$Ba^{135}(n, \gamma)$ Reaction and Level Structure of Ba^{136}†

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The γ rays from the $Ba^{135}(n_{th}, \gamma)Ba^{136}$ reaction have been studied in singles and in coincidence with a 9-cm^3 Ge(Li) detector and a Ge(Li)-NaI detector combination. Of the 78 γ rays assigned to Ba^{136}, 16 have been identified as primary transitions deexciting the compound nucleus. These primary γ rays have energies (in keV) and relative intensities [I(818 keV) = 100] as follows: 9106.5±1.3 (2.9), 8288.2±0.8 (1.8), 7554.3±1.0 (0.24), 7526.6±2.0 (0.07), 7026.4±0.7 (0.7), 6978.2±0.7 (0.2), 6707.4±0.8 (0.3), 6574.9±0.6 (0.5), 6087.4±0.5 (0.3), 6063.5±0.4 (3.5), 5673.2±0.6 (0.4), 5601.8±0.6 (1.0), 5415.8±0.5 (2.2), 5340.3±0.7 (0.2), 5311.9±0.6 (3.7), and 5181.5±2.6 (0.9). These data, together with the information obtained from the coincidence studies and from previous decay scheme and neutron capture γ-ray studies, establish levels in Ba^{136} with energies 818.6±0.2, 1550.5±0.4, 1579.2±0.4, 1866.3±0.4, 2030.0±0.5, 2053.5±0.6, 2079.9±0.6, 2128.3±0.8, 2139.6±0.6, 2206.3±0.5, 2398.6±0.3, 2531.8±0.5, 3019.9±0.5, 3043.6±1.4, 3433.2±0.5, 3504.9±1.1, 3690.8±1.5, 3767.1±1.0, 3795.4±0.9, and 3925.7±1.2 keV. The neutron separation energy was found to be 9106.4±0.8 keV. The level scheme of Ba^{136} is discussed. The branching ratio $B(E2; 2+'\rightarrow 0+)/B(E2; 2+'\rightarrow 2+)$ was measured and found to be 0.029±0.006, in agreement with measured values of the same quantity for other near-harmonic nuclei.

I. INTRODUCTION

OUR knowledge of the properties of the low-lying levels of the Ba^{136} nucleus rests mainly on studies[1–9] of the radioactive decay of 12.9-day Cs^{136}.

The currently accepted decay scheme for Cs^{136} was originally proposed by Reising and Pate.[6] These authors studied the decay of Cs^{136} with a double-focusing β spectrometer, NaI scintillation counters, and γ-γ coincidence and sum-coincidence spectrometry. They combined their results with the earlier β- and γ-ray measurements of Olsen and O'Kelley,[1] Girgis and Van Lieshout,[2] and the angular correlation measurements of Grabowski, Gustafsson, and Marklund[3] to construct a decay scheme for Cs^{136}. This decay scheme, appropriately altered to take account of more recent measurements discussed below, is shown in Fig. 1.

Bernstein and Forster[4] and Sugiyama, Sekiguchi, and Hayashibe[5] had studied γ-γ angular correlations in Ba^{136} following Cs^{136} decay earlier. The former authors concluded from their study of the 1065–830-keV correlation that the spin parity of the 1900-keV level is 2+ instead of 4+, as assigned later by Reising and Pate.[6] Sugiyama *et al.* studied the 830–1065- and 830–340-keV γ-γ correlations as well as the correlation of an observed 830–830-keV γ-ray cascade. In agreement with Grabowski *et al.*[3] and Reising and Pate[6] they assigned spins 2+, 4+, and 6+ to the 830-, 1900-, and 2240-keV levels. In addition they proposed a level at 1660 keV with spin parity 2+ on the basis of the observed 830–830-keV cascade. The existence of this level has not been confirmed by later studies.

The decay of 0.37-sec Ba^{136m} was studied by Ruddy and Pate.[7] They were able to show that this short lived activity is due to the decay of the 7− state in Ba^{136} at 2030 keV. Fujioka, Miyachi, and Adachi[8] measured, by the delayed coincidence technique, the half-lives of the 2206.1-keV (6+) and 2139.4-keV (5−) states in Ba^{136} to be 3.3±0.3 nsec and ≤1 nsec, respectively. Recently, Frana, Rezanka, Spalek, and Mastalka[9] measured the γ-ray spectrum from the decay of Cs^{136} with a Ge(Li) detector and obtained more accurate γ-ray energies and hence more accurate level energies. All of these more recent results have been incorporated in the decay scheme shown in Fig. 1.

Since the ground state of Cs^{136} has spin and parity 5+ we may expect that some low-lying low-spin states in Ba^{136} will not be observed in the radioactive decay of Cs^{136}. The resulting gap in our knowledge has now been partly filled by the measurements of Julian and Fessler[10] and Griffioen, Meyer, and Gunnink[11] on the radioactive decay of 9.0-min La^{136} and the resonance neutron capture γ-ray studies of Becvar, Vrzal, Liptak, and Urbanec.[12] Since the ground state of La^{136} has spin parity 1+ we expect low-spin levels in Ba^{136}, which were not observed in the decay of Cs^{136}, to be populated in the decay of La^{136}. Of the six excited states reported

