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Level structure of ^{131}Cs and the decay energy of ^{131}Ba†

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The decay of ^{131}Ba (11.7 day) has been studied with Ge(Li) spectrometers and with a Ge(Li) γ-γ coincidence system. Twelve γ transitions and three levels in ^{131}Cs at 919, 1170, and 1342 keV have been identified which were not reported previously. Upper limits are given for the γ-ray intensities of previously reported transitions at 323 and 508 keV which were not observed in this experiment. The Q value for the decay of ^{131}Ba was determined from the (electron capture)/β^+ intensity ratio to be 1372^{+10}_{-20} keV. This value agrees with the latest atomic mass evaluation, but disagrees with the only previous measurement by 207 keV. Our (electron capture)/β^+ intensity ratio and the Q value deduced from a reaction study suggest that the (electron capture)/β^+ ratio is not anomalous in contrast to some recent predictions. The ^{131}Cs level structure and γ transition probabilities are compared to the results of an intermediate-coupling calculation.

[RADIOACTIVITY ^{131}Ba; measured E_γ, I_γ, γ-γ coincidence; deduced Q value, logft. ^{131}Cs deduced levels, γ branching. Isotope separation, Ge(Li) detectors.]

I. INTRODUCTION

As regards its nuclear properties, ^{131}Cs is situated in one of the regions of the so-called transitional nuclides. A number of recent developments has led to renewed interest in the level structure of the odd-mass I, Cs, and La isotopes in this mass region. Analysis[1] of the energy spectrum of the high-spin unique-parity states excited in heavy-ion-induced reactions has provided evidence that the cores of these nuclei may be characterized by rather stable triaxial shapes; and, in the specific case of ^{135}La, the predictions of this triaxial-rotor-plus-particle model concerning the properties of the low-spin states are supported by the results of radioactive-decay studies.[2] From a somewhat different point of view, a new microscopic theory of collective excitations in the "spherical" odd-mass nuclei has been developed [see, e.g., Ref. 3, and references contained therein], the results of which have been applied to the description of the properties of certain low-lying states in a number of nuclides, including the odd-mass I, Cs, and La isotopes.[4] In addition, recently published intermediate-coupling calculations[5] have now been rather successful in describing many of the properties of the level structure of the nuclide ^{199}Hg, which lies in another transition region to which several different theoretical models have been applied. It is thus of interest to explore the extent to which these ideas can account for the features of the lower-Z transitional nuclei, of which ^{131}Cs is one example.

Several investigations[6-11] of the level scheme of ^{131}Cs as observed in the decay of ^{131}Ba ($T_{1/2} = 11.7$ day) have been reported in the literature. These, however, contain a number of disagreements regarding the existence and the placement of some of the γ-ray transitions. In addition, the decay energy (Q value) of the ^{131}Ba $\rightarrow$ ^{131}Cs decay has been reported[12] to be 1165 ± 14 keV. However, in their 1971 atomic mass evaluation, Wapstra and Gove[13] point out that this value is ~200 keV lower than that deduced from other mass-related information.

In the present work, we give the results of an investigation of the ^{131}Cs level scheme as observed in the decay of ^{131}Ba. In addition to resolving the problems of the placement of several of the previously unplaced γ-ray transitions, a number of new γ rays and three additional energy levels have been found. The Q value for the ^{131}Ba decay has been inferred from the measured electron-capture to positron branching and found to be consistent with that expected from the atomic mass evaluation. The results of an intermediate-coupling model calculation[14] of the positive-parity states in ^{131}Cs are compared with our experimental results.

II. EXPERIMENTAL METHODS AND RESULTS

A. Source preparation

The ^{131}Ba activity was produced by ~600–800 MeV proton bombardment of stacked thin Pr-metal foils in the Clinton P. Anderson Meson Physics Facility (LAMPF) at LASL. The total thickness of the irradiated Pr was ~0.03 cm, and typical bombardments involved integrated beam currents of ~15 μA h. Following bombardment, the irradiated foils were shipped to the Idaho National Engineering Laboratory for study. Isotopically pure sources of ^{131}Ba were obtained by chemical extraction of the Ba fraction followed by isotope separation.

B. Singles γ-ray measurements

Singles γ-ray spectra were measured with a 65-cm^3 closed end coaxial Ge(Li) detector with an energy resolution of ~2 keV fullwidth at half maximum (FWHM) at 1 MeV. A typical γ-ray spectrum of ^{131}Ba is shown in Fig. 1. γ-ray spectra of sources from four irradiations were each measured over a period of about two weeks to assure that all of the γ rays decayed with the ^{131}Ba half-life.

The energies of the more intense γ rays were determined from spectra containing lines from ^{131}Ba and various sources which emit γ rays whose energies are known precisely.[15,16] Sources of ^{210}Pb, ^{241}Am, ^{109}Cd, ^{153}Gd, ^{139}Ce, ^{203}Hg, ^{51}Cr, ^{113}Sn, ^{7}Be, ^{207}Bi, ^{137}Cs, ^{94}Nb, ^{54}Mn, ^{88}Y, ^{65}Zn, and ^{60}Co were used in this procedure, with eight or more γ rays of known energy being used in each energy-calibration run. The adopted ^{131}Ba γ-ray energies were determined from a linear or quadratic function (energy vs channel) obtained from a least-squares fit to the calibration line energies and positions. The uncertainty in each γ-ray energy was determined by adding in quadrature the contribution from the peak location with a standard reference error (13 ppm below 350 keV and 19 ppm above 350 keV). In some cases the uncertainties computed in this manner were the same as those of the energy calibration lines in the same energy region; in this case the uncertainties were arbitrarily adjusted upward by 1 or 2 eV. The energies of the weaker γ rays were determined by the same technique but with the stronger ^{131}Ba γ rays used as energy standards.

