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On-line γ-γ angular correlations of transitions in ^{140}Ba †

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Angular-correlation measurements were made on 12 direct cascades and 5 skip cascades in ^{140}Ba. Levels in ^{140}Ba were populated from the 64-sec β decay of ^{140}Cs, which was populated from the decay of mass-separated ^{140}Xe. The most intense transitions were measured in coincidence with the first-excited state-to-ground-state transition in even-even ^{140}Ba. Definite spin assignments were made for eight levels and tentative spin assignments for five levels. Values are given for the angular-correlation coefficients, and multipolarity mixing ratios are listed where applicable. Systematics for $N=84$ isotones are discussed in light of assignments made for ^{140}Ba.

[RADIOACTIVITY ^{140}Cs (from ^{140}Xe decay); measured γ-$\gamma(\theta)$. ^{140}Ba deduced J, π. Mass-separated ^{140}Xe activity.]

I. INTRODUCTION

This work contains the results of the first on-line angular-correlation measurements of neutron-rich fission product nuclei produced by the TRISTAN isotope separator facility.[1,2] The multidetector angular-correlation system used in this study was previously employed off line to investigate cascades in ^{138}Ba (Ref. 3) and ^{142}Ce (Ref. 4). The apparatus has now been connected directly to the isotope separator in order to make possible the study of shorter-lived nuclei.

The first experiment performed on the decay of ^{140}Cs to ^{140}Ba was a half-life measurement by Sugarman and Richter.[5] A more recent measurement by Carlson *et al.*[6] established the more precise value of 63.7 ± 0.3 sec. Wahlgren and Meinke[7] reported the first γ-ray spectroscopy measurements on ^{140}Cs decay. More extensive measurements were done by Zherebin, Krylov, and Polikarpov[8] through the use of NaI detectors. These first spectroscopy studies identified relatively few distinct γ rays in the singles spectra, while other γ rays were seen as unresolved multiplets. The First Ge(Li) detector study of the ^{140}Cs decay scheme was performed by Alvager *et al.*[9] The fission products of a ^{252}Cf sample were mass-separated to produce ^{140}Xe, which decays through ^{140}Cs to populate levels in ^{140}Ba. The source strength was not sufficient to allow coincidence measurements to be made. However, a tentative decay scheme was proposed from energy relationships of 26 γ rays assumed to be in the ^{140}Cs decay. A NaI(Tl)-Ge(Li) study of the ^{140}Cs decay was performed by Schussler *et al.*[10] to produce the first extensive level scheme for ^{140}Ba. Coincidences were obtained at two angles, 125° and 180°, in order to obtain approximate anisotropy values. Only two cascades were found to have sufficiently large anisotropies to give useful results. Extensive Ge(Li)-Ge(Li) coincidence measurements were reported by Schick and Talbert[11] from activity produced by the TRISTAN isotope separator system. The 196 γ rays identified in the singles spectra and over 100 coincidence relationships allowed these authors to propose a detailed energy level scheme for the decay of ^{140}Cs. This decay scheme will be adopted in the present work.

II. EQUIPMENT AND PROCEDURE

The angular-correlation apparatus is adequately described eslewhere[3,4,12] so only a brief outline will follow. The apparatus consists of six NaI(Tl) detectors carefully positioned at specific angles of 45°, 90°, 135°, 180°, 225°, and 292.5° relative to one Ge(Li) detector. Simultaneous γ-γ coincidences are established between the six Ge(Li)-NaI(Tl) pairs by virtue of six independent fast coincidence circuits. Energy pulses from each NaI(Tl) detector are selected by the energy window setting in a corresponding single channel analyzer. In this study each of the six single channel analyzers was set on the first-excited-to-ground-state transition at 602 keV.

In order to facilitate the study of shorter-lived activities, the angular-correlation apparatus has been modified to permit it to be connected directly to the isotope separator. The ion beam from the separator is deposited on an aluminized Mylar tape, which transports the activity automatically to the correlation chamber (see Ref. 2). For this study, a beam of ^{140}Xe was deposited on the tape for 90 sec, then interrupted for 30 sec to permit the ^{140}Xe to decay away. The ^{140}Cs daughter activity was then transported to the correlation chamber for 120 sec of data accumulation, while a new sample of ^{140}Xe was being collected simultaneously. The source strength was monitored throughout the experiment and held below 7 μCi so that the ratio of accidental to true coincidences was small enough (less than 2%) to make an accidentals correction unnecessary.

The procedure followed here to fit angular-correlation data to the form $W(\theta) = 1 + A_2P_2(\cos\theta) + A_4P_4(\cos\theta)$, and to determine the errors in A_2 and A_4, is discussed adequately elsewhere.[3,4,12] The mixing ratio δ for mixed transitions is defined in accordance with the sign convention of Taylor *et al.*[13]

III. RESULTS

A partial level scheme for ^{140}Ba, showing only those transitions studied in the present work, is presented in Fig. 1. The dashed arrows in this figure represent transitions studied in γ-skip-γ cascades. The 602-keV transition from the first excited state to the ground state was the gating transition in all cases and was assumed to be a pure $E2$, $2^+ \rightarrow 0^+$ transition in the resulting analysis. A typical Ge(Li) singles γ-ray spectrum is shown in Fig. 2. Some representative $W(\theta)$ curves are shown in Fig. 3. There are two data points at 135° in these plots, corresponding to the 135° and 225° detectors.