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[1] J. L. Olsen and G. D. O'Kelley, Phys. Rev. **95**, 1539 (1954).
[2] R. K. Girgis and R. Van Lieshout, Nucl. Phys. **12**, 204 (1959).
[3] Z. Grabowski, S. Gustafsson, and I. Marklund, Nucl. Phys. **20**, 159 (1960).
[4] H. Bernstein and H. H. Forster, Nucl. Phys. **24**, 601 (1961).
[5] K. Sugiyama, H. Sekiguchi, and S. Hayashibe, J. Phys. Soc. Japan **16**, 2353 (1961).
[6] R. Reising and B. D. Pate, Nucl. Phys. **65**, 609 (1965).
[7] F. Ruddy and B. D. Pate, Nucl. Phys. **69**, 471 (1965).
[8] M. Fujioka, T. Miyachi, and H. Adachi, Nucl. Phys. **A95**, 577 (1967).
[9] J. Frana, I. Rezanka, A. Spalek, and A. Mastalka, Czech. J. Phys. **B17**, 1048 (1967).
[10] G. M. Julian and T. E. Fessler, Phys. Rev. **172**, 1208 (1968).
[11] R. D. Griffioen, R. A. Meyer, and R. Gunnink, Bull. Am. Phys. Soc. **13**, 1467 (1968).
[12] F. Becvar, J. Vrzal, J. Liptak, and J. Urbanec, J.I.N.R. Report No. P3-3695, Dubna, 1968 (unpublished); and Brookhaven National Laboratory Report No. BNL-TR-209, 1968 (unpublished).

by Julian and Fessler the levels at 1578.9±0.3, 2080.2±0.9, 2128.4±0.5, 2141.0±0.4, and 2315.6±0.8 keV had not been previously reported. Griffioen *et al.* report additional levels at 1550.8, 2284.5, 2485.4, and 2609.9 keV and a possible level at 2770 keV. It seems reasonable to assume that these are levels of low spin.

Because of the low spins of the 24.5- (1+), 82- (2+), 88- (2+), and 106-eV (1+) resonances in the $Ba^{135}(n, \gamma)Ba^{136}$ reaction, whose decay was studied by Becvar *et al.*, we expect low-spin levels in Ba^{136} to be observed in this case also. The results of these authors confirm the existence of the levels at 1550, 1579, 2080, and 2128 keV, which were observed[10,11] in the decay of La^{136}, but not the existence of the levels at 2141.0, 2284.5, 2315.6, 2485.4, 2609.9, and 2770 keV. In addition they also observe new levels at 3431 and 3504 keV. They assign spin parities 2+ and 0+ to the levels at 1551 and 1578 keV, respectively.

Very little information on the excited states of Ba^{136} is available from charged-particle reaction studies. Alster, Martens, and Alpert[13] have studied the angular distributions of inelastically scattered α particles from Ba^{136} with an over-all energy resolution of 130–150 keV. They report that the most strongly excited levels are the lowest-lying 2+ and 3− states at 0.83 and 2.50 MeV, respectively. They also report levels in Ba^{136} at 2.10, 2.8, 3.1, 3.50, and 3.65 MeV. Morrison, Williams,

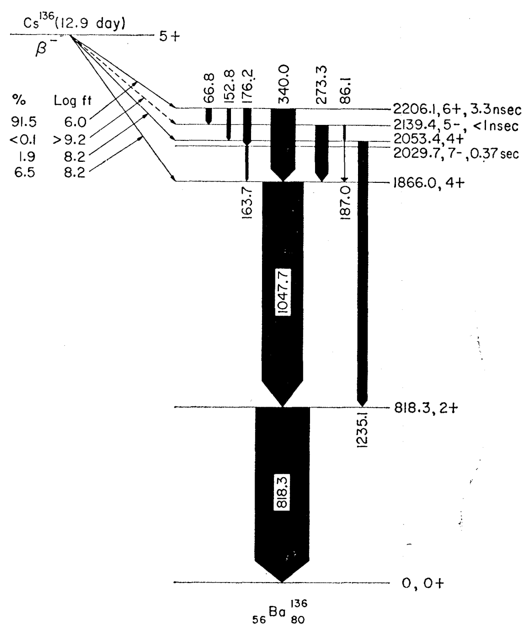

FIG. 1. Decay scheme of Cs^{136} as established by Reising and Pate (Ref. 6). The γ-ray and level energies (in keV) are taken from Frana *et al.* (Ref. 9). The half-life of the isomeric level at 2029.7 keV was measured by Ruddy and Pate (Ref. 7). The half-lives of the 2139.4- and 2206.1-keV levels were measured by Fujioka *et al.* (Ref. 8).

[13] J. Alster, E. J. Martens, and N. M. Alpert, Bull. Am. Phys. Soc. **13**, 70 (1968).

Nolen, and von Ehrenstein[14] have reported that they are studying the $Ba^{135}(d, p)Ba^{136}$ reaction. At the time of writing the results of their studies are not available.

The present work consists of an investigation of the γ rays in the energy range 0–9 MeV emitted in the thermal neutron capture reaction on Ba^{135}. Since the capture state in Ba^{136} has spin and parity 1+ or 2+ this reaction is expected to populate directly low-energy, low-spin states (spins 0 to 3) in Ba^{136}. The study of this reaction should provide more complete information on the existence and properties of low-spin states in Ba^{136}.

The experimental procedure has been described at length in an earlier publication.[15] Only those details, which are relevant to the discussion of the present work, are described in Sec. II below. The construction of the level scheme is presented in Sec. III and the results are discussed in Sec. IV.