The full-energy peak efficiency of the Ge(Li) detector had been determined using the techniques described in Refs. 17 and 18. For most of the γ rays, the relative intensities were determined from a weighted average of five measurements. The corresponding uncertainties were computed by adding in quadrature the statistical uncertainty in the mean intensity and the estimated error in the ratio of the efficiency to that at 496 keV. Although this process gives errors as low as 0.2%, a mini-

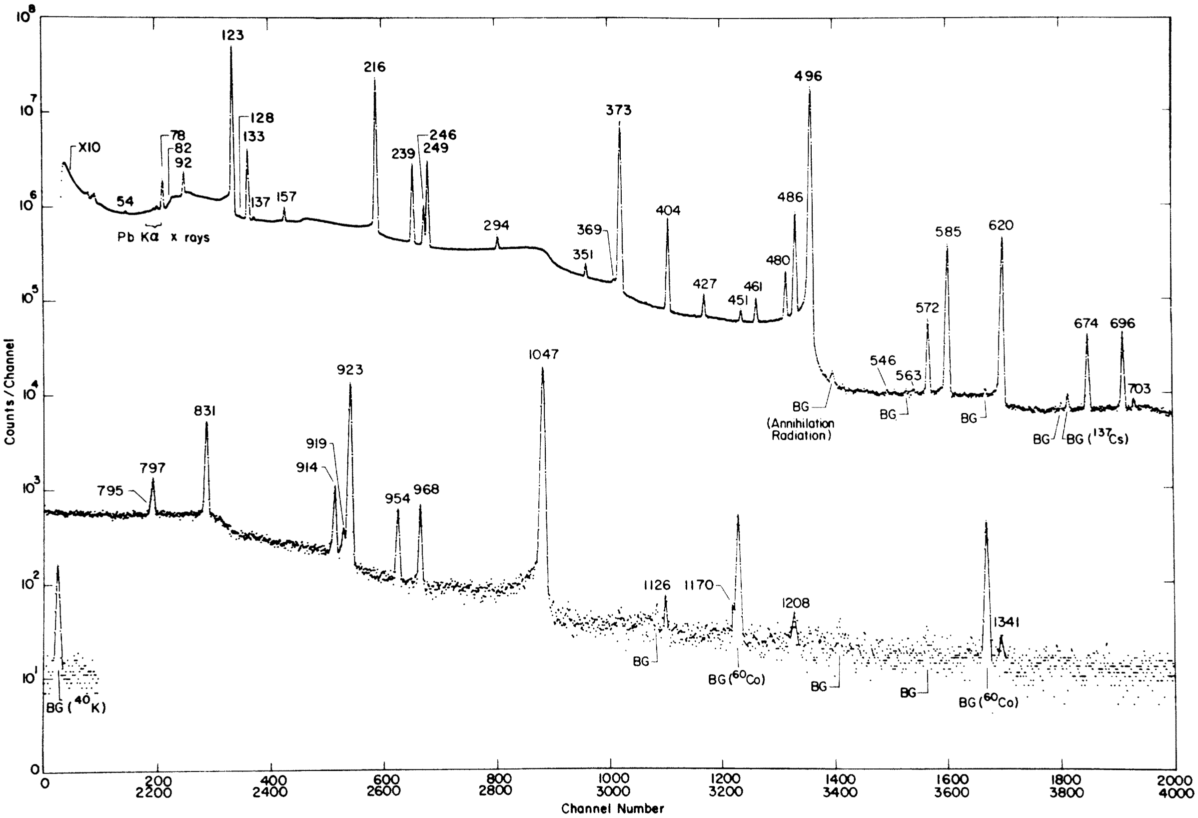

FIG. 1. γ-ray spectrum of ^{131}Ba obtained with a 65 cm^3 Ge(Li) detector, with a source-detector distance of 10 cm. The peaks identified by BG are background lines.

TABLE I. Energies and relative intensities of γ rays from the decay of ^{131}Ba.

Energy (keV)	Relative intensities			
Present experiment	Present experiment[a]	R. Singh *et al.*[b]	L. Hasselgren *et al.*[c]	T. Kučarova *et al.*[c]
54.96 ± 0.11	0.198 ± 0.010	0.047	0.29 ± 0.5	0.19 ± 0.04
78.764 ± 0.016	1.56 ± 0.05	2.08	1.70 ± 0.08	1.9 ± 0.4
82[d]	<0.4		0.045 ± 0.003	
92.289 ± 0.014	1.37 ± 0.18	1.81	1.85 ± 0.08	1.54 ± 0.33
123.802 ± 0.008	61.9 ± 1.8	72.2	66.4	59 ± 9
128.09 ± 0.14	0.037 ± 0.012			
133.612 ± 0.014	4.61 ± 0.13	5.2	4.51 ± 0.25	4.2 ± 0.8
137.357 ± 0.039	0.068 ± 0.004			<0.38
157.147 ± 0.009	0.406 ± 0.011	0.081	0.58 ± 0.04	0.54 ± 0.17
216.073 ± 0.008	42.2 ± 0.9	42.5	51.4 ± 0.3	41.7
239.623 ± 0.008	5.13 ± 0.09	4.7	6.26 ± 0.24	5.0 ± 1.0
246.879 ± 0.012	1.37 ± 0.04	0.81	1.54 ± 0.12	1.5 ± 0.8
249.426 ± 0.008	6.03 ± 0.12	6.8	7.3 ± 0.5	6.1 ± 1.3
294.508 ± 0.020	0.356 ± 0.009	0.21	0.375 ± 0.021	0.37 ± 0.09
323[d]	≤0.004			<0.13
334[e]				
351.188 ± 0.024	0.218 ± 0.014		0.38 ± 0.09	0.33 ± 0.17
369.11 ± 0.13	0.051 ± 0.010			
373.237 ± 0.011	29.9 ± 0.8	≡29.9	31.0 ± 2.0	31.5 ± 3.2
404.036 ± 0.011	2.79 ± 0.03	3.1	3.00 ± 0.23	2.8 ± 0.3
427.559 ± 0.017	0.210 ± 0.006	0.077	0.233 ± 0.027	0.25 ± 0.08
451.407 ± 0.015	0.088 ± 0.004	0.20	0.106 ± 0.020	<0.17
461.246 ± 0.024	0.220[f]	0.157	0.25 ± 0.04	0.21 ± 0.06
			0.26 ± 0.04	
480.395 ± 0.013	0.691 ± 0.017	0.74	1.03 ± 0.09	1.3 ± 0.5
486.510 ± 0.012	4.43 ± 0.05	5.1	4.29 ± 0.21	4.1 ± 1.3
496.313 ± 0.013	≡100	77.3	≡100 ± 4.7	≡100 ± 10
508[d]	<0.02			0.23 ± 0.11
546.27 ± 0.09	0.011 ± 0.002			
550.75 ± 0.32	0.009 ± 0.002			
563.06 ± 0.24	0.009 ± 0.002			0.067 ± 0.021
572.672 ± 0.015	0.332 ± 0.009	0.47	0.43 ± 0.04	0.33 ± 0.08
585.026 ± 0.015	2.61[g]	2.36	2.64 ± 0.16	2.9 ± 0.6
620.095 ± 0.017	2.91 ± 0.18	3.41	2.97 ± 0.16	3.0 ± 0.8
674.415 ± 0.020	0.285 ± 0.007	0.20	0.30 ± 0.04	0.29 ± 0.09
696.470 ± 0.020	0.317 ± 0.010	0.23	0.31 ± 0.04	0.39 ± 0.12
703.42 ± 0.08	0.015 ± 0.001			
795.8 ± 0.5	0.016 ± 0.004			
797.43 ± 0.06	0.075 ± 0.004			
831.599 ± 0.031	0.494 ± 0.013	1.18	0.51 ± 0.08	0.63 ± 0.17
914.050 ± 0.021	0.098 ± 0.003	0.23	0.100 ± 0.019	0.17 ± 0.08
919.78 ± 0.15	0.019 ± 0.004			
923.846 ± 0.022	1.56 ± 0.04	1.49	1.61 ± 0.24	1.7 ± 0.4
954.590 ± 0.026	0.071 ± 0.002			
968.918 ± 0.026	0.072 ± 0.002	0.060	0.087 ± 0.015	0.11 ± 0.04
1047.571 ± 0.025	2.84[h]	3.05	2.91 ± 0.25	3.3 ± 0.7
1125.94 ± 0.16	0.0051 ± 0.0003			
1170.5 ± 0.5	0.0036 ± 0.0010			
1208.7 ± 0.3	0.0047 ± 0.0010			
1341.85 ± 0.15	0.0027 ± 0.0008			