Spin-parity assignments for the various ^{140}Ba

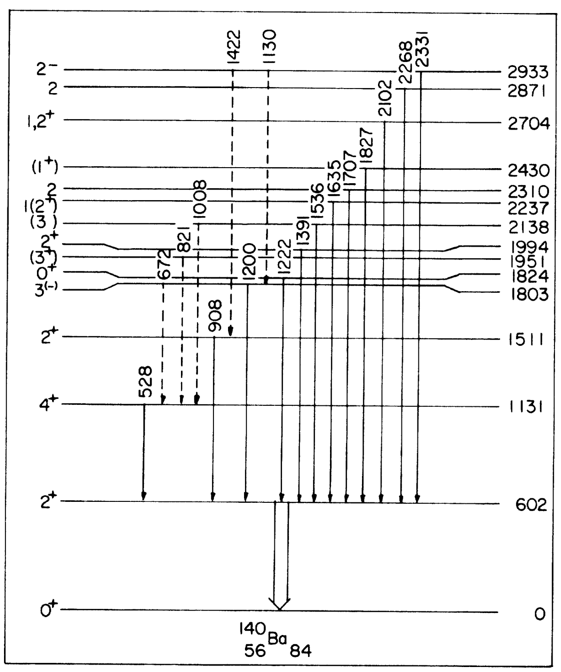

FIG. 1. Partial level scheme for ^{140}Ba, showing only those transitions studied in the present work.

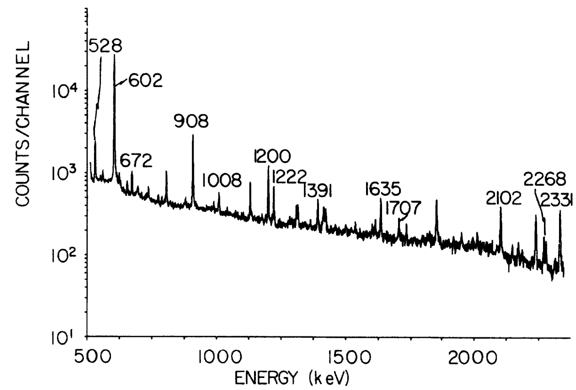

FIG. 2. ^{140}Cs singles γ-ray spectrum taken with the Ge(Li) detector.

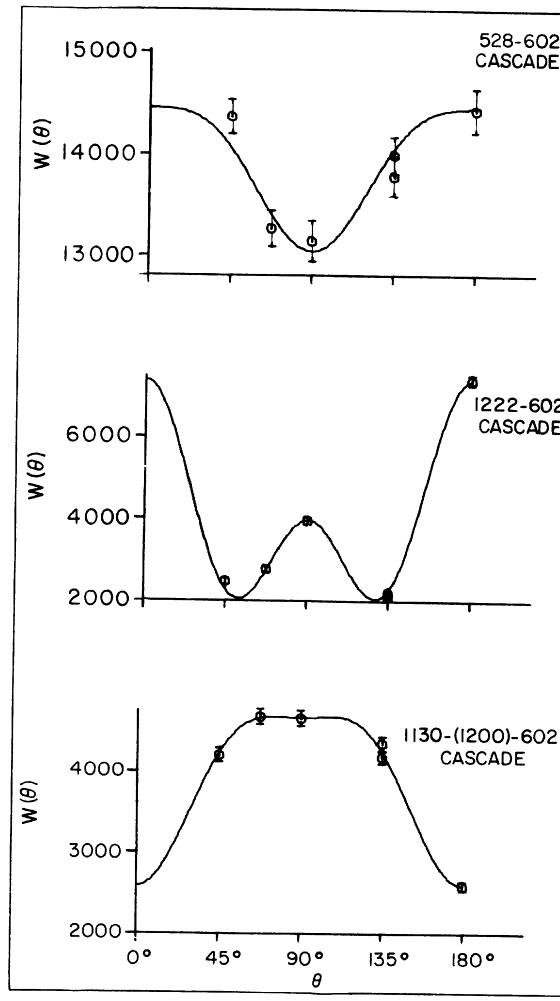

FIG. 3. Experimental data points and fit-function curves for selected cascades.

TABLE I. Results from the ^{140}Ba experiment.

Level (keV)	Cascade	A_2	A_4	Spin sequence	Mixing ratio	$L=2$ (%)
1131	528-602	0.083 ± 0.021	-0.027 ± 0.023	4-2-0		
1511	908-602	0.436 ± 0.023	0.147 ± 0.028	2-2-0	$-1.1^{+0.14}_{-0.10}$	55^{+6}_{-5}
1803	672-(528)-602	-0.143 ± 0.038	-0.008 ± 0.042	3-4-2-0	0.0 ± 0.05	≤0.2
	1200-602	-0.065 ± 0.015	0.015 ± 0.018	3-2-0	-0.01 ± 0.02	≤0.08
1824	1222-602	0.352 ± 0.055	1.275 ± 0.059	0-2-0		
1951	820-(528)-602	0.389 ± 0.101	-0.158 ± 0.113	3-4-2-0	-0.51 to -2.4	20 to 85
1994	1391-602	0.126 ± 0.041	0.014 ± 0.045	2-2-0	0.16 ± 0.06	2.6 ± 1.8
2138	1008-(528)-602	0.080 ± 0.071	0.001 ± 0.086	3-4-2-0	$-0.27^{+0.09}_{-0.10}$	$6.6^{+5.4}_{-3.5}$
	1536-602	0.006 ± 0.102	-0.168 ± 0.118	3-2-0	$3.6^{+3.7}_{-1.3}$	93^{+5}_{-9}
				3-2-0	$0.10^{+0.16}_{-0.13}$	$1.0^{+5.2}_{-1.0}$
2237	1635-602	-0.267 ± 0.051	0.040 ± 0.053	1-2-0	0.02 ± 0.04	≤0.4
				2-2-0	0.74 to 4.5	36 to 95
2310	1707-602	0.154 ± 0.061	0.048 ± 0.065	2-2-0	0.13 ± 0.08	1.6 ± 1.4
2430	1827-602	0.324 ± 0.175	-0.300 ± 0.185	1-2-0	$-0.55^{+0.20}_{-0.35}$	23^{+22}_{-12}
2704	2102-602	-0.061 ± 0.031	0.031 ± 0.034	1-2-0	-0.16 ± 0.03	2.6 ± 0.9
				2-2-0	0.42 ± 0.05	15 ± 3
2871	2268-602	0.379 ± 0.064	0.059 ± 0.068	2-2-0	$-0.20^{+0.11}_{-0.15}$	$3.9^{+7.1}_{-3.0}$
2933	1130-(1200)-602	-0.294 ± 0.018	-0.174 ± 0.020	2-3-2-0	[a]	
	1422-(908)-602	-0.057 ± 0.054	0.008 ± 0.062	2-2-2-0	$0.60^{+0.70}_{-0.26}$	26^{+38}_{-16}
				2-2-2-0	$8.3^{+2.7}_{-6.5}$	99^{+1}_{-23}
	2331-602	0.215 ± 0.068	0.055 ± 0.081	2-2-0	0.03 ± 0.10	≤1.7

