PHYSICAL REVIEW C VOLUME 11, NUMBER 5 MAY 1975

γ-γ angular correlations of transitions in ^{142}Ce†

G. J. Basinger,* W. C. Schick, Jr., and W. L. Talbert, Jr.
Ames Laboratory-ERDA and Department of Physics, Iowa State University, Ames, Iowa 50010
(Received 4 February 1975)

Angular correlation measurements have been performed on 12 direct and 4 skip cascades in ^{142}Ce, all involving the 641-keV $2^+ \rightarrow 0^+$ transition. The ^{142}Ce levels were populated in the β^- decay of fission-product ^{142}La produced as a decay product of ^{142}Xe at the TRISTAN on-line isotope-separator facility. Spin-parity assignments or preferences have been made for all 13 excited levels below 3 MeV previously known to be populated in this decay. In addition, a new 0^+ level is established at 2030 keV in ^{142}Ce. These levels are described in terms of vibrations of a spherical nucleus. An alternate interpretation in terms of quasirotational bands is also presented.

[RADIOACTIVITY ^{142}La(from ^{142}Xe decay); measured γ-$\gamma(\theta)$. ^{142}Ce deduced J, π. Mass-separated ^{142}La activity.]

I. INTRODUCTION

This work is one of a series of studies of neutron-rich fission product nuclei produced by the TRISTAN on-line isotope-separator system.

The decay of ^{142}La to ^{142}Ce was investigated some years ago by Schuman, Turk, and Heath,[1] by Ryde and Herrlander,[2] and by Prestwich and Kennett,[3] using scintillation detectors. The decay was found to be complex. More recent studies using Ge(Li) detectors were performed by Alvager *et al.*,[4] by Tong, Prestwich, and Fritze,[5] and by Larsen, Talbert, and McConnell.[6] The latter two works included level diagrams for ^{142}Ce. Only the study by Larsen *et al.*[6] contains extensive Ge(Li)-Ge(Li) coincidence data, so the level scheme proposed by these authors will be adopted in the present work.

Measurements of γ-γ angular correlations in the decay of ^{142}La were performed by Prestwich and Kennett[7] using two NaI(Tl) detectors. The cascades studied may now be seen to be complex, consisting of closely spaced peaks unresolvable with a NaI(Tl) detector. Thus, a reinvestigation of the angular correlations using a Ge(Li) detector is in order.

The levels in ^{142}Ce may also be investigated in reaction studies. A Coulomb-excitation experiment by Hansen and Nathan[8] located the lowest 2^+ and 3^- levels. Mulligan *et al.*[9] used the ^{140}Ce(t,p) reaction to identify 22 levels in ^{142}Ce below 3 MeV. L values were assigned for only a few of these levels, because the similarity of the angular distributions for different L values precluded definite assignments in most cases.

The present study was undertaken to determine the spins and parities of as many levels in ^{142}Ce as possible. The use of a multidetector angular-correlation system has made possible the study of a number of weak cascades in a reasonable length of time. In all, 12 direct and 4 skip cascades (triple cascades with the intermediate transition unobserved) were investigated.

II. EQUIPMENT AND PROCEDURE

The angular-correlation apparatus has been described in detail elsewhere[10,11] so only a brief description will be given here. The apparatus includes six NaI(Tl) detectors, 5 cm diam by 5 cm high, and one Ge(Li) detector with an active volume of 58 cm^3 and an efficiency of 9%. All detectors are fixed in position. The NaI(Tl) detectors are located at angles of 45°, 90°, 135°, 180°, 225°, and 292.5° relative to the Ge(Li) detector. Coincidences between the Ge(Li) detector and each of the NaI(Tl) detectors are established in six independent fast twofold coincidence circuits, each with a resolving time 2τ of 40 nsec. A single-channel analyzer window is set on a peak in each of the NaI(Tl) spectra, and the coincident Ge(Li) spectra are recorded in six 2048-channel sections of a large-memory multichannel analyzer. In the present experiment the windows were set on the 641-keV $2^+ \rightarrow 0^+$ transition from the first excited state in ^{142}Ce.