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[a] The absolute γ-ray intensities can be obtained by normalization such that (47.1 ± 2.0)% of the 11.7 day ^{131}Ba decays through the 496-keV γ ray.

[b] Data normalized with 373-keV γ ray ≡29.9 due to apparent error in intensity of 496-keV γ ray.

[c] The original data of Hasselgren *et al.* are normalized to $I_\gamma(123) = 100$, and those of Kučarova *et al.* normalized to $I_\gamma(216) = 100$.

[d] Not observed in singles spectra of present experiment.

[e] Observed only in coincidence spectrum; no intensity computed.

[f] No error assigned to intensity because peak is a unresolved doublet.

TABLE I. (*Continued*)

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[g] No error assigned to intensity because peak is an unresolved doublet. Weaker γ-ray component observed in coincidence spectrum: no intensity computed.

[h] No error assigned to intensity because peak is an unresolved doublet. The intensity ratio of the 1046.9 keV : 1047.6 keV γ rays is about 1 : 8.

mum uncertainty of 1.0% is quoted for these relative γ-ray intensities. For γ rays with intensities <1% of that of the 496-keV γ ray, a minimum uncertainty of 2.5% is quoted. Corrections were applied to those γ-ray transitions whose intensities are appreciably affected by coincidence summing (i.e., the 620- and 696-keV γ rays) and the errors on their intensities were increased to account for the uncertainty in this correction.

A list of the γ-ray energies and their relative intensities is given in Table I. The present intensity values are compared there with three recent investigations.[8,9,11] The data of Singh *et al.*,[11] which do not include any uncertainties, are in poor agreement with our results (even after special normalization due to an apparent error in the intensity of the strong line at 496 keV). The data reported by Hasselgren *et al.*[9] and by Kučarova, Kracik, and Zvolska[8] are in good agreement with those of the present experiment.

The absolute intensity of the 496-keV γ ray is found to be $(0.471 \pm 0.020)\gamma$/decay. This value is based on 100% population of the ^{131}Cs ground state by γ-ray transitions from the upper levels (i.e., no electron-capture feeding of the ^{131}Cs ground state). The intensities of the ground state transitions (see the decay scheme in Fig. 4) were determined from the relative γ-ray intensities of the present investigation and the γ-ray multipolarity assignments of Horen, Hollander, and Graham.[6] The theoretical conversion coefficients were determined from the tables of Hager and Seltzer.[19] The intensity contribution of the $N+O+\cdots$ shells[20] to the total conversion coefficients were included for γ-ray transitions <137 keV.

C. γ-γ coincidence measurements

Coincidence measurements were made using a 50-cm^3 closed end coaxial Ge(Li) detector to gate on the γ ray of interest (with a single-channel analyzer) and a 55-cm^3 open-ended coaxial Ge(Li) detector to accumulate the coincident γ-ray spectrum (in a multichannel analyzer). The detectors were positioned at 180° relative to one another for all but the 216-keV gate. The detectors were placed at 90° for the 216-keV gate to observe the 511-keV annihilation-radiation photons which are in coincidence with the 216-keV γ ray. The timing of the coincidence circuit was determined by two constant-fraction timing single-channel analyzers and a coincidence circuit whose resolving time 2τ was 220 ns for those gates run with the detectors at 180° and 60 ns for the 216-keV gate. Interpretation of the coincidence spectra was accomplished by visual and computer analyses.

γ-ray spectra were accumulated with single-channel gates on the peaks at 123, 133, 216, 373, 585, and 620 keV. Each of these transitions is from a level of the same energy to the ground state. Examples of the coincidence data are given in Figs. 2 and 3. The following is a summary of the coincidence results.

(1) The 123-keV gate confirms the direct feeding of the 123-keV level by the 92-, 249-, 461-, 496-, 572-, 923- and 1047-keV γ rays. The 795-keV γ ray was not observed in coincidence due to insufficient statistics.