[a] Data point closest to 2-3-2-0 ellipse, but does not intercept it.

levels are made under the assumption that no transitions of significant intensity have multipole order L greater than 2. It is further assumed that mixed dipole/quadrupole transitions in which the quadrupole contribution to the total intensity is greater than about 10% are $M1/E2$ transitions, rather than $E1/M2$, and that these transitions therefore connect states of the same parity. Similarly, spin 2 levels which display significant branching to the 0^+ ground state are assumed to have even parity.

A summary of all angular-correlation results is given in Table I. The results for the individual levels will be discussed in order of increasing level energy.

1131-keV level. The experimental data points and the fit-function curve for the 528-602 cascade are shown in Fig. 3. The values for A_2 and A_4 are consistent with the theoretical values for a 4-2-0 cascade, as shown in Fig. 4, but spin assignments of 3, 2, or conceivably even 1 for the 1131-keV level cannot be ruled out by the angular-correlation data. No other low-lying level, however, is compatible with a spin 4 assignment; and in view of the systematics of $N=84$ isotones (which will be discussed later), it is very likely that this is the expected 4^+ level.

In a previous study of the ^{140}Ba levels[11] a tentative assignment of 2^+ was made for the 1131-keV level and 4^+ for the 1511-keV level, based on the apparent observation of a crossover transition to the ground state from the former level but not from the latter. A crossover transition to the ground state from the 1131-keV level would have an energy almost identical to that of an intense transition known to lie between the levels at 2933 and 1803 keV. This latter transition is in coinci-

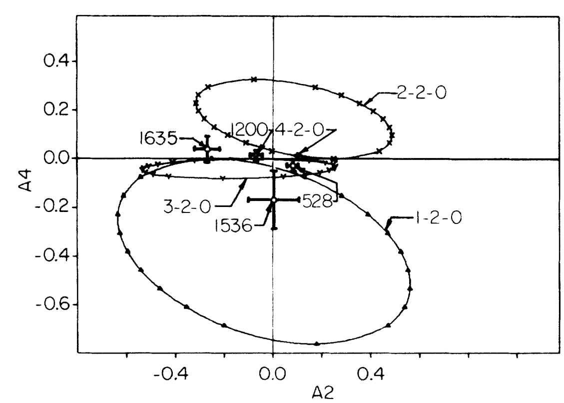

FIG. 4. Results for direct cascades. The curves are the theoretical values of A_2 and A_4 as functions of the dipole-quadrupole mixing in the first transition of the cascade. Increments of 10% mixing are indicated by the points on the ellipses. The experimental data points are identified by the energy of the first transition in the cascade.

dence with the 602-keV γ ray, while the former transition would not be. It was observed in Ref. 11 that the relative intensity of the 1130-keV peak is much less in coincidence with the 602-keV γ ray than in singles. As Fig. 3 shows, however, the 1130-602 keV angular correlation has a most unusual pattern, with the count rate at 180° (the angle at which the coincidence measurements in Ref. 11 were made) being much less than at all other angles. Thus, the reduced coincidence intensity of the 1130-keV transition is an angular-correlation effect (as was observed in Ref. 11 might possibly be the case) rather than an indication of a crossover transition from the 1131-keV level.

Further evidence for the existence of a crossover from the 1131-keV level was sought for in Ref. 11 by searching for an 1131-keV peak in coincidence spectra gated by transitions feeding this level. The most intense feeding transition, at 672 keV, is no help in this regard because it is also in coincidence with the 1130-keV γ ray. The next most intense feeding transition, at 1008 keV, is unfortunately a member of an unresolved doublet. While a gate on this doublet did indeed show a peak at the right energy (see Fig. 3 of Ref. 11), it was not possible to establish which member of the doublet was the gating transition. The 1130-602-keV angular correlation (discussed below in connection with the 2933-keV level) tends to substantiate the conclusion that the 1130-keV peak does indeed have two components—but that both components are in coincidence with the 602-keV transition, which would not be true if one component were a crossover from the 1131-keV level. It thus appears that the occurrence of the 1130-keV peak in the (1008+1011)-keV gate should be taken to indicate the existence of an 1130 component lying elsewhere in the decay scheme.

Still another consideration in the spin assignment for the 1131-keV level is the β branching to this level. In Ref. 14 it was established that the ground state of ^{140}Cs is probably either 1^- or 2^-. Angular-correlation measurements presently in progress on transitions in ^{140}Cs indicate that the 1^- assignment is most likely correct. Whereas a 2^- state might β decay directly to a 4^+ level in the daughter (a first-forbidden unique transition), a 1^- state would not (a third-forbidden transition). However (as Schussler *et al.*[10] also point out), the γ-ray intensity balance for the 1131-keV level is consistent with zero direct β feeding if there is no crossover transition to the ground state, and therefore consistent with a 4^+ assignment. This assignment also removes the ambiguity in the placement of the 693-keV transition reported in Ref. 11; this transition can no longer be placed as feeding the 1131-keV level from the 1824-keV level (which would require an $E4$ multipolarity).

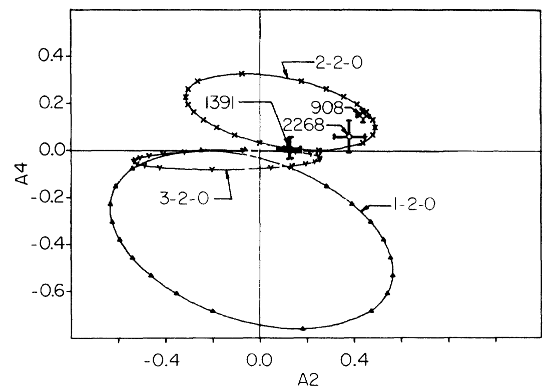

FIG. 5. Direct cascade results (continued).