II. EXPERIMENTAL METHODS AND RESULTS

A. Equipment

The target material consisted of 6.26 g of $Ba(NO_3)_2$, which was enriched in Ba^{135}, with an isotopic composition[16] of <0.03% Ba^{130}, <0.03% Ba^{132}, 0.62% Ba^{134}, 92.9% Ba^{135}, 1.56% Ba^{136}, 0.91% Ba^{137}, and 4.0% Ba^{138}. In thermal neutron capture, the contributions of the Ba isotopes of masses 134, 135, 136, 137, and 138 to the capture cross section are 0.52, 98.0, 0.33, 0.76, and 0.33%, respectively. The contributions of the other Ba isotopes to the total thermal neutron-capture cross section are negligible. The sample was enclosed in a Teflon capsule and irradiated in an external neutron beam from the Brookhaven Graphite Research Reactor with an intensity of $\sim 8\times10^6$ neutrons/cm^2 sec. The neutron beam was collimated to a diameter between 2.0 and 8.0 mm in the different runs.

Singles γ-ray spectra were obtained with an $\sim$9-cm^3 Ge(Li) detector. Coincidences between γ rays were studied with a 3×3-in. NaI(Tl) detector and the same Ge(Li) diode in 180° geometry.

The electronic equipment used in the handling and storage of the pulses from these detectors and the procedure applied in the analysis of the data have been described in an earlier publication.[15]

B. Energy and Intensity Measurements

The singles γ-ray spectrum emitted in the $Ba^{135}(n, \gamma)Ba^{136}$ reaction was measured over the energy range 25 keV to 9 MeV in nine separate runs of different energy range and dispersion. Figure 2 shows the γ-ray

[14] G. C. Morrison, N. Williams, J. A. Nolen, Jr., and D. von Ehrenstein, Bull. Am. Phys. Soc. **13**, 70 (1968).

[15] M. A. J. Mariscotti, W. Gelletly, J. A. Moragues, and W. R. Kane, Phys. Rev. **174**, 1485 (1968).

[16] The target material was obtained from the Stable Isotopes Division, Oak Ridge, Tenn.

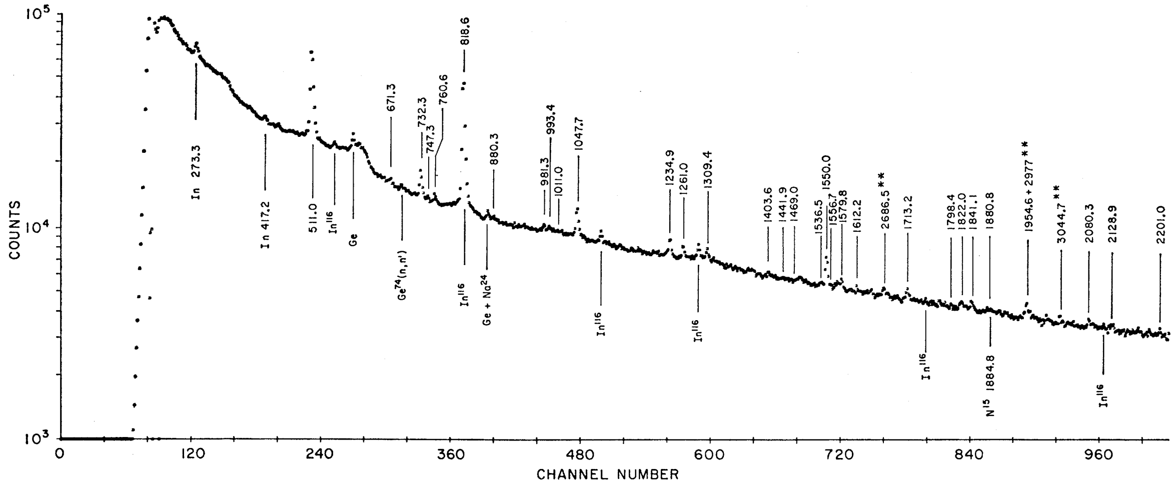

FIG. 2. γ-ray spectrum from the Ba^{135} (n, γ) Ba^{136} reaction over the energy range 0.2–2.2 MeV. The energy dispersion is approximately 2.2 keV/channel. The energies of γ rays assigned to this reaction are indicated above the spectrum. The energies and origins of some of the observed background lines are indicated below the spectrum. (Single and double asterisks indicate one- and two-escape peaks.) It should be noted that this spectrum is cut off at the low-energy end by the electronic system. The logarithmic scale on the ordinate axis should also be noted.

spectrum from 0.2–2.2 MeV at a dispersion of ~2.2 keV per channel. This spectrum was accumulated in 8 h counting with the neutron beam collimated to a diameter of 8.0 mm. Figure 3 shows the spectrum from 2.2–4.4 MeV. This spectrum was accumulated in 14 h under the same conditions as the spectrum in Fig. 2. Figure 4 shows the high-energy γ-ray spectrum taken at a higher dispersion of ~1 keV per channel. These data were accumulated in 14 h with the neutron beam collimated to a diameter of 8.0 mm. The data shown in Figs. 2–4 were chosen to give the reader some idea of the complexity of the Ba^{136} γ-ray spectrum and of the quality of the data obtained in the present experiment. Many weak lines were only observed in runs of longer duration in which the number of counts in the low-energy region of the spectrum exceeded the analyzer memory capacity.