(2) The 133-keV gate confirms the direct feeding of the 133-keV level by the 82-, 239-, 451-, 486-, 563-, and 914-keV γ rays. The 1208-keV γ ray was not observed in coincidence due to insufficient statistics.

(3) The 216-keV gate, see Fig. 2, confirms the direct feeding of the 216-keV level by the 157-, 369-, 404-, 480-, 703-, 831-, 954-, and 1126-keV γ rays.

(4) The 373-keV gate, see Fig. 3, confirms the direct feeding of the 373-keV level by the 246-, 546-, 674-, and 797-keV γ rays. These data do not confirm the existence of a previously reported 323-keV γ ray feeding the 373-keV level. However, the existence of the 351-keV peak in this coincidence spectrum implies that there is either direct or indirect γ-ray feeding of the 373-keV level from the 696-keV level (i.e., the unobserved 323-keV transition or a two-step cascade).

(5) The 585-keV gate confirms direct feeding of the 585-keV level by the 461-keV γ ray and indicates possible feeding by a 334- and a second 585-keV γ ray.

(6) The 620-keV gate confirms direct feeding of the 620-keV level by the 427-keV γ ray. The 550-keV γ ray was not observed in coincidence due to insufficient statistics.

Figure 2 illustrates the spectrum of γ rays in coincidence with the 216-keV ground-state γ-ray transition. The presence of 511-keV photons in this spectrum indicates the presence of a positron component in the electron-capture transition feed-

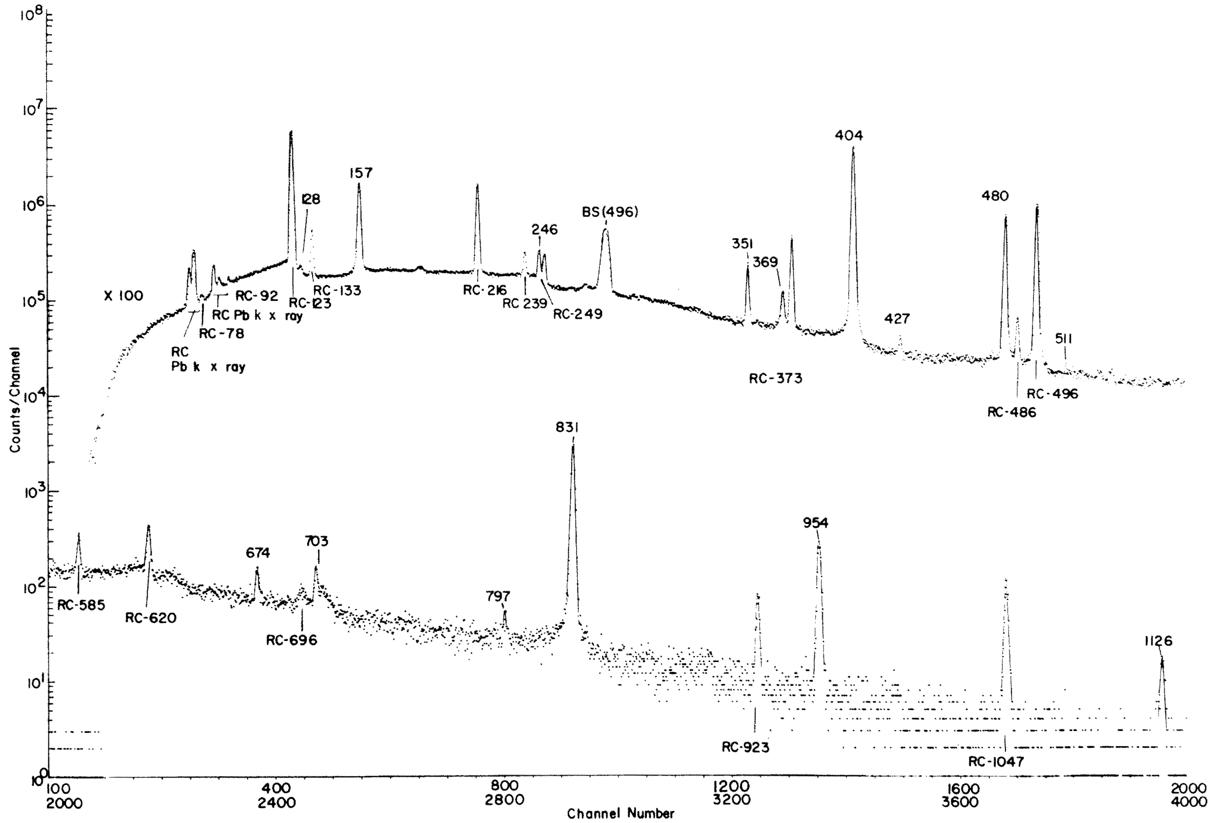

FIG. 2. Spectrum of ^{131}Ba γ radiation in coincidence with the 216-keV γ ray. Peaks labeled RC result from random coincidence; those labeled BS result from back-scattering between the detectors; the energy of the primary γ ray is in parentheses.

ing the 216-keV state (see the proposed decay scheme in Fig. 4). Consequently, these coincidence data can be used to obtain an estimate of the intensity of this positron component and, hence, the electron-capture-to-positron intensity ratio for this transition. From the data shown in Fig. 2, we obtain for the relative intensities of the 511- and 480-keV peaks the value

$$I(511)/I(480) = (2.8 \pm 1.4) \times 10^{-3}.$$

From the absolute intensity of the 480-keV line (0.328%), we obtain

$$I(\beta^+ \text{ to } 216\text{-keV level}) = (4.5 \times 10^{-4})\%.$$

This value can be used to infer the Q value for the ^{131}Ba decay, as discussed in Sec. III below.

III. DECAY SCHEME

The proposed decay scheme shown in Fig. 4 is consistent with the coincidence data and the measured γ-ray energies and relative intensities of the present experiment. The level energies reported in Fig. 4 are from a linear least-squares fit of the γ-ray energies with corrections applied for nuclear recoil. The errors input to the least-squares fit included only the measurement uncertainties (i.e., they excluded the reference error contribution from the energy scale based on the ^{198}Au 411-keV line). The energy-scale contribution was added in quadrature to the errors from the output of the fit.