In summary, then, there appear to remain no arguments against a 4^+ assignment for the 1131-keV level. Since (as the next section shows) the systematics strongly favor a 4^+ assignment, this assignment is adopted.

1511-keV level. The 908-602-keV angular-correlation result, shown in Fig. 5, definitely establishes the spin of this level as 2, and the large (about 55%) quadrupole mixing indicates that the parity is even. This substantiates the observation of Schussler *et al.*[10] that the anisotropy of the 908-602-keV cascade is too great for a 4^+ assignment. The absence of a transition to the ground state, established in Ref. 11, remains a mystery. Although this crossover transition from the second 2^+ state is forbidden in the simple vibrational phonon model, it usually occurs with an intensity at least as great as a few percent of that of the stopover transition.

1803-keV level. The data point for the 1200-602-keV correlation, shown in Fig. 4, is consistent with spin assignments of 1 or 3 for the 1803-keV level, with spin 2 being a remote possibility. The data point for the 672-(528)-602 skip cascade, shown in Fig. 6 (plotted under the assumption that the 1131-keV level is 4^+ and the unobserved 528-keV transition is pure $E2$), is consistent with assignments of 3 or 5, with 4 being a remote possibility. The combined results give a unique spin 3 assignment.

This level was tentatively assigned spin-parity 3^+ in Ref. 11, based primarily on an apparent similarity between the levels in ^{140}Ba and ^{134}Ba. This similarity has been destroyed, however, by the interchange of the 2^+ and 4^+ assignments previously made for the 1131- and 1511-keV levels in ^{140}Ba. It seems more likely, in view of the $N = 84$ systematics to be discussed below, that the parity of the 1803-keV level is odd. An odd-parity assignment is consistent both with the absence of direct β feed-

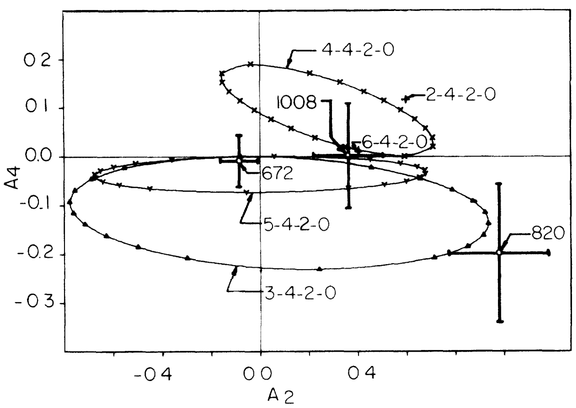

FIG. 6. Results for skip cascades.

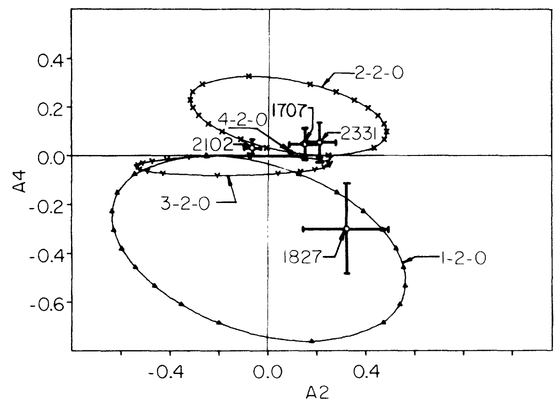

FIG. 7. Direct cascade results (continued).

ing to this level and with the pure dipole nature of both the 672- and 1200-keV transitions, as indicated in Table I.

1824-keV level. The 1222-602-keV correlation shows unequivocally that this is a 0-2-0 cascade, as was proposed in both Refs. 10 and 11. It also establishes (if previously there was any doubt) that the first excited state is indeed 2^+.

1951-keV level. The 820-(528)-602 skip cascade (Fig. 6) suggests rather strongly, in spite of the large error bars due to poor statistics, that this level has spin 3. The large quadrupole mixing of the 820-keV γ ray further suggests that the parity is even. There is no transition from this level to either the ground or first excited state.

1994-keV level. The data point for the 1391-602-keV cascade (Fig. 5) is equally consistent with spins of 2, 3, or 4 for this level. However, there is a crossover transition to the ground state with an intensity of 24% of the stopover transition and a placement which is well established by coincidence measurements. This defines a unique 2^+ assignment for the level. The 1391-keV transition is nearly, but not quite, pure dipole.

2138-keV level. The error bars are rather large for both the 1536-602 direct cascade (Fig. 4) and the 1008-(528)-602 skip cascade (Fig. 6). Nevertheless, the results would appear to indicate a spin of 3 of this level. Neither spin 2 nor spin 4 is definitely ruled out by the data, but both choices are rather unlikely. Since both deexcitation transitions may be nearly pure dipole, the parity of the 2138-keV level is not determined.

2237-keV level. The 1635-602-keV cascade (Fig. 4) is consistent with a spin of 1 or 3 for this level, but the presence of an intense crossover to the ground state rules out the spin 3 assignment. Spin 2 is also a possible, but less likely, assignment. The systematics to be discussed in the following section suggest that this may be a 1^- level; if so, the angular correlation is consistent with a pure $E1$ multipolarity for the 1635-keV transition. It may also be mentioned that this level deexcites to both of the lower-lying 0^+ levels and to both lower-lying 2^+ levels.

2310-keV level. The data point for the 1707-602-keV cascade, as shown in Fig. 7, is consistent with 2, 3, or 4 for the spin of this level. The branching to the ground state is greater than 20%, so the most probable assignment is 2^+.