The ^{142}La parent activity was produced by the TRISTAN on-line isotope-separator facility.[12,13] This facility, located at the Ames Laboratory research reactor, produces isotopically pure radioactive sources of noble-gas fission products and their daughters. For angular-correlation experiments the activity is deposited on Al foil in the form of a line source 2 to 4 mm wide and about 25 mm high. The sources in the present experiment were made by depositing a beam of

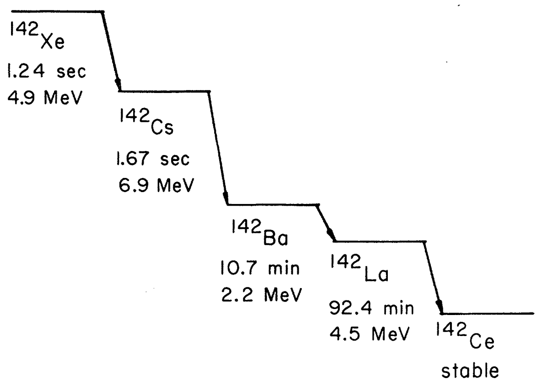

FIG. 1. The mass 142 decay chain.

^{142}Xe from the separator on a removable source holder[10] and allowing the ^{142}La activity to grow in according to the decay chain shown in Fig. 1. In the time required to remove the sources from the isotope separator and transport them to the angular-correlation chamber (about 10 min), all the ^{142}Xe and ^{142}Cs activity and much of the ^{142}Ba activity had decayed away. The ^{142}Ba activity remaining at the start of data accumulation presented no problem. Each ^{142}La source was used for 2 h before replacement. Typical source strengths were 5–10 μCi at the start of data accumulation. A typical Ge(Li) singles spectrum is shown in Fig. 2. Figure 3 shows a NaI(Tl) singles spectrum obtained just after removal of the source from the isotope separator. It may be seen that the 641-keV peak provides a clean coincidence gate.

The peaks in the Ge(Li) coincidence spectra were fit to a skewed-Gaussian line shape using the computer program SKEWGAUS.[14] The area of each peak was divided by the singles count rate in the window of the corresponding NaI(Tl) detector to correct for source eccentricity and for differences in the intrinsic efficiencies of the NaI(Tl) detectors. (The variation in singles rates among the various detectors was never more than 5%.) The normalized areas were then fitted to a Legendre polynomial expansion of the form $1 + A_2P_2(\cos\theta) + A_4P_4(\cos\theta)$. Corrections for the finite solid angle of the NaI(Tl) detectors and for the finite extent of the line source were applied according to the method of Feingold and Frankel,[15] and the correction for the finite solid angle of the Ge(Li) detector was determined from the tables of Camp and van Lehn.[16] No correction was applied for accidental coincidences, since the accidental rate (averaging well under 1% of the true coincidence rate) was negligibly small.

The uncertainties in the corrected values of A_2 and A_4 were determined by standard statistical methods. A description of the method used to obtain the uncertainties, as well as an analysis of possible sources of systematic error, is given in Ref. 10.

III. RESULTS

A skeletal level scheme for ^{142}Ce, showing only those transitions studied in this work, is given in Fig. 4. This scheme includes all levels found by Larsen *et al.*[6] below an energy of 3 MeV, and one additional level at 2030 keV whose existence is indicated by the present study.

The experimental results for the direct cascades are compared in Figs. 5 and 6 with the theoretical values for spin sequences of the form x-2-0, where $x = 1$, 2, 3, or 4. These figures are conventional parametric plots of A_4 vs A_2 with variation in the amount of dipole-quadrupole mixing in the first transition of the cascade. Spins higher than 4 for the initial state of the cascade were not considered because all of the states investigated