As a result of the present investigation, previously unreported levels in ^{131}Cs have been identified at 919, 1170, and 1341 keV. These levels are based on the placement of previously unreported γ rays of 128, 546, 703, 795, 919, 1046, 1126, 1170, 1208, and 1341 keV and on previously reported[8] but unplaced γ rays at 797 and 954 keV. The γ-ray spectra in coincidence with the 216-keV and the 373-keV gates (see Figs. 2 and 3, respectively) indicate that the 546- and 703-keV γ rays decay from 919-keV level, the 797- and 954-keV γ rays decay from 1170-keV level and the 1126-keV γ ray decays from the 1341-keV level. A newly reported γ ray at 369 keV, feeding the 216-keV level from the 585-keV level has been placed in the decay scheme on the basis of coincidence in-

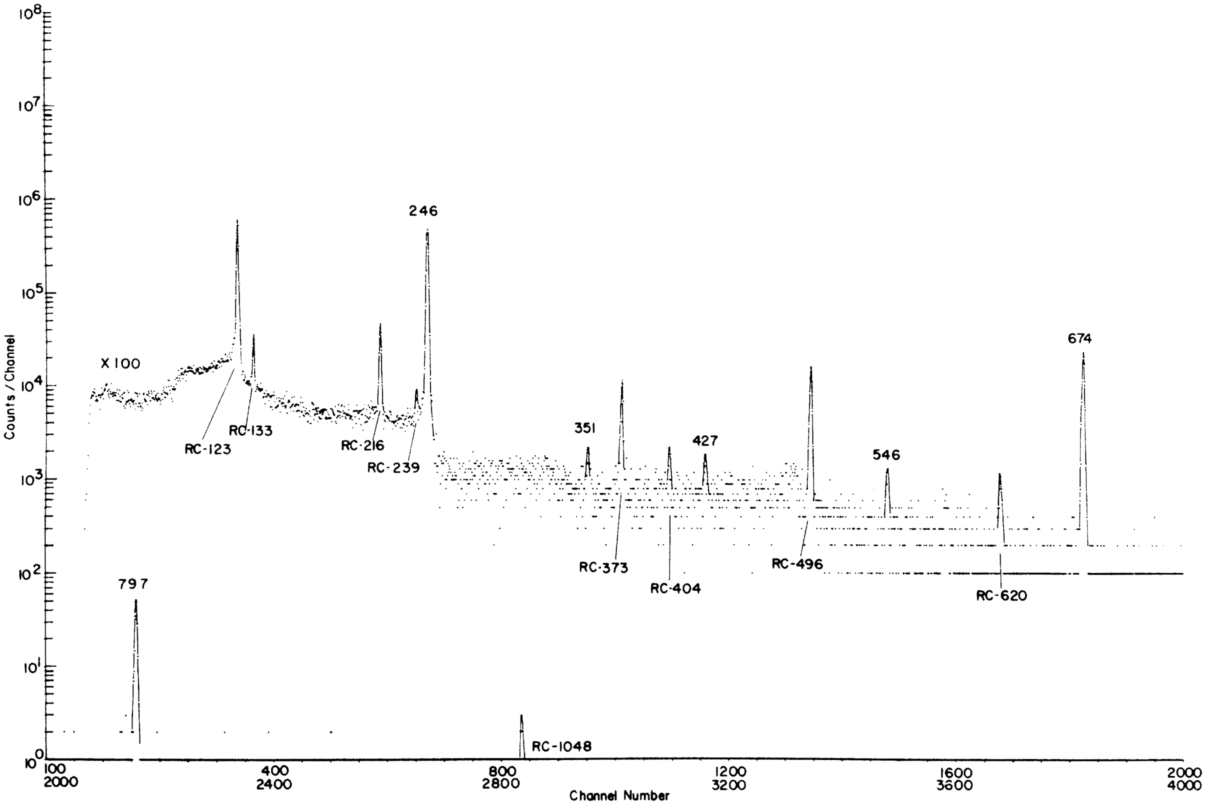

FIG. 3. Spectrum of ^{131}Ba γ radiation in coincidence with the 373-keV γ ray. Peaks labeled RC result from random coincidences.

formation and its energy. γ rays at 128, 550, 795, 1170, 1208, and 1341 keV were placed in the level scheme on the basis of their energy only. Possible peaks at 334 and 585 keV were observed in the γ-ray spectrum in coincidence with the 585-keV gate and are tentatively placed feeding the 585-keV level. The existence of the 137-keV γ ray as reported and placed by Horen *et al.*[6] is confirmed. The γ

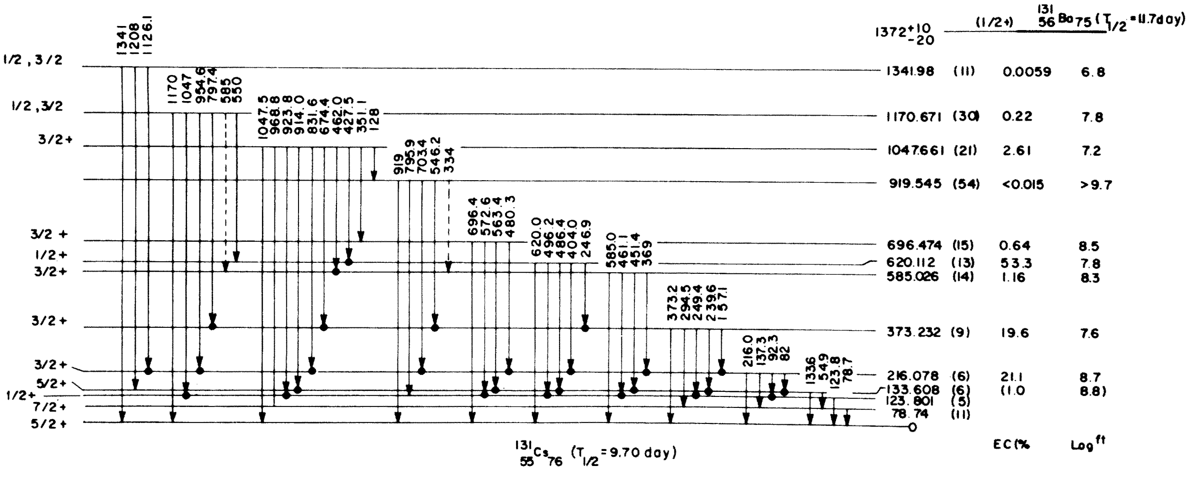

FIG. 4. Decay scheme of ^{131}Ba. The intensities and the log *ft* values are given for the electron-capture branches. The dots indicate those γ rays entering each level that were observed in coincidence with the ground-state transition.