2430-keV level. While the error bars for the 1827-602-keV correlation are large (Fig. 7), the choice of spin 1 is rather strongly indicated. Furthermore, the large quadrupole mixing suggests even parity. There is a strong branch from this level to the ground state, and a weaker branch (supported by coincidence data) to the second 2^+ level. A weak transition to the 4^+ level, shown in Fig. 4 of Ref. 11, is not supported by coincidence data and could perhaps be misplaced. (One would not expect to detect a transition between 1^+ and 4^+ levels.)

It may be observed here that a level in ^{142}Ce at 2398 keV has decay and angular-correlation[4] properties remarkably similar to those of the 2430-keV level in ^{140}Ba.

2704-keV level. The data point for the 2102-602-keV correlation (Fig. 7) is consistent with spin choices 1, 2, or 3; the last choice is rejected, however, because there is an intense crossover to the ground state. If the spin is 1, the 2102-keV transition is nearly (but not quite) pure dipole, leaving the parity undetermined; if the spin is 2, the transition has significant quadrupole mixing, indicating even parity.

2871-keV level. The data point for the 2268-602-keV cascade lies on the 2-2-0 elipse, as shown in Fig. 5. The amount of quadrupole mixing may be small, so no statement can be made about the parity of the level. Also, there is no crossover tran-

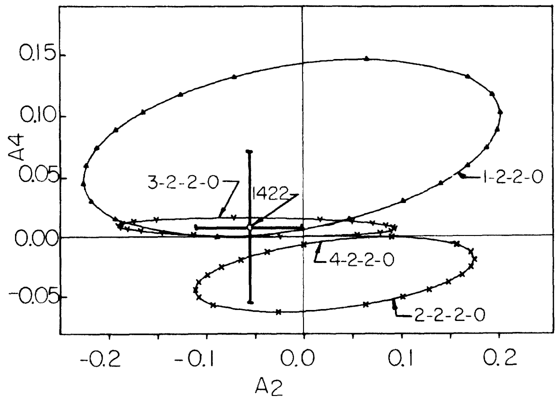

FIG. 8. Skip cascade results (continued).

sition to the ground state; indeed, there are no other tr^nsitions at all of significant intensity from this level.

2933-keV level. The 2331-602-keV correlation (Fig. 7) is consistent with a spin of either 2 or 3 for this level, with 4 being a remote possibility. The 1422-(908)-602 skip cascade (Fig. 8) unfortunately adds little additional information. This cascade was analyzed under the assumption that the unobserved 908-keV transition is 55% quadrupole, as deduced from the 908-602-keV correlation. The data point for the 1130-(1200)-602 skip cascade is shown in Fig. 9. This point requires some additional comment.

The 1200-keV transition was shown above to be pure dipole. In parallel with this transition is a 672-528-keV cascade with an intensity about one-fourth as great. Thus, the 1130-602-keV correlation must be analyzed as a composite skip (or 1-3) and double skip (or 1-4) cascade. The result of the analysis, however, is not consistent with the data point for any possible spin of the 2933-keV level, as Fig. 9 shows. It was observed above in connection with the spin of the 1131-keV level that

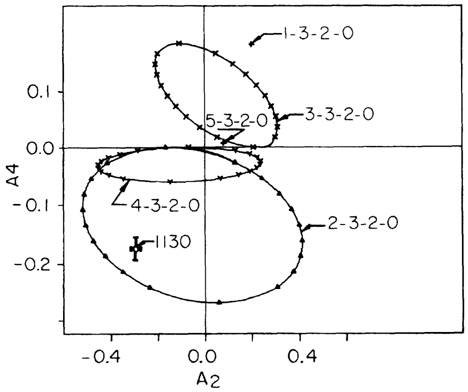

FIG. 9. Skip cascade results (continued).

the 1130-keV transition is probably a doublet. If the "other" component of the 1130-keV peak is also in coincidence with the 602-keV γ ray (which would necessitate that this component be something other than a crossover from the 1131-keV level), it would of course affect the 1130-602-keV correlation. Unfortunately, the placement of this "other" 1130 component is not known; it might be coincident with either the 1008- or the 1011-keV transition. Since the multipolarity of the latter of these transitions has not been established, it is difficult to estimate quantitatively the effect of the "other" 1130 component on the 1130-602-keV correlation. On the other hand, the coincidence intensities indicate that the majority of the 1130 intensity lies between the levels at 2933 and 1803 keV, as indicated in Fig. 1. One may therefore hope that the presence of the "other" 1130 component does not drastically affect the position of the data point in Fig. 9. In particular, if the correlation with the "other" transition has a small or positive A_4, then Fig. 9 indicates that the 2933-keV level has spin 2 and that its deexcitation transition is predominantly quadrupole. Any other spin assignment for the 2933-keV level would require the "other" correlation to have an unreasonably large negative value for A_4. Since the 1803-keV level has (presumably) odd parity, we conclude therefore that the 2933-keV level has spin-parity 2^-.

Returning to the 2331-602-keV cascade, we see that a 2^- assignment for this level is consistent with a pure $L=1$ multipole order for the 2331-keV transition. The 1422-(908)-602 skip cascade is a bit more of a problem, since Fig. 8 would seem to indicate that the 1422-keV transition (to the 2^+ 1511-keV level) has significant quadrupole mixing if the spin of the initial state is 2; still, in view of the large error bars, it seems reasonable to say that this does not contradict the odd-parity assignment for the 2933-keV level.

Further support for the 2^- assignment comes from the small log*ft* value of 6.3 for the β branch to this level. This value, which is significantly smaller than that for the β branches to all the lower-energy levels, would be unusually small for a first-forbidden β decay in this region of the Chart of the Nuclides and is much more likely to represent an allowed transition.