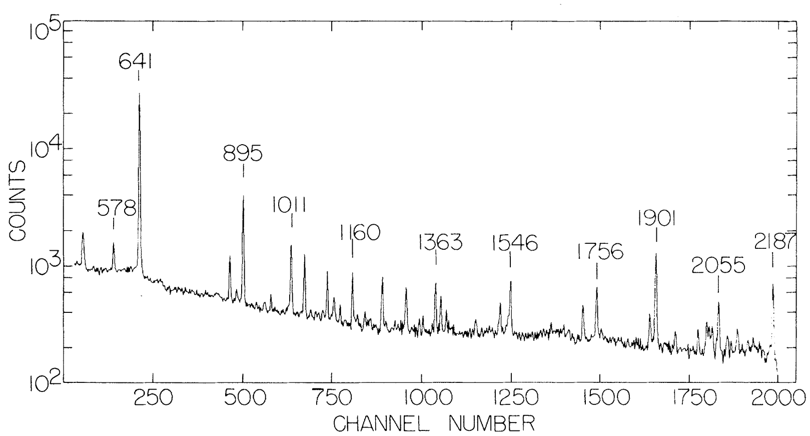

FIG. 2. ^{142}La singles spectrum obtained with a Ge(Li) detector.

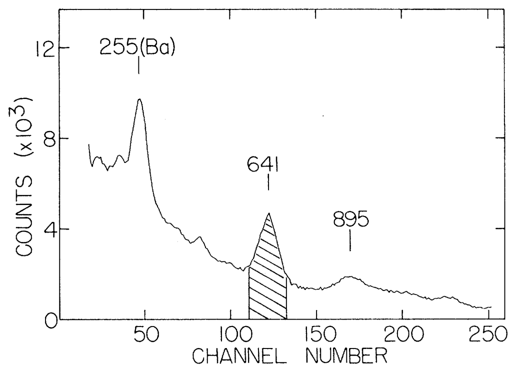

FIG. 3. NaI(Tl) singles spectrum of a freshly collected ^{142}La source, showing the energy gate used for angular-correlation measurements.

are directly populated in the β^- decay of ^{142}La (spin-parity 2^-) by transitions with logft values between 7.2 and 9.0.[6] Only one cascade was found to have the very large value of A_4 characteristic of a 0-2-0 spin sequence. The results for all cascades are tabulated in Table I.

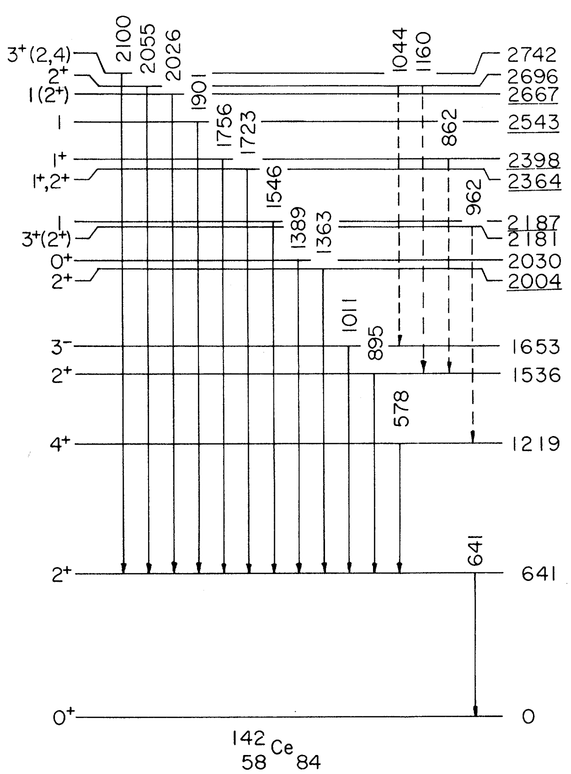

FIG. 4. Partial level scheme for ^{142}Ce, showing spins and parities assigned in the present work. Angular-correlation measurements were made for all transitions shown. Dashed transitions were studied in skip cascades. Levels with underlined energies also decay directly to the ground state.