The Ba^{135} nucleus has a small thermal neutron capture

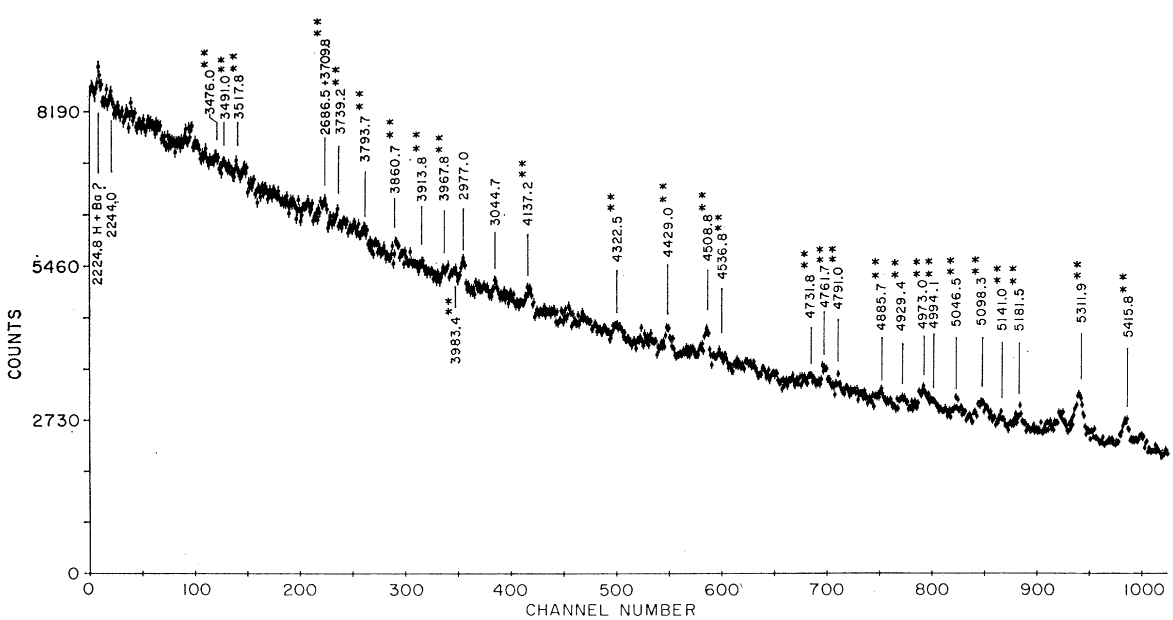

FIG. 3. γ-ray spectrum from the $Ba^{135}(n, \gamma)Ba^{136}$ reaction over the energy range 2.2–4.5 MeV. The energy dispersion is approximately 2.2 keV/channel. The lines assigned to the $Ba^{135}(n, \gamma)Ba^{136}$ reaction are indicated on the figure. One- and two-escape peaks are indicated by single and double asterisks.