Finally, it should be observed that the decay of the 2933-keV level is quite consistent with the 2^- assignment. There is no decay to the ground state or to the excited 0^+ or 4^+ levels, but there is decay to most other levels. In particular, in addition to the strong decay to the 3^- level, there is also a reasonably intense (in view of the low transition energy) transition to the 2237-keV level, which is most probably 1^-. Thus, it appears that

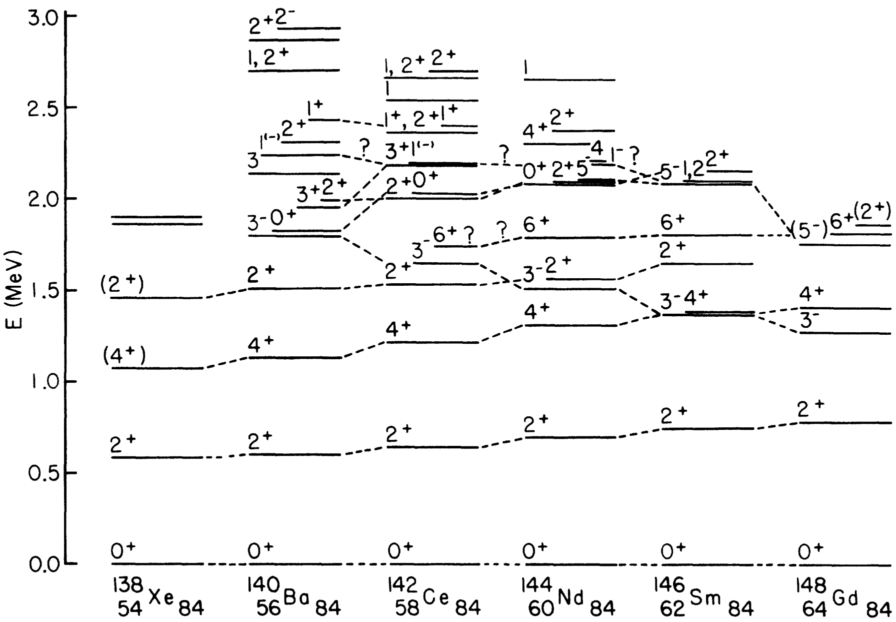

FIG. 10. Level systematics for the $N=84$ isotones. References are indicated in the text.

there are strong interconnecting transitions among the odd-parity levels in this nucleus.

IV. DISCUSSION

Experimental information is now available on six isotones with $N=84$. This information is displayed in Fig. 10. The references are as follows: ^{138}Xe, communication from Western[15] concerning a study of the decay of ^{138}I presently in progress at this laboratory; ^{140}Ba, present work; ^{142}Ce, the angular-correlation study of Basinger, Schick, and Talbert[4] and the ^{140}Ce (t, p) study of Mulligan *et al.*[6]; ^{144}Nd, the angular-correlation study of Behar, Grabowski, and Raman[17] and references quoted therein; ^{146}Sm, the decay scheme work of Antman *et al.*[18] and Paperiello *et al.*[19]; ^{148}Gd, the decay scheme work of Bowman, Haenni, and Sugihara[20] and the in-beam study of Krien *et al.*[21]

The first 2^+ state is seen to increase monotonically in energy with increasing proton number. It would be interesting to see if the energy reaches a maximum at ^{148}Gd, due to the closing of the $g_{7/2}$-$d_{5/2}$ subshell at $Z=64$. It would also be interesting to see if the apparent trend toward lower energy continues with still lighter isotones such as ^{136}Te, in spite of the proximity to the closed major proximity to the closed major proton shell at $Z=50$.

The first 4^+ state shows the same general behavior as the first 2^+ state. The energy ratio of these two states varies only slightly, but the variation is systematic: 1.82 for ^{138}Xe, 1.88 for ^{140}Ba, 1.90 for ^{142}Ce, 1.89 for ^{144}Nd, 1.85 for ^{146}Sm, and 1.81 for ^{148}Gd.

The second 2^+ state likewise increases monotonically in energy with increasing Z, but less rapidly. In all cases the crossover transition from this state to the ground state is weak or nonexistent. Furthermore, the angular-correlation studies in ^{140}Ba, ^{142}Ce, and ^{144}Nd show that the transition to the first 2^+ state has considerable $E2$ contribution, with the same sign of the mixing ratio in each case. (The reader is cautioned that in Ref. 4, we employed a different sign convention for the mixing ratio than that used in the present work. We use here the sign convention given in the *Nuclear Data Tables*.[13]) These facts suggest at least a partly collective interpretation for this level. It would be inviting to call the second 2^+ level a two-phonon vibrational state, especially in view of the weakness of the transition to the ground state. There are two problems with this interpretation. The 0^+-2^+-4^+ triplet would then have to be those seen at 1824, 1511, and 1131 keV, respectively, which is very wide spacing. More fundamental, perhaps, is the rather large $M1$ transition strength to the first 2^+ level.

The first 3^- level drops rapidly with increasing Z, in contrast with the even-parity levels. The ratio $B(E1; 3^- \to 4^+)/B(E1; 3^- \to 2^+)$ is 1.46 in ^{140}Ba and 1.23 in ^{142}Ce. The ratio is not yet known in ^{138}Xe, and in the higher Z isotones the 3^- level is too low in energy for the ratio to be determined.

The first 6^+ state shows a very slow increase in energy with increasing Z. This state has not been observed in ^{140}Ba, and its assignment in ^{142}Ce is highly tentative.

The second 0^+ level is definitely established only in ^{140}Ba, ^{142}Ce, and ^{144}Nd. Its energy is consistently more than 3 times that of the first excited state, so its interpretation as a member of the two-phonon triplet is quite tenuous.

The first 3^+ state is seen only in ^{140}Ba and ^{142}Ce. In both nuclei the decay of this level is largely to the 4^+ state, via a transition with considerable quadrupole mixing. This would suggest at least a partial collective character for the level, probably in terms of a three-phonon oscillation. An alternative interpretation for the 3^+ level in ^{142}Ce, proposed in Ref. 4, is that it might be the second member of a quasirotational band built on the 2_2^+ state. This interpretation seems less promising in ^{140}Ba than in ^{142}Ce, since in the former nucleus the 3^+-2_2^+ separation is considerably less than the 2^+-0^+ separation, whereas in an axial rotational nucleus the separations would be equal.