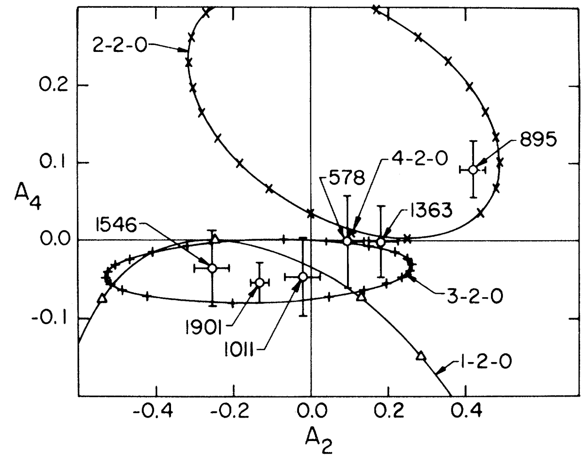

FIG. 5. Direct cascade results. The points on the ellipses represent increments of 10% in the amount of dipole-quadrupole mixing in the first transition of the cascade, for the spin sequences shown. The experimental data points are identified by the energy of the first transition in the cascade.

In the following discussion of the individual cascades it will be assumed that states which also decay by direct transitions to the 0^+ ground state of ^{142}Ce (states whose energies are underlined in Fig. 2) have spin-parities of $1^{\pm}$ or 2^+. It will also be assumed that transitions for which the amount of quadrupole mixing is greater than about 10% of the total transition strength are $M1$-$E2$ transitions, rather than $E1$-$M2$. Both assumptions are based on the observation that $M2$ and higher multipole order transitions generally do not compete successfully with transitions of lower multipole order.

578-641-keV cascade. The results are consistent with spin assignments of 4, 3, 2, or 1 for the 1219-keV level. A 4^+ assignment seems most

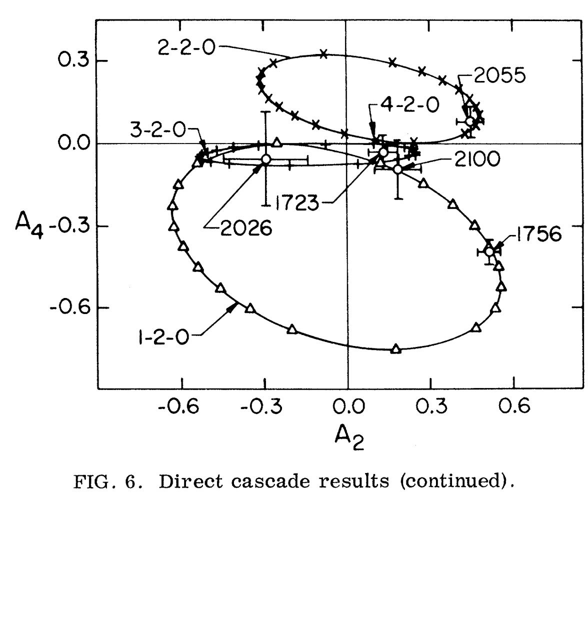

FIG. 6. Direct cascade results (continued).

TABLE I. Angular correlations in ^{142}Ce.