ray at 563 keV, which was previously reported by Kučarova *et al.*[8] but not placed in their decay scheme, has been confirmed and placed in the proposed decay scheme on the basis of coincidence information. The existence of reported γ rays at 323 (Ref. 7) and 508 (Ref. 8) keV could not be verified. Upper limits on the relative intensities of these γ rays are reported in Table I. The results of the present coincidence measurements are summarized in the level scheme by dots indicating those γ rays entering the level which are in coincidence with the ground-state transition.

The intensities of the electron-capture branches were determined from the intensity balances of the transitions populating and depopulating each of the ^{131}Cs levels. The relative electron intensities of Horen *et al.*[6] were used to determine the conversion coefficients in those cases where no definitive multipolarity assignments have been reported. These relative electron intensities were normalized so that the sum for the K, L_1, L_2, and L_3 shells[19] associated with the 123-keV γ ray corresponded to the theoretical sum for a 95%$E2$ + 5%$M1$ multipolarity. The intensities of the electron-capture branches are given on the decay scheme shown in Fig. 4. The possibility of electron-capture feeding of the levels at 78, 123, 133, and 919 keV cannot be ruled out by our intensity-balance results. They indicate possible electron-capture branches to these levels of (0.24 ± 0.12)%, (1.0 ± 1.3)%, (−0.12 ± 0.14)%, and (0.000 ± 0.009)%, respectively.

From the total intensity of the electron-capture branch feeding the 216-keV state and the measured intensity of the β^+ component of this branch (see Sec. II above), we obtain a value for the EC/β^+ ratio of

$$[I(\mathrm{EC})/\beta^+)]_{216\ \mathrm{keV}} = (4.8 \pm 2.5) \times 10^4.$$

From the tables of Gove and Martin,[21] this value implies a β^+ endpoint energy of 134^{+10}_{-20} keV for this transition and hence a Q value of 1372^{+10}_{-20} keV for the ^{131}Ba electron-capture decay. The log*ft* values given in Fig. 4 were calculated using this Q value (1372 keV) and the computer code described in Ref. 21.

The ground-state spin of ^{131}Cs has been measured[22] to be $\frac{5}{2}$. The parity of this state as well as the spin and parity values of the ^{131}Ba ground state and of the previously established levels in ^{131}Cs are those which are currently accepted.[23] The present data are consistent with these assignments. The spins of the newly reported levels at 1170 and 1341 keV are restricted to the range $\frac{1}{2}, \frac{3}{2}$, based on their observed decay modes and the log*ft* values of the electron-capture transition feeding them. For the 919-keV level the possible spin and parity values are $\frac{1}{2}^+$, $\frac{3}{2}^\pm$, or $\frac{5}{2}^+$. Some support for the last-mentioned possibility is provided by the nonobservation of a feeding electron-capture (EC) transition ($\log ft > 9.7$) and by the results of the intermediate-coupling calculations described in Sec. IV B below.

IV. DISCUSSION

A. Q value determination and the EC/β^+ ratio

The observation in this work of positron emission in the ^{131}Ba decay has made it possible to measure the capture-to-positron ratio of the transition to the 216-keV level in ^{131}Cs. Because of the relatively small β^+ endpoint energy involved, this ratio, together with the conventional theory as tabulated by Gove and Martin,[21] provides a rather precise estimate for the Q value of the decay.

Recently, however, evidence has been reported (see Ref. 24 and references contained therein) which suggests the existence of cases where the experimental electron-capture-to-positron ratios are "anomalously" large, in some cases by quite large factors. Such a possibility casts doubt on the Q value determined from any measured capture-to-positron ratio. From the figures given in Ref. 24, it is somewhat difficult to extrapolate to the specific case of ^{131}Ba. However, if it is assumed that such effects are indeed present in the ^{131}Ba decay and that they are of the magnitude predicted in Ref. 24, a crude estimate suggests that the Q value deduced above from the EC/β^+ intensity ratio may be low by ~100 keV.

On the other hand, additional evidence exists which can shed light on the question of the ^{131}Ba decay Q value and its relation to the electron-capture-to-positron intensity ratio. From the measured Q value of the ^{130}Ba(d,p) reaction,[25] a value of 1348 ± 7 keV is deduced[23] for the ^{131}Ba β-decay energy. This value is in good agreement with that which we calculated from the measured EC/β^+ ratio. The lower limit on this Q value can be increased somewhat since our data indicate EC feeding of a level at 1342 keV, and the log*ft* value of this feeding transition must be at least as large as ~4.5. From the Q value as determined from the (d,p) reaction and the resulting limits, the "skew ratio" (the ratio of the experimental EC/β^+ ratio to the theoretical value[24]) is $0.38^{+\sim 0.7}_{-\sim 0.2}$ for the transition to the 216-keV level. This skew ratio is thus compatible with the conventional theory (i.e., skew ratio = 1.0 is possible) for the Q value deduced from the (d,p) data. Further, any discrepancy that might exist implies a skew ratio less than unity, whereas the situations illustrated in Fig. 1 of Ref. 24 all have ratios larger than unity. We thus conclude that the use of our EC/β^+ ratio to deduce the Q value is justified for the ^{131}Ba decay and that the anomalies described in Ref. 24 do not occur here.