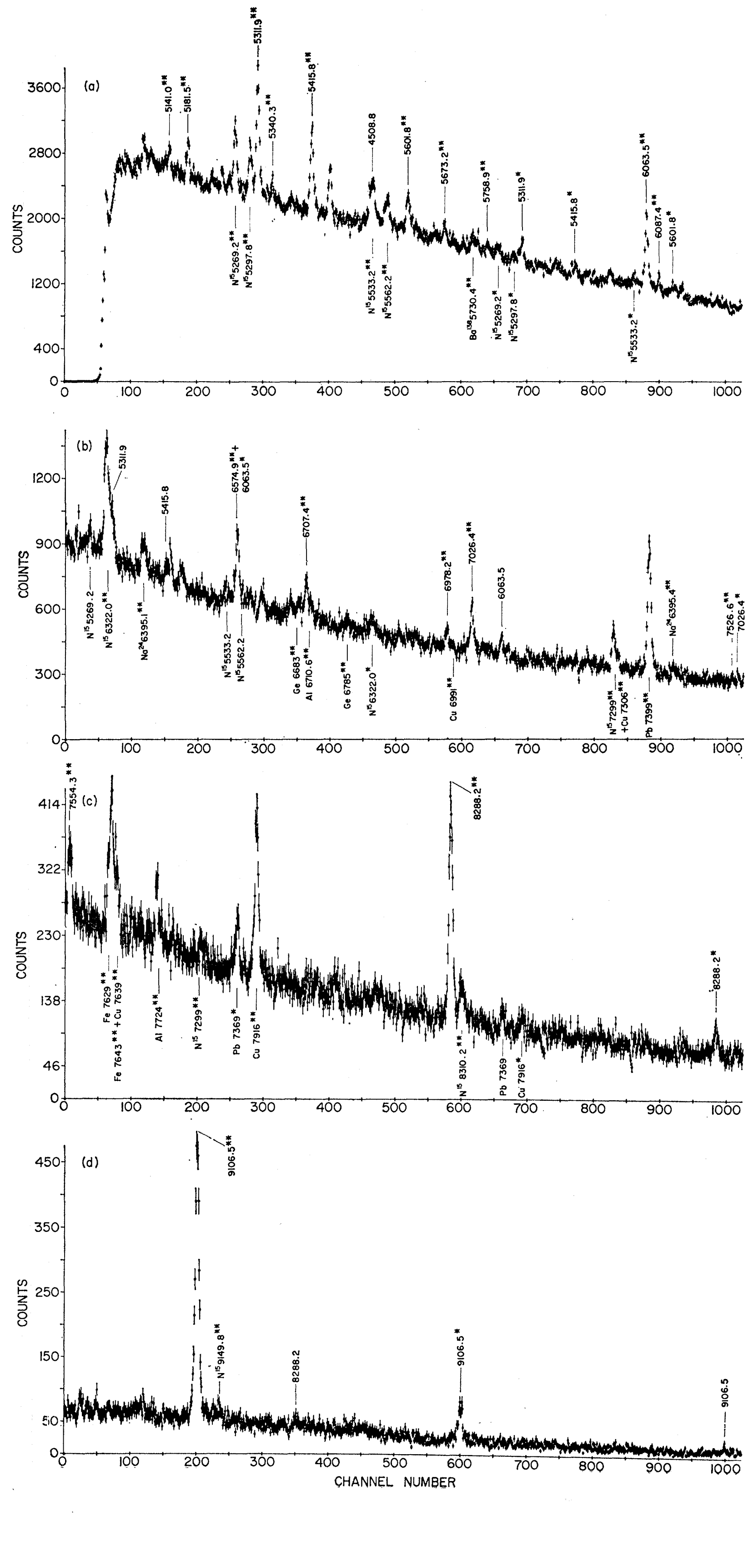

FIG. 4. γ-ray spectrum from the $Ba^{135}(n,\gamma)Ba^{136}$ reaction over the energy range 4–9 MeV. This spectrum was accumulated in 4096 channels of the TMC analyser. It is shown here in four successive sections (a)–(d) each of 1024 channels. The lines assigned to the $Ba^{135}(n,\gamma)Ba^{136}$ reaction are indicated above the spectrum. Some of the assigned background lines are indicated below the spectrum. Single and double asterisks indicate single- and double-escape peaks. Some of the lines, which are barely seen in this spectrum [e.g., 7526.6** in (b)], were clearly observed in runs of longer duration. The three peaks due to the intense 8288.2- and 9106.5-keV $M1$ transitions from the capture state to the 818.6-keV and ground states are clearly visible in parts (c) and (d). It should be noted that the spectrum is cut off at the low-energy end by the electronic system.

cross section ($\sim$5b). As a result the γ-ray spectra observed in the present experiment are complicated by the presence of many lines from the other target materials and from the background. The assignment of γ rays to the $Ba^{135}(n, \gamma)Ba^{136}$ reaction was aided and confirmed by a careful comparison of the Ba^{136} γ-ray spectrum with the γ-ray spectra of a sample of natural $BaCO_3$ and $Ba(NO_3)_2$ samples enriched in Ba^{137} and Ba^{138}. In addition background spectra were obtained with a piece of graphite in the target position to enhance the scattering of neutrons. The complexity of the γ-ray spectrum is such that it remains possible that some of the weakest lines have been incorrectly assigned to Ba^{136}. Table I contains a list of the γ rays assigned to the $Ba^{135}(n, \gamma)Ba^{136}$ reaction.

The energies of the observed Ba^{136} γ rays were obtained in different ways in the low-energy (0–2.2 MeV), medium-energy (2–5 MeV) and high-energy (4–9 MeV) regions of the spectrum.

In the low-energy region the γ rays from the $Cr^{53}(n, \gamma)Cr^{54}$ reaction were recorded together with the Ba^{136} γ rays. At intervals during the measurement the same spectrum was routed into another section of the analyzer together with a set of pulser peaks to correct for the nonlinearity of the electronic system. The energies of the Ba^{136} lines were obtained by comparison with the 511.006±0.002 (annihilation radiation), 834.86±0.05, 1217.07±0.10 (two-escape peak of the 2239.07-keV γ ray), and 1784.66±0.10 keV (Cr^{54} lines, Ref. 17) lines. The 511-keV γ ray is generally regarded as being a poor energy standard because of the line broadening due to annihilation in flight. Some allowance was made for this in assigning errors to the Ba^{136} γ rays.

The γ rays from the $N^{14}(n, \gamma)N^{15}$ reaction on the N^{14} present in the $Ba(NO_3)_2$ target appear clearly in the high-energy region of the spectrum (see Fig. 4). Since the energies of the N^{15} lines have been carefully measured by Greenwood[18] these lines served as energy standards in this region of the spectrum. A set of pulser peaks was again used to correct for nonlinearities.

The medium-energy region is the most difficult in which to measure γ-ray energies because of the high density of lines (see Fig. 3) and the increased background due to higher-energy γ rays. Many of the lines in this region are members of unresolved multiplets and their positions and areas were determined graphically. The pulser was not used in the calibration of this region of the spectrum. Instead we adopted certain lines as energy references and calculated the energies of the remaining lines from the energies of these adopted standards on the assumption that there is a linear relationship between energy and channel number in the intervening regions. In calculating the error on the measured energies in this region some allowance was made for possible deviations from linearity in these intervening regions. The lines adopted as energy standards were the following: 2080.3±0.5, 2128.9±1.0, 2977.0±0.4 (Ba^{136} lines whose full energy or two-escape peak energy was obtained from the low-energy spectrum), 2509.9±0.2, 3486.8±0.3, 4247.2±0.3 (two-escape peaks of N^{15} lines, Ref. 18), 4289.9±0.6, and 4393.8±0.5 keV (two-escape peaks of Ba^{136} lines seen in the high-energy spectrum of Ba^{136}).

The results of these energy measurements are listed in column 1 of Table I. Column 3 of this table shows the initial and final levels between which the observed γ ray occurs. Column 4 gives the difference between the γ-ray energy and the difference in the initial and final level energies to show the degree of agreement obtained.

The relative intensities of the observed γ rays were determined with the use of an efficiency curve, which was determined for our Ge(Li) detector according to a method described elsewhere.[19] The intensities of the γ rays, relative to the intensity of the 818.6-keV γ ray, are given in column 2 of Table I.

C. γ–γ Coincidences

To help in the unravelling of the Ba^{136} decay scheme measurements of γ-γ coincidences were also made. In two separate runs γ rays of energies 0–2.0 and 4.9–7.5 MeV were counted in the 9-cm^3 Ge diode in coincidence with γ rays of energies 0.1–1.8 and 0.06–1.5 MeV detected in a 3×3-in. NaI counter. The neutron beam was collimated to a diameter of 6.0 mm in these runs. The pulses from the two counters ranged over 256 and 64 channels, respectively, and were stored in the 16384-channel memory of a TMC analyzer.