The third 2^+ state occurs in the vicinity of the 0_2^+ and 3^+ levels, which might tempt one to suggest a three-phonon character for the state. In ^{140}Ba and ^{142}Ce, however, the decay of the state is inconsistent with the phonon model in that the decay is primarily by an $M1$ transition to the first 2^+ state with significant branching to the ground state. The pure phonon model predicts only $E2$-enhanced branches to the two-phonon states. In ^{144}Nd, on the other hand, there is no branching to the ground state and the transition to the first 2^+ state is largely $E2$. It may be, therefore, that there is a gradual change in the properties of this level as Z increases (along with the gradual increase in energy which is characteristic of nearly all the even-parity levels).

The first 1^- level is definitely established only in ^{144}Nd. However, a tentative connection is made in Fig. 10 with levels in ^{140}Ba and ^{142}Ce having a similar mode of decay and for which the 1^- assignment, though not definite, is consistent with the experimental data. The reduced branching ratio to the first excited and ground states, $B(E1; 1^- \rightarrow 2^+)/B(E; 1^- \rightarrow 0^+)$, is 2.10 in ^{140}Ba, 1.59 in ^{142}Ce, and 1.23 in ^{144}Nd. The energy decreases with increasing Z as does that of the 3^- state, but not as rapidly.

The first 1^+ level is established in ^{140}Ba and ^{142}Ce. In both cases, this level decays to the first excited state (2^+) via a transition which involves considerable quadrupole mixing. The sign of the mixing ratio is the same in both cases. The strong quadrupole mixing suggests considerable collective character for this level. From symmetry requirements, neither phonon models nor collective rotor models presently allow for the existence of 1^+ pure collective states. It would seem therefore, that the most fruitful approach to understanding these $N=84$ nuclei would involve a unified model embodying both particle and collective degrees of freedom. Heyde and Brussaard[22] have given a description of three $N=84$ nuclei by considering the coupling of two neutrons in the $f_{7/2}$ level to the phonon oscillation core. More recently, Vanden Berghe[23] has extended this model to include several particle orbits and has applied this extension, in an average manner, to five $N=84$ nuclei.

In both the Heyde and Brussaard and Vanden Berghe calculations the model Hamiltonian is written

$$H = H_{\text{coll}} + H_p + H_{\text{int}},$$

where H_{coll} is the Hamiltonian for quadrupole surface oscillations of the doubly even core. The term H_p is the sum of single-particle Hamiltonians for the pair of neutrons and also includes a residual interaction between the pair. The term H_{int} describes the direct interaction, assumed adiabatic, between these extracore nucleons and the surface vibrations of the core. The form used is

$$H_{\text{int}} = C \sum_{j=1}^{2} [\alpha^2 Y^2(\hat{r}_j)]^0$$

in which the $\alpha_\mu{}^2$ are the surface coordinates, $Y_\mu{}^2(\hat{r}_j)$ is a second order spherical harmonic in the coordinates of the jth extracore nucleon, and the coupling of these two second rank tensors is to angular momentum zero; C is a constant which specifies the strength of the interaction.

The basis states used to diagonalize the model Hamiltonian consist of the states of the extracore nucleons coupled to angular momentum $J, |(j_1 j_2)J\rangle$, coupled to the phonon core states, $|NL\rangle$, to form states of total angular momentum I. The notation is $|(j_1 j_2)J; NL: IM\rangle$. In both cases the phonon basis is truncated at $N=3$ phonons. Furthermore, Heyde and Brussaard require $j_1 = j_2 = \frac{7}{2}$ $(2f_{7/2})$, while Vanden Berghe allows j_1 and j_2 to be any of the orbitals; $3p_{1/2}$, $3p_{3/2}$, $2f_{5/2}$, $2f_{7/2}$, $1h_{9/2}$, and $1i_{13/2}$. The calculations also differ in that Heyde and Brussaard use a spin-exchanged Gaussian residual interaction between the pair, while Vanden Berghe uses a pairing interaction. In both cases the model states are labeled by $|I_n\rangle$, where n is an ordinal number labeling the states of given I in order of energy.

The calculation of Heyde and Brussaard correctly predicts the inhibition of the crossover transition from the 2_2 state to the ground state 0_1, relative to the 2_2 to 2_1 transition. But, this calculation incorrectly assigns a positive quadrupole moment to the 2_1 state known to be negative in both ^{144}Nd and ^{142}Ce. The inclusion of the other orbitals by Vanden Berghe rectifies this deficiency. Therefore, we shall interpret our results in terms of this latter calculation.

The model state functions given as linear combinations of the above-mentioned basis are quoted in Ref. 23 for the positive-parity states: 0_1, 0_2, 2_1, 2_2, 2_3, 3_1, 4_1, and 6_1. The last value will play no role here, since we have not observed the 6_1^+ state. It must be stressed that the state functions quoted are those corresponding to an average fit to the five $N=84$ nuclei, ^{140}Ba, ^{142}Ce, ^{144}Nd, ^{146}Sm, and ^{148}Gd. The adjustable parameters of the model have not been optimized for ^{140}Ba and the agreement between theory and experiment is only qualitative for the energies of the levels. Correspondingly, we may only expect the state functions to be in qualitative agreement with experiment regarding their physical content other than total spin and parity. We have not made an energy calculation to optimize the parameters for ^{140}Ba. Rather, for this discussion, we content ourselves with using the Vanden Berghe state functions to calculate transition probabilities and mixing ratios in order to assess the applicability of this model and the value of future extended calculations based on this approach. To aid in this assessment, we have continued Vanden Berghe's calculations to extract transition probabilities, which were not included in Ref. 23.

For purposes of computing $M1$ transition probabilities we have used, as did Vanden Berghe, the gyromagnetic ratios, $g_{\text{core}}=Z/A$, $g_l=0$, $g_s=-3.826$. Our program reproduces the quoted value $\mu_{2_1}=0.30\mu_N$ to two significant figures which is the extent to which the wave function components are given.[23] Our program also reproduces the two different quoted values for the $B(E2;\, 2_1^+\rightarrow 0_1^+)$ when the core strength parameter given by Vanden Berghe is used and the neutron effective charge is taken as e and $0.5e$, respectively. These served as checks upon our consideration of the Vanden Berghe approach.