Cascade	Counts [a]	A_2	A_4	Spin sequence	Mixing ratio δ	$L=2$ (%)
578-641	1630	0.094 ± 0.055	-0.003 ± 0.060	1-2-0	0.30 ± 0.05	9 ± 3
				2-2-0	-0.20 ± 0.08	4 ± 3
				3-2-0	-0.24 ± 0.09	6 ± 4
				3-2-0	-2.48 ± 0.60	84 ± 6
				4-2-0		
895-641	6520	0.417 ± 0.034	0.089 ± 0.036	2-2-0	0.61 ± 0.18	27 ± 11
1011-641	2630	-0.023 ± 0.045	-0.049 ± 0.050	3-2-0	0.06 ± 0.06	<1.5
1363-641	900	0.181 ± 0.044	-0.004 ± 0.047	2-2-0	-0.09 ± 0.06	<2.2
1389-641	150	0.231 ± 0.281	1.436 ± 0.332	0-2-0		
1546-641	1060	-0.257 ± 0.045	-0.037 ± 0.049	1-2-0	-0.01 ± 0.04	<0.3
1723-641	500	0.138 ± 0.055	-0.033 ± 0.062	1-2-0	0.35 ± 0.05	11 ± 3
				2-2-0	-0.15 ± 0.07	<5
1756-641	900	0.519 ± 0.043	-0.401 ± 0.047	1-2-0	1.06 ± 0.13	53 ± 6
1901-641	2120	-0.133 ± 0.024	-0.055 ± 0.026	1-2-0	0.10 ± 0.02	1.0 ± 0.3
2026-641	280	-0.291 ± 0.154	-0.056 ± 0.173	1-2-0	-0.05 ± 0.15	<4
				2-2-0	-0.60 ± 0.05	30 ± 6
2055-641	650	0.455 ± 0.047	0.077 ± 0.053	2-2-0	0.55 ± 0.27	24 ± 16
2100-641	270	0.192 ± 0.085	-0.097 ± 0.108	1-2-0	0.40 ± 0.09	14 ± 5
				2-2-0	-0.08 ± 0.04	1.8 ± 1.6
				3-2-0	$-2.3<\delta<-0.2$	$6-83$
				4-2-0		
962-(578)-641	390	0.346 ± 0.095	-0.094 ± 0.102	3-4-2-0	$1.01^{+2.08}_{-0.46}$	51^{+40}_{-28}
862-(895)-641	1500	-0.029 ± 0.036	-0.004 ± 0.040	1-2-2-0	0.12 ± 0.12	<5
1160-(895)-641	1030	-0.016 ± 0.043	0.015 ± 0.049	2-2-2-0	-0.49 ± 0.30	15^{+23}_{-12}
1044-(1011)-641	2000	-0.143 ± 0.041	0.057 ± 0.046	2-3-2-0	0.03 ± 0.04	<0.6

[a] Average number of counts per angle.

probable on the basis of systematics of nearby nuclei. A 4^+ level is expected at an energy roughly twice that of the first excited state, and no other low-lying level is compatible with a 4^+ assignment. In addition, the β branching to this level is very small, as might be expected for a first-unique β branch which must compete with allowed or first forbidden nonunique β branches of comparable energy. Also, the angular distribution for this level in the ^{140}Ca(t, p) reaction[9] is consistent with (but not limited to) $L=4$.

It may be noted here that we do not support the assertion by Tong *et al.*[5] that the 578-keV transition is considerably weaker in coincidence with the 641-keV peak than in singles. On the contrary, we find no significant difference between the relative intensity in singles and in coincidence, when the angular-correlation effects are taken into account. There would appear, therefore, to be no justification for placing part of the 578-keV intensity elsewhere in the decay scheme.

895-641-keV cascade. Figure 5 clearly indicates that this is a 2-2-0 cascade, although the theoretical curve is slightly outside the error bars. The values quoted for the mixing ratio and for percent of $L=2$ in Table I are based on the experimental value of A_4 and its uncertainty. Since the quadrupole contribution is significant, the parity of the 1536-keV level is probably even.

1011-641-keV cascade. The coefficients for this cascade are consistent with the known[8] spin and parity of 3^- for the 1653-keV level, with the 1011-keV transition being essentially pure $E1$.

1363-641-keV cascade. The results for this cascade are consistent with spin assignments of 1, 2, or 3 for the 2004-keV level. The (t, p) reaction data[9] indicate a spin of 2 for this level. The presence of a transition to the ground state suggests that the parity is even. The angular-correlation results show that the 1363-keV transition is nearly pure dipole.

1389-641-keV cascade. The 1389-keV transition was not placed in the decay scheme by Larsen *et al.*[6] Analysis of the angular-correlation data is complicated by the fact that the 1389-keV peak includes a contribution from the single escape of the more intense 1901-keV γ ray. Before correcting for this contribution the correlation coefficients are $A_2=0.092\pm0.175$ and $A_4=0.936\pm0.199$. The 1901-keV single escape contribution to the composite 1389-keV peak ranges from 17% at 90° to 48% at 135°. After correction, the 1389-641 cascade has $A_2=0.231\pm0.281$ and $A_4=1.436\pm0.332$. These are to be compared with the theoretical values of $A_2 = 0.357$ and $A_4 = 1.143$ for a 0-2-0 cascade. Since all other spin sequences have much smaller values of A_4, there can be no doubt that the 1389-keV transition proceeds from a 0^+ level at 2030 keV.