The spectrum in coincidence with each γ ray could be obtained with a computer program[20] which allowed us to sum spectrum slices associated with the peak under study and subtract an equal number of slices associated with the background to obtain the net coincidence spectrum. Figure 5 shows six representative spectra in coincidence with peaks detected in the Ge diode. It should be noted that chance coincidences are not subtracted from the total in this procedure. They are not a significant fraction of the total counts in these spectra. Great care must be exercised in interpreting these coincidence spectra, which are complicated in the low-energy region by the large number of transitions and by true coincidences between γ rays from other target materials and from the surroundings, and in the high-energy region by insufficient counts.

The results obtained from the coincidence studies are summarised in Table II. Where appropriate they are also discussed below.

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[17] W. R. Kane, M. A. J. Mariscotti, and G. T. Emery (to be published).

[18] R. C. Greenwood, Phys. Letters **27B**, 274 (1968).

[19] W. R. Kane and M. A. J. Mariscotti, Nucl. Instr. Methods **56**, 189 (1967).

[20] M. A. J. Mariscotti, Nucl. Instr. Methods **50**, 309 (1967); Brookhaven National Laboratory Report No. BNL 10904 (unpublished).

TABLE I. Energies, relative intensities, and assignments of γ rays observed in the $Ba^{135}(n, \gamma)Ba^{136}$ reaction.

E_γ (keV)	I_γ (relative)	Level (keV) from to	$\Delta L-E_\gamma$ [a] (keV)
157.8±0.5	2.7±0.5	3925.7–3767.1	0.8±1.5
671.3±0.3	1.8±0.3	3690.8–3019.9	−0.4±1.9
732.3±0.3	9.7±1.6	1550.5–818.6	−0.4±0.6
747.3±0.3	1.7±0.6	3767.1–3019.9	−0.1±1.5
760.6±0.3	2.1±0.4	1579.2–818.6	···[b]
818.6±0.2	100	818.6–g.s.	···[c]
880.3±0.3	0.6±0.2	3925.7–3043.6	1.8±1.9
981.3±0.6	1.6±0.4	2531.8–1550.5	0±0.9
993.4±0.4	1.2±0.3	···	···
1011.0±0.8	*W*	···	···
1047.7±0.3	12.2±1.3	1866.3–818.6	···[b]
1234.9±0.5	6.4±1.0	2053.5–818.6	···[b]
1261.0±0.5	4.4±1.2	{3767.1–2531.8, 2079.9–818.6}	0.3±0.8
1309.4±0.7	4.1±1.0	2128.3–818.6	0.3±1.1
1403.6±0.6	2.5±0.7	···	···
1441.9±1.0	1.3±0.5	3019.9–1579.2	1.2±1.5
1469.0±1.0	*W*	3019.9–1550.5	0.4±1.5
1536.5±0.6	2.3±0.6	···	···
1550.0±0.6	11.9±1.4	1550.5–g.s.	0.5±0.7
1556.7±0.7	0.4±0.3	···	···
1579.8±0.4	5.4±1.7	2398.4–818.6	0±0.6
1612.2±0.7	1.3±0.5	3690.8–2079.9	−1.3±1.8
1713.2±0.6	3.5±0.4	2531.8–818.6	0±0.8
1798.4±0.7	1.2±0.5	3925.7–2128.3	−1.0±1.6
1822.0±1.5	2.2±0.5	3690.8–1866.3	2.5±2.2
1841.1±1.0	2.6±0.5	···	···
1880.8±1.5	0.8±0.4	···	···
1954.6±1.0	3.5±1.4	3504.9–1550.5	−0.2±1.5
2080.3±0.5	4.2±1.4	2079.9–g.s.	−0.4±0.8
2128.9±1.0	1.7±0.3	2128.3–g.s.	−0.6±1.3
2201.0±0.4	1.4±0.5	3019.9–818.6	0.3±1.1
2224.8±2.0[d]	···	3043.6–818.6	0.2±2.4
2244.0±1.0	0.6±0.3	3795.4–1550.5	0.9±1.4
2686.5±2.0	2.4±1.0	3504.9–818.6	−0.2±2.3
2977.0±0.4	3.6±0.5	3795.4–818.6	−0.2±1.0
3044.7±0.7	1.5±0.5	3043.6–g.s.	−1.1±1.5
3476.0±3.0	*W*	···	···
3491.0±3.0	*W*	···	···
3517.8±2.2	*W*	···	···
3709.8±2.5	*W*	···	···

TABLE I. (*Continued*).