B. Intermediate-coupling calculation

A number of intermediate-coupling calculations have been carried out to elucidate the level structure of the odd-Z isotopes in this mass region (see, e.g., Refs. 26 and 27 and the references contained therein). Although these different reported calculations have had varying degrees of success, none has yet provided a completely satisfying description of the level spectrum and transition probabilities of many of these nuclides. In view of the fact that a similar situation existed in the transitional nuclei in the Hg region and a recently published intermediate-coupling calculation[5] provided a much improved description of the features of the ^{199}Hg level scheme, it appeared to be of interest to see to what extent the approach employed there could be applied to the ^{131}Cs level scheme.

The calculation was kindly carried out by Mathews.[14] The formalism and other details underlying it are described in detail in Ref. 5. For the specific case of ^{131}Cs, core states consisting of up to (and including) three phonons were included; and the $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, and $s_{1/2}$ single-particle states were assumed to be available to the odd proton. To partially account for anharmonicities, the experimental core energies, rather than a harmonic spectrum, were used. It was found that a reasonable description of the ^{131}Cs spectrum could be obtained for values of the parameter α (the factor by which theoretical coupling strength must be multiplied) in the range ~0.4 to ~0.5, a range which is typical of such values in other mass regions.[5]

The ^{131}Cs energy-level spectrum, calculated[14] for a value of 0.45 for the parameter α, is shown in Fig. 5. Also shown, for purposes of comparison, is the ^{131}Cs level scheme as observed in the present work. For simplicity, only the lowest predicted $\frac{9}{2}^+$ state is shown. γ-ray transition probabilities were also calculated. Those involving the first four excited states, for which half-life values or upper limits are known, are summarized in Table II.

With several exceptions noted below, the agreement between the calculated and the observed energy-level spectrum is good, taking into account the fact that most of the higher-spin states have not yet been observed. In particular, the occurence of a low-lying $\frac{1}{2}^+$ state is quite well accounted for, in contrast with the calculations presented in Refs. 26 and 27. The $B(E2)$ of the transition deexciting this state is also quite well reproduced. The calculations predict that this state consists largely (~60%) of the $d_{5/2}$ single-particle state coupled to the 2^+, one-phonon state of the core, with smaller contributions of ~15% and ~10%, respectively, from the $d_{5/2}$ single-particle state coupled to the 2^+, two-phonon state and from the $s_{1/2}$ single-particle state. The ground state is largely (~60%) the $d_{5/2}$ state and contains ~25% of the $d_{5/2}$ state coupled to the 2^+ one-phonon state. The 78-keV, $\frac{7}{2}^+$ state is predicted to be a nearly pure (~94%) $g_{7/2}$ state.

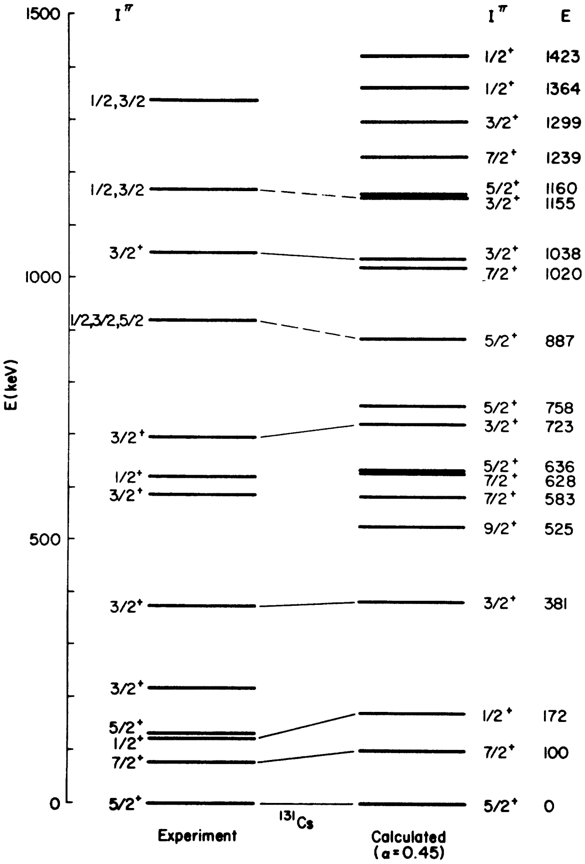

FIG. 5. Comparison of the experimental level-energy structure of ^{131}Cs with that predicted by the intermediate-coupling model described in Refs. 5 and 14. The value of the parameter α gives the factor by which the theoretical coupling strength is attenuated.

It is tempting to associate the newly reported state at 919 keV with the calculated level at 887 keV (see Fig. 5). Our data on the 919-keV state are quite consistent with an I^π value of $\frac{5}{2}^+$, but they do not uniquely determine it. The calculation indicates that this state (if the indicated association is correct) has a rather complex makeup, the two largest components being those in which the odd proton in the $d_{5/2}$ state is coupled to the two-phonon core states with $I^\pi = 2^+$ and 0^+, respectively. Further, the new level at 1170 keV may possibly be

TABLE II. Comparison of experimentally deduced reduced transition probabilities with predictions of the intermediate-coupling model (Ref. 5, 14). The level lifetimes and the γ-ray multipolarities used in obtaining the experimental quantities are those of Ref. 6.

Initial state		Final state		E_γ	$B(M1)$		$B(E2)$	
					$(e\hbar/2mc)^2\times10^3$		(e^2b^2)	
E(keV)	I^π	E(keV)	I^π	(keV)	Expt.	Theory	Expt.	Theory
78.7	$\frac{7}{2}^+$	0	$\frac{5}{2}^+$	78.7	3.00	2.04	0.0035	0.013
123.8	$\frac{1}{2}^+$	0	$\frac{5}{2}^+$	123.8			0.282	0.355
133.6	$\frac{5}{2}^+$	0	$\frac{5}{2}^+$	133.6	0.662	53.0[a]	0.0134	0.0007[a]
		78.7	$\frac{7}{2}^+$	54.9	0.041	0.11[a]	0.225	0.175[a]
216.0	$\frac{3}{2}^+$	0	$\frac{5}{2}^+$	216.0	>8.3	900.0[a]	>0.0026[b]	0.048[a]
		78.7	$\frac{7}{2}^+$	137.3			>0.004	~0.0[a]
		123.8	$\frac{1}{2}^+$	92.3	>3.5	86.0[a]		

[a] The 133- and 216-keV states are not believed to be accounted for within the framework of this model, and thus the calculated transition probabilities are not expected to agree with the experimental values. The calculated values given are those predicted by the model for the deexcitation of the second $\frac{5}{2}^+$ state and the first $\frac{3}{2}^+$ state, respectively.

