Klapdor *et al.*, Phys. Lett. 53B, 147 (1974).
[4]J. J. Kolata, Ph. Gorodetzky, J. W. Olness, A. R. Poletti, and E. K. Warburton, Phys. Rev. C 9, 953 (1974); J. J. Kolata, J. W. Olness, and E. K. Warburton, Phys. Rev. C 10, 1663 (1974).
[5]W. Kutschera *et al.*, Phys. Rev. Lett. 33, 1108

(1974).

[6]J. J. Simpson *et al.*, Phys. Rev. C (to be published).

[7]A. Tellez *et al.*, J. Phys. (Paris) 34, 281 (1973).

[8]The authors of Ref. 7 considered the possibility that the 6930-keV state was a doublet because of a slight discrepancy in γ-ray energy and lifetime measurements. Using their data with the knowledge of the existence of a doublet, we place the member which decays to the 3737-keV state at 6927.0 ± 1.5 keV.

[9]The (^{6}Li,d) reaction on ^{36}Ar also suggests a 6^+ state at 6.93 MeV. H. T. Fortune, in *Proceedings of the International Conference on Nuclear Structure and Spectroscopy, Amsterdam, 1974,* edited by H. P. Blok and A. E. L. Dieperink (Scholar's Press, Amsterdam, 1974), Vol. 2, p. 367.

[10]P. M. Endt and C. Van der Leun, Nucl. Phys. A214, 1 (1973).

[11]J. A. Grau *et al.*, Phys. Rev. Lett. 32, 677 (1974).

[12]D. F. Geesaman *et al.*, Phys. Rev. Lett. 34, 326 (1975).

[13]If the γ ray from the 6930-keV doublet to the 5278-keV 4^+ state observed in Ref. 7 is from the 6^+ state, then the lifetime implies a $B(E2;\ 6\rightarrow 4)$ value of $(440 \pm 120)e^2$ fm^4 (54 W.u.), in reasonable agreement with the rotational model.

[14]L. Zamick, Phys. Lett. 19, 580 (1965).

Asymmetry of Beta-Ray Angular Distribution in Polarized Nuclei and *G*-Parity Nonconservation

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We have derived an equation for the β-ray angular distribution including Coulomb corrections, radiative corrections, induced effect, and higher-order nuclear matrices. With this equation and the experimental data on β-ray asymmetries in polarized ^{12}B and ^{12}N, we conclude that the strength of the second-class induced tensor is $f_T/f_A = -(0.96 \pm 0.35)\times 10^{-3}$ in the limit of the impulse approximation. A possible modification of this value due to mesonic corrections is discussed.

Since Weinberg proposed a measurement of the ft-value ratio in mirror β decays to test a possible existence of the second-class currents in weak interactions,[1] there have been a number of articles published on this subject. Among those, Wilkinson and his co-workers have made an extensive search for the asymmetries of the ft values experimentally.[2] The results were originally thought to be a direct indication for the induced tensor interaction. Later on, these were, however, recognized as the sum of the effects due to nuclear structure, the induced tensor term f_T [see Eq. (4)], and possible meson-exchange currents. In a model calculation,[3] Kubodera, Delorme, and Rho adopted the meson-exchange effect due to $\omega\rightarrow \pi e\nu$, and they gave a ratio

$$(ft)_+/(ft)_- - 1 = \delta_{\exp} = \delta_{scc} + \delta_{nucl}.$$

Here

$$\delta_{scc} = -4(\lambda/f_A)J + (2/3f_A)(\lambda L - 2\zeta)(E_0^- + E_0^+)$$

and δ_{nucl} represents the nuclear-structure effect. The effect of the second-class current, δ_{scc}, is also dependent on the nuclear model through J and L, while λ is a combination of the strong-coupling constants including the ω-ρ mixing parameter, and ζ is nearly equal to f_T. Wilkinson made an analysis of $\delta_{\exp}$ in the region of mass number $A=8$–30 systematically, using available nuclear models. He obtained as limits for the parameters[2]

$$|\zeta| \leq 2.5\times 10^{-3}\ \text{MeV}^{-1} \text{ and } |\lambda| \leq 10\times 10^{-3}.$$

Here the combination $\zeta = \lambda = 0$ is not necessarily excluded, while the theory does not give us a single value of λ, since it contains a logarithmic divergence.

Less ambiguous information for the second-class current can be obtained from the measurement of the β-ray asymmetries in polarized nuclei. A long-awaited experiment on ^{12}B and ^{12}N was recently performed successfully by Sugimoto, Tanihata, and Göring.[4] In order to derive a conclusion about G-parity nonconservation from this experiment, we have to be careful to include all induced effects, higher-order corrections, etc., in the equation for the angular distribution of β rays.[5-8] In particular, the radiative corrections