E_γ (keV)	I_γ (relative)	Level (keV) from to	$\Delta L-E_\gamma$ [a] (keV)
3739.2±3.0	1.1±0.3	···	···
3793.7±2.0	0.5±0.2	···	···
3860.7±1.5	0.7±0.2	···	···
3913.8±1.0	0.2±0.1	···	···
3967.8±2.0	*W*	···	···
3983.4±2.0	*W*	···	···
4137.2±1.4	1.4±0.4	···	···
4322.5±1.5	1.3±0.4	···	···
4429.0±2.0	2.1±0.4	···	···
4508.8±2.0	1.5±0.2	···	···
4536.8±2.3	0.4±0.2	···	···
4731.8±2.0	0.3±0.2	···	···
4761.7±2.0	0.9±0.2	···	···
4791.0±2.0	0.2±0.1	···	···
4885.7±2.4	*W*	···	···
4929.4±1.7	0.8±0.3	···	···
4973.0±1.5	1.2±0.3	···	···
4994.1±2.4	0.4±0.2	···	···
5046.5±1.9	1.0±0.4	···	···
5098.3±5	2.5±0.4	···	···
5141.0±1.7	0.4±0.2	···	···
5181.5±2.6	0.9±0.2	9106.4–3925.7	−0.9±2.7
5311.9±0.6	3.7±0.4	9106.4–3795.3	−1.0±1.4
5340.3±0.7	0.2±0.1	9106.4–3767.1	−1.1±1.5
5415.8±0.5	2.2±0.3	9106.4–3690.8	−0.3±1.6
5601.8±0.6	1.0±0.2	9106.4–3504.9	−0.4±1.7
5673.2±0.6	0.4±0.1	9106.4–3433.2	···[e]
5758.9±0.9	0.2±0.1	···	···
6063.5±0.4	3.5±0.6	9106.4–3043.6	−0.8±1.7
6087.4±0.5	0.3±0.1	9106.4–3019.9	−1.0±1.5
6574.9±0.6	0.5±0.1	9106.4–2531.8	−0.5±1.1
6707.4±0.8	0.3±0.05	9106.4–2398.6	0.2±1.2
6978.2±0.7	0.2±0.05	9106.4–2128.3	−0.3±1.3
7026.4±0.7	0.7±0.1	9106.4–2079.9	−0.1±1.2
7526.6±2.0	0.07±0.04	9106.4–1579.2	0.4±2.2
7554.3±1.0	0.24±0.08	9106.4–1550.5	1.4±1.3
8288.2±0.8	1.8±0.4	9106.4–818.6	−0.7±1.2
9106.5±1.3	2.9±0.3	9106.4–g.s.	−0.4±1.5

[a] ΔL denotes the difference in energy of the levels between which the transition takes place minus the recoil energy of the γ ray.

[b] The energy of this transition was used, together with the energy (818.6 keV) of the first excited state to define the energy of the upper level.

[c] The energy of this transition defines the energy of the first excited state.

[d] This line coincides in energy with the hydrogen-capture γ ray. See Sec. III M.

[e] In this case the level energy was determined by the difference in energy between the neutron binding energy and the energy of this transition.

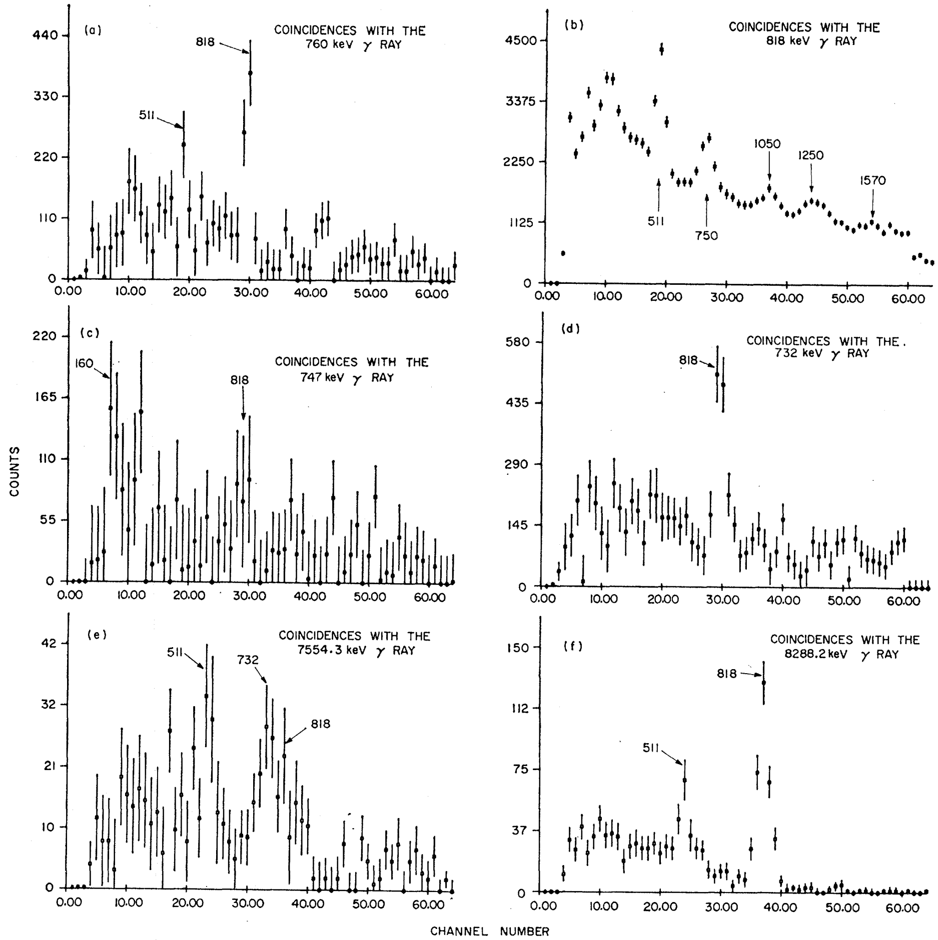

FIG. 5. Net coincidence spectra from the 3×3-in. NaI detector gated with the (a) 760.6-, (b) 818.6-, (c) 747.3-, (d) 732.3-, (e) 7554.3-, and (f) 8288.2-keV γ rays which were detected in the Ge(Li) diode. The spectra shown in parts (e) and (f) are taken at different dispersion from those in parts (a)–(d). Each spectrum was obtained as a computer output from the program PALMUD (Ref. 20), which summed the spectrum slices associated with the gating γ ray and subtracted an equal number of background slices. It should be noted that this procedure does not include the subtraction of chance coincidences from the total spectrum. Chance coincidences are not a significant fraction of the total counts in these spectra.