[b] Calculated assuming a 1% $E2$ component in the 216-keV transition (see Ref. 23).

identified as the predicted $\frac{3}{2}^+$ state at 1155 keV. Several calculated levels exist which can be associated with the state at 1342 keV, and it is not possible to make a definite association at the present time.

Several low-lying ($\lesssim$0.6 MeV) states are not accounted for by the model, suggesting that they arise from mechanisms not included in it. Of these, the states at 133 and 216 keV have received considerable attention. In a series of papers, Kuriyama *et al.* describe the occurrence and properties of a new type of fermion collective mode in spherical odd-A nuclei, a so-called "dressed three-quasiparticle mode," with spin $j-1$ associated with the one-quasiparticle state of spin j. In the application of these ideas to the odd-mass I, Cs, and La isotopes,[4] these authors show that the 133-keV, $\frac{5}{2}^+$ state can be well accounted for as a dressed three-quasiparticle state associated with the $g_{7/2}$ state. The calculated $B(E2)$ value from this state to the $\frac{7}{2}^+$ state is ~0.11 e^2b^2, which agrees to within a factor of ~2 with the experimental value of ~0.23 e^2b^2 (cf. Table II). The association of the lowest $\frac{3}{2}^+$ state, at 216 keV, as a similar type of state, built on the $d_{5/2}$ single-particle state, is less clear, however. In such a case, the $B(E2)$ value of the transition to the $\frac{5}{2}^+$ state is calculated[4] to be roughly 5 times larger than that of the transition to the $\frac{7}{2}^+$ state, whereas it appears to be roughly 50% weaker. It is thus tempting to interpret this state as the $I=j-2$ state associated with the $g_{7/2}$ single-quasiparticle state and to conjecture that it contains a significant component of the "dressed five-quasiparticle state"[28] built on this orbital.

The success[1,2] of the triaxial-rotor-plus-particle model[1] in describing the properties of the unique (i.e., negative) parity states of the odd-Z nuclide ^{135}La suggests that a similar approach might provide a good description of the positive-parity states observed in ^{131}Cs as well. To do this, however, requires the inclusion in this model of more than one single-particle state for the odd particle, and such a treatment has not yet been developed.

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[1] J. Meyer-ter-Vehn, Nucl. Phys. A249, 141, 111 (1975).

[2] E. A. Henry and R. A. Meyer, Phys. Rev. C 13, 2063 (1976).

[3] A. Kuriyama, T. Marumori, and K. Matsuyanagi, in

Problems of Vibrational Nuclei, edited by G. Alaga, V. Paar, and L. Sips (North-Holland, Amsterdam/American Elsevier, New York, 1975), p. 87.

[4] A. Kuriyama, T. Marumori, K. Matsuyanagi, and R. Okamoto, Prog. Theor. Phys. 53, 489 (1975).

[5] G. J. Mathews, F. M. Bernthal, and J. D. Immele, Phys. Rev. C 11, 587 (1975).

[6] D. J. Horen, J. M. Hollander, and R. L. Graham, Phys. Rev. 135, B301 (1964).

[7] K. Karlsson, Ark. Fys. 33, 47 (1966).

[8] T. Kučarova, B. Kracik, and V. Zvolska, Yad. Fiz. 7, 713 (1969) [Sov. J. Nucl. Phys. 7, 433 (1968)].

[9] L. Hasselgren, S. Antman, H. S. Sahota, and J. E. Thun, Nucl. Phys. A153, 625 (1970).

[10] R. Strum, F. W. Thiele, R. Thielman, and E. Grunberg, Z. Phys. 252, 312 (1972).

[11] R. Singh, C. Rangacharyulu, and G. K. Mehta, Z. Phys. 258, 12 (1973).

[12] B. L. Robinson, Bull. Am. Phys. Soc. 7, 541 (1962).

[13] A. H. Wapstra and N. B. Gove, Nucl. Data A9 (Nos. 4-5), 265 (1971).

[14] G. J. Mathews (private communication).

[15] R. C. Greenwood, R. G. Helmer, and R. J. Gehrke, Nucl. Instrum. Methods 77, 141 (1970).

[16] R. G. Helmer, R. C. Greenwood, and R. J. Gehrke, Nucl. Instrum. Methods 96, 1973 (1971).

[17] R. C. Greenwood, USAEC Report No. ANCR-1088, 1972 (unpublished), p. 405.

[18] R. G. Helmer and R. C. Greenwood, USAEC Report No. ANCR-1088, 1972 (unpublished), p. 396.

[19] R. S. Hager and E. C. Seltzer, Nucl. Data A4, 1 (1968).

[20] O. Dragoun, H. C. Pauli, and F. Schmutzler, Nucl. Data A6, 235 (1969).

[21] N. B. Gove and M. J. Martin, Nucl. Data A10 (No. 3), 206 (1971).

[22] E. H. Bellamy and K. F. Smith, Phil. Mag. 44, 33 (1953).

[23] R. L. Auble, H. R. Hiddleston, and C. P. Browne, Nucl. Data Sheets 17 (No. 4), 573 (1976).

[24] R. B. Firestone, R. A. Warner, W. C. McHarris, and W. H. Kelly, Phys. Rev. Lett. 35, 713 (1975).

[25] D. von Ehrenstein, G. C. Morrison, J. A. Nolen, Jr., and N. Williams, Phys. Rev. C 1, 2066 (1970).

[26] N. Freed and W. Miles, Nuovo Cimento 60B, 301 (1969).

[27] D. C. Choudhury and J. N. Friedman, Phys. Rev. C 3, 1619 (1971).

[28] See, e.g., A. Kuriyama, T. Marumori, and K. Matsuyanagi, Suppl. Prog. Theor. Phys. 58, 53 (1975).