1546-641-keV cascade. The angular-correlation coefficients are consistent with a spin of either 1 or 3 for the 2187-keV level, but the presence of an intense transition to the ground state from this level eliminates the spin 3 choice. Since the 1546-keV γ ray is seen to be essentially pure dipole, nothing can be said about the parity of the 2187-keV level.

1723-641-keV cascade. The results for this cascade, as shown in Fig. 6, are consistent with values of 1, 2, 3, or 4 for the spin of the 2364-keV level, but the presence of a moderately intense crossover transition to the ground state rules out the latter two choices. If the spin is 1, the quadrupole mixing is at least 8% so the parity is probably even; if the spin is 2, the mixing is smaller but the parity is still probably even (assuming that the ground-state transition is not $M2$).

1756-641-keV cascade. In this case the angular-correlation results are unambiguous, indicating a spin of 1^+ for the 2398-keV level and approximately equal $M1$ and $E2$ contributions to the 1756-keV transition.

1901-641-keV cascade. Although the curve for a 1-2-0 sequence shown in Fig. 5 lies slightly outside the experimental error in A_4 for this cascade, 1 is the preferred spin for the 2543-keV level. A spin of 3, which would agree somewhat better with the angular-correlation data, is ruled out because of the presence of an intense crossover transition to the ground state. A spin of 2, as proposed by Larsen *et al.*,[6] is clearly not acceptable. This proposal was based on the placement of a 1323-keV transition between the 2543-keV level and the (presumably) 4^+ level at 1218 keV. Since this placement is not supported by coincidence measurements and since the 1323-keV transition is weak, it seems quite possible that the transition should be placed elsewhere in the level scheme. A spin 1 assignment for the 2543-keV level is also suggested by the (t, p) data.[9]

2026-641-keV cascade. Because of the weakness of the 2026-keV transition, the error bars are large. Nevertheless, it may be seen that if the 2667-keV level has spin 1 (the most probable choice), the transition is predominantly dipole. A spin of 2 is also reasonably compatible with the data. A spin of 3 is ruled out by the presence of a transition to the ground state.

2055-641-keV cascade. A unique spin assignment of 2 is made for the 2696-keV level, with the parity probably even.

2100-641-keV cascade. Again, the angular-correlation results permit several different assignments. In this case there is no transition to the ground state, so the higher spin values may not be ruled out. A spin 1 assignment is unlikely because the degree of quadrupole mixing would favor even parity, whereas Larsen *et al.*[6] indicate a transition to the 3^- level at 1653 keV (unsupported by coincidence information, however) which would not be expected from a 1^+ level. The absence of a transition to the ground state also provides a weak argument against a 1 or 2^+ assignment.

962-(578)-641-keV cascade. The results for this skip cascade are plotted in Fig. 7. The data have been analyzed under the assumption that the 1219-keV level is 4^+ and that the unobserved 578-keV γ ray is $E2$. It is clear that a spin of 3 is favored

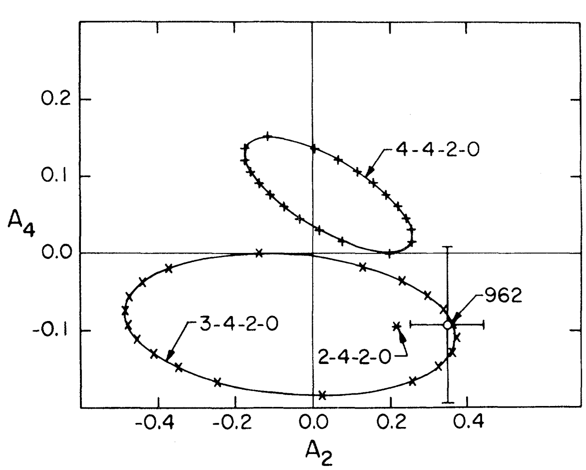

FIG. 7. Skip cascade results.