Our ability to compare calculations results with experiment is limited on one hand by the experimental information available and on the other by the number of states for which the state functions are given. Accordingly, we may compare the $E2/M1$ mixing ratios and relative branching for four levels; identified as the 2_2^+ at 1511 keV, 0_2^+ at 1824 keV, 3_1^+ at 1951 keV, and the 2_3^+ at 1994 keV. In every case we find considerable improvement in the comparison between theory and experiment if we (i) reduce the strength of the collective $E2$ contribution by 20% and (ii) use an effective neutron charge of $e_n^{\text{eff}}=0.4e$. The first of these changes is consistent with the smaller values of Z, mean radius, and intrinsic core energy appropriate for ^{140}Ba, in contrast to the corresponding values used for the average calculation. The second change is consistent with Vanden Berghe's alternative use of $e_n^{\text{eff}}=0.5e$. The results of our calculations continuing the use of Vanden Berghe's model are tabulated in Table II.

In the case of the 1511-keV, 2_2^+ level the (modified) model correctly predicts the sign and nearly gives the correct value for the $E2/M1$ mixing ratio for the $2_2^+\rightarrow 2_1^+$ transition. The model assigns too much $E2$ strength to the crossover transition however. This indicates that a ^{140}Ba optimized 2_2^+ state should have a much larger $N=2$, $L=2$ (two phonon) contribution than the average function possesses. Direct use of the Vanden Berghe average parameters for core and particle contributions results in theoretical values of $\delta=-2.45$ and 40/60 ratio of the crossover transition. Clearly these are in worse agreement with the experimental facts for ^{140}Ba.

The modified model correctly predicts the branching for transitions depopulating the 0_2^+ level. The calculated transition intensity for the $0_2^+\rightarrow 2_2^+$ transition, given in the table as ~0, is actually 0.02. The model independent energy factor only yields a value of 0.1, so the model prediction for the ratio $B(E2;\, 0_2^+\rightarrow 2_2^+)/B(E2;\, 0_2^+\rightarrow 2_1^+)$ is consistent with experimental observation.

The model has similar success in correctly predicting the branching of transitions from the 2_3^+ level. The branching is remarkably close although the $E2/M1$ mixing is not so well described.

The transitions from the 3_1^+ level are very poorly accounted for using either set of parameters but somewhat better using the ^{140}Ba adjusted set. The model incorrectly predicts the sign of the $E2/M1$ mixing for the $3_1^+\rightarrow 4_1^+$ transition and fails badly in predicting the branchings from this level. The quoted state function for this state has no three-phonon contribution. The pure phonon model would predict essentially zero crossover, as is seen, so it seems clear that a more correct 3_1^+ level description would include considerable three-phonon core contribution. This lack of three-phonon core component to the 3_1^+ state may be the result of truncating the phonon space at three phonons. This would result in inhibiting the three-phonon state strength by omitting coupling matrix elements to the four- and higher-phonon basis states and indirectly by the coupling matrix elements of these higher states with the lower ones already included in the basis. The three-phonon core state is, of course, the first state to contain $L=3$.

In summary, it appears that the model of Heyde

TABLE II. Comparison of transition branchings and multipolarity mixings in ^{140}Ba from this work and the theoretical approach of Vanden Berghe (Ref. 23) (modified as described in the text).

Level (keV)	I_n^π	Transition to: I_n^π	E_γ (keV)	δ_{calc}	δ_{expt}	Relative I_γ ($M1,E2$) Calc	Expt
1511	2_2^+	0_1^+	1511	···	···	12(0,12)	~0
		2_1^+	908	−1.7	−1.1	88(23,65)	100(45,55)
		4_1^+	380	···	···	~0	~0
1824	0_2^+	2_1^+	1222	···	···	100(0,100)	100(0,100)
		2_2^+	313	···	···	~0	~0
1951	3_1^+	2_1^+	1349	0.14	···	57(55,2)	~0
		4_1^+	821	0.37	−0.51	33(29,4)	100(15-80,85-20)
		2_2^+	440	0.15	···	10(9.6,0.4)	~0
1994	2_3^+	0_1^+	1994	···	···	18(0,18)	19(0,19)
		2_1^+	1392	0.61	0.16	81(59,22)	81(79,2)
		4_1^+	863	···	···	1(0,1)	~0
		2_2^+	483	−0.13	···	~0	~0
		0_2^+	170	···	···	~0	~0
		3_1^+	43	−0.01	···	~0	~0

and Brussaard and Vanden Berghe has reasonable qualitative agreement with the observed experimental facts for ^{140}Ba. Some details require further improvements in the model, but this limited comparison suggests the merit of further consideration.

The question of the negative parity levels remains open even though some calculations have been done[23,24] involving the coupling of quadrupole and octupole phonons. To include the particle effects requires as a practical matter a perturbation approach, since the basis becomes very large and in any case there remains the nagging question of how to treat the core transition operators properly in shape-changing transitions. The interesting behavior of the negative parity levels seen in the $N=84$ nuclei indicates that the detailed nature of their structure will have to receive considerable further study.

On the experimental side also there are avenues for fruitful further research. It would be worthwhile to perform reaction studies on both ^{138}Xe and ^{140}Ba, especially to locate the higher-spin levels in these nuclei. They could be reached by the reactions ^{136}Xe(t,p) and ^{138}Ba(t,p), respectively. It would be of interest to extend Fig. 10 to ^{150}Dy, to determine the effect of the closing of the $Z=64$ subshell, and to ^{136}Te and ^{134}Sn, to see what happens as the closed shell at $Z=50$ is approached. Work presently in progress at the TRISTAN facility on the development of methods for producing a wider range of fission-product chemical species should make possible in the near future a much more detailed study of ^{138}Xe, and subsequently, it is hoped, nuclei such as ^{136}Te should become available for investigation.

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