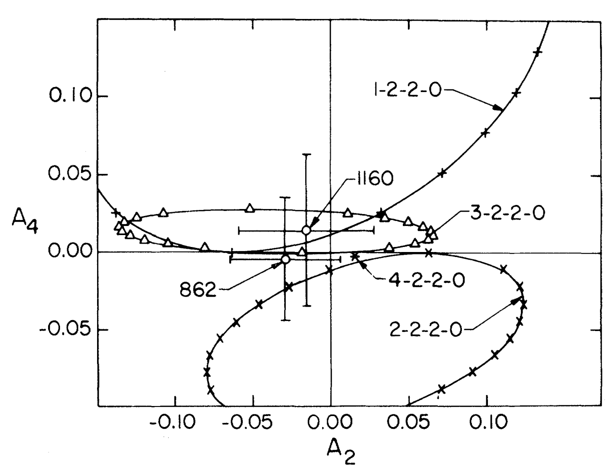

FIG. 8. Skip cascade results (continued).

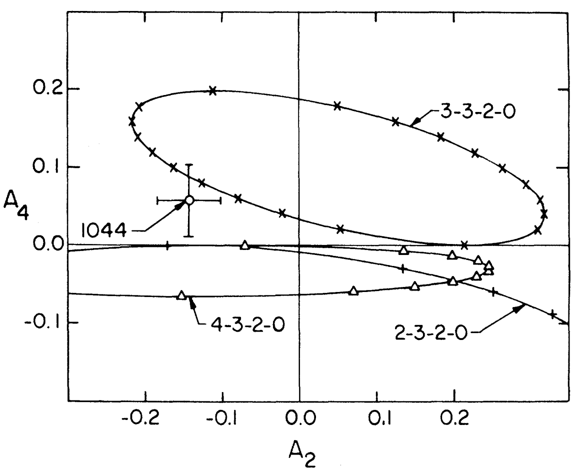

FIG. 9. Skip cascade results (continued).

for the 2181-keV level, although a spin 2 assignment is also possible. In either case the 962-keV transition is at least partially quadrupole so the parity is probably even.

862-(895)-641-keV cascade. The results for this and the following cascade are plotted in Fig. 8. These cascades were analyzed under the assumption that the 1536-keV level is 2^+ and that the 895-keV transition is 73% dipole-27% quadrupole, as obtained above. The results for the 862-(895)-641-keV cascade are consistent with the 1^+ assignment made previously for the 2398-keV state, and they indicate that the 862-keV transition is less than 5% quadrupole.

1160-(895)-641-keV cascade. The angular-correlation coefficients are consistent with the 2^+ assignment made above for the 2696-keV level, with the 1160-keV transition being 3–39% $E2$.

1044-(1011)-641-keV cascade. The results are plotted in Fig. 9. In this case the unobserved intermediate transition has been assumed to be pure dipole. The 2-3-2-0 curve (consistent with the 2^+ assignment previously made for the 2696-keV level) lies just outside the uncertainty in A_4. The results indicate a nearly pure $E1$ multipolarity for the 1044-keV transition.

IV. DISCUSSION

The results of the angular-correlation measurements, coupled with previously available experimental data, lead to rather definite spin assignments for ten excited levels in ^{142}Ce and to choices between two assignments for three additional levels. One might attempt to explain these levels in terms of oscillations about a spherical equilibrium shape, since the neutron number for ^{142}Ce differs by only 2 from the closed shell at $N=82$. In this model the first excited state would be a one-phonon excitation, and the levels at 1219 keV (4^+) and 1536 keV (2^+) would be members of a two-phonon triplet. The absence of a transition to the ground state from the 1536-keV level (forbidden in the model because it involves the destruction of 2 phonons) lends support to this interpretation, as does the significant quadrupole admixture in the transition between the two 2^+ levels.

The only candidate for the 0^+ member of the two-phonon triplet is the level at 2030 keV. The energy of this level is quite high, being more appropriate for a three-phonon state. Indentification of possible three-phonon states is difficult, but one candidate is the 3^+ level at 2181 keV. This level decays rather strongly to the two-phonon level at 1219 keV by a transition whose quadrupole strength may be rather large. The transition to the one-phonon state (forbidden in the model) was not studied in this work, but its reduced transition probability[6] is apparently significantly less than that for the transition to the two-phonon state.

The 2^+ level at 2004 keV is at the right energy for a three-phonon state, but its mode of decay (strong to the ground and one-phonon states; weak to the two-phonon states) suggests that it is more probably a quasiparticle excitation instead.

Another possible approach to the levels of ^{142}Ce is the quasirotational model of Sakai.[17] In this model the levels at 641 and 1219 keV would be interpreted as the 2^+ and 4^+ members of the ground-state quasirotational band. It is not likely that the 6^+ member of this band would be populated in the decay of ^{142}La, but it may have been observed at 1742 keV in the ^{140}Ce(t, p) reaction.[9] The 2^+ level at 1536 keV could be interpreted as the first member of a quasi-γ band, with the 3^+ level at 2181 keV being the second member of the band. It may be noted that the separation between these levels is almost identical with that between the first two members of the ground-state band. Likewise, one may note that the 0^+ level at 2030 keV and the 2^+ level at 2696 keV have nearly the same separation, and may perhaps be the first two members of a quasi-β band. (However, the absence of a transition between these two levels tends to argue against this interpretation.) Finally, the 3^- level at 1653 keV is perhaps the first member of an octupole band. The usual order of levels in such a band in near-spherical nuclei is $3^-, 1^-, 5^-, \ldots$. Any of the spin 1 levels at 2187, 2543, or 2667 keV could be the second member of this band.

The authors would like to acknowledge the assistance of J. R. McConnell in the use of the isotope separator and of L. J. Alquist in some aspects of the data analysis.

† Prepared for the United States Energy Research and Development Administration under Contract No. W-7405-eng-82.

*Present address: Bettis Atomic Power Laboratory, Westinghouse Electric Corporation, West Mifflin, Pennsylvania 15122.

[1] R. P. Schuman, E. H. Turk, and R. L. Heath, Phys. Rev. 115, 185 (1958).

[2] H. Ryde and C. J. Herrlander, Ark. Fys. 13, 177 (1958).

[3] W. V. Prestwich and T. J. Kennett, Phys. Rev. 134, B485 (1964).

[4] T. Alvager, R. A. Naumann, R. F. Petry, G. Sidenius, and T. D. Thomas, Phys. Rev. 167, 1105 (1968).

[5] S. L. Tong, W. V. Prestwich, and K. Fritze, Can. J. Phys. 49, 1179 (1971).

[6] J. T. Larsen, W. L. Talbert, Jr., and J. R. McConnell, Phys. Rev. C 3, 1372 (1971).

[7] W. V. Prestwich and T. J. Kennett, Nucl. Phys. 67, 302 (1965).

[8] O. Hansen and O. Nathan, Nucl. Phys. 42, 197 (1963).

[9] T. J. Mulligan, E. R. Flynn, O. Hansen, R. F. Casten, and R. K. Sheline, Phys. Rev. C 6, 1802 (1972).

[10] G. J. Basinger, W. C. Schick, Jr., and W. L. Talbert, Jr., Nucl. Instrum. Methods (to be published).

[11] G. J. Basinger, Ph.D. thesis, Iowa State University, 1974 (unpublished).

[12] W. L. Talbert, Jr., and J. R. McConnell, Ark. Fys. 36, 99 (1967).

[13] W. L. Talbert, Jr., and D. Thomas, Nucl. Instrum. Methods 38, 306 (1965).

[14] W. C. Schick, Jr., USAEC Report No. 1S-3460 (unpublished).

[15] A. M. Feingold and S. Frankel, Phys. Rev. 97, 1025 (1955).

[16] D. C. Camp and A. C. van Lehn, Nucl. Instrum. Methods 76, 192 (1969).

[17] M. Sakai, Nucl. Phys. A104, 301 (1967).