III. CONSTRUCTION OF THE LEVEL SCHEME

The level scheme of Ba^{136}, which is shown in Fig. 6, was constructed from the data of Tables I and II together with the information available from previous investigations.

The basis of our interpretation of the observed γ-ray spectrum was the observation in the singles spectrum of the strong 9106.5- and 8288.2-keV transitions [see Figs. 4(c) and 4(d)] with a difference in energy of 818.3 keV, and their assignment as primary transitions to the ground state and 818.6-keV first excited state. This assignment was confirmed by the failure to observe any γ rays in coincidence with the 9106.5-keV transition and the observation that the 8288.2-keV transition is strongly in coincidence with the 818.6-keV transition [see Fig. 5(f)], which de-excites the first excited state. Becvar *et al.*[12] also assigned these γ rays as primary γ rays. It should be pointed out that the primary γ-ray energies measured by Becvar *et al.* are systematically 5–6 keV higher than those reported here. In general, the differences in their primary γ-ray energies are in good agreement with those reported in the present work.

The remainder of the level scheme was constructed as follows: (1) First the energies of the 818.6- and 1550.5-keV levels were determined from the energies of the observed 732.3-, 818.6-, and 1550.0-keV transitions. (2) This allowed us to determine the neutron binding energy from the energy sums 9106.5, 8288.2+818.6, and 7554.3+1550.5 keV. With appropriate corrections for the nuclear recoil energy, these energy sums lead to a weighted average value for the neutron binding energy of 9106.4±0.8 keV. This result disagrees with the value of 9230±70 keV given by Mattauch, Thiele, and Wapstra.[21] (3) The preliminary assumption was made that the observed high-energy γ rays ($E_\gamma > 4$ MeV) are primary transitions from the neutron capture state. The difference in energy between the neutron binding energy and the measured primary γ-ray energy then gave a preliminary value for the level energy (E_L). (4) The γ-ray singles spectra were then examined for the presence of secondary γ rays whose energies equalled the difference in energy between E_L and the energies of levels of lower energy, which had already been established. In general, the secondary transitions

[21] J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. **67**, 32 (1965).

TABLE II. Results of the γ-γ coincidence measurements.

A. High-energy–low-energy coincidences

γ ray (keV)[a]	Coincident peaks (MeV)
8288.2	0.82
7554.3	0.73, 0.82
7026.4	0.82, 1.27
6978.2	0.82
6707.4	0.82
6574.9	(0.73), 0.82
6087.4	(0.82)
6063.5	(0.82)
818.6[b]	5.10, 5.15, 5.20, 5.31, 5.40, 6.07, 6.72, 7.00, 7.03, 7.52, 7.56, 8.29

B. Low-energy–low-energy coincidences

γ ray (keV)[a]	Coincident peaks (MeV)
157.8[b]	0.66, 0.73, 0.75, 0.82, 1.05, 1.4
671.3	0.16, 0.82
732.3	0.82
747.3	0.16, 0.82
760.6	0.82
818.6[b]	0.16, 0.67, 0.73, (0.75), 0.76, 0.99, 1.05, 1.24, 1.26, 1.31, 1.58, 1.68[c]
1047.7	0.15, 0.82
1234.9	0.82
1261.0	0.82
1309.4	0.82

[a] With the exception of the 157.8- and 818.6-keV γ rays, the gating γ ray, whose energy is shown in the left-hand column, was detected in the 9-cm^3 Ge(Li) detector and the coincident peaks shown on the right were observed in the NaI detector. As a result the error associated with the energies quoted on the right is ± 20 keV.

[b] In these cases the Ge(Li) detector spectrum was examined in coincidence with the appropriate gate in the NaI detector. The error on the energies of the coincident peaks is ± 20 keV for the 818.6-keV γ-ray gate in part A, and ± 10 keV for the 157.8- and 818.6-keV gates in part B.

[c] This peak is thought to be due to the two-escape peak of the 2686.5-keV γ ray.

were placed in the level scheme on the basis of their energies alone, but in some cases the placing of the transition was also supported by the coincidence results. In the absence of further support from previous studies or from the coincidence measurements a level was regarded as being established only if three transitions were found which lead into or out of the level. (5) A precise value for E_L was then determined from the weighted mean of values obtained from the energies of all transitions into and out of the level. (6) Following this readjustment of the level energies steps 4 and 5 were repeated.

The energies of those levels, which were not observed to be populated in the (n, γ) reaction but had been established in previous studies, were redetermined from our more precise level energies and the γ-ray energies of Frana *et al.*[9]

Comments on the properties of the individual levels in Ba^{136} follow.

A. Level at 818.6±0.2 keV

This state, the first excited state in Ba^{136}, was firmly established in studies[1–6] of the decay of Cs^{136}. The assigned spin and parity (2+) are consistent with the systematics[22] of even-even nuclei and with measurements of the directional correlations[3–5] of γ-ray cascades through this level. The level energy given here is in excellent agreement with the recent measurements of Frana *et al.*,[9] Julian and Fessler,[10] and Griffioen *et al.*[11]

This level is fed from the capture state by the strong 8288.2-keV transition.

B. Level at 1550.5±0.4 keV

A level at this energy was first proposed by Becvar *et al.*[12] Its existence was confirmed in the present work by the observation of five incoming transitions of energies 981.3, 1954.6, 2244, 1469, and 7554.3 keV and two outgoing transitions of energies 732.3 and 1550.0 keV. The weak 7554.3-keV primary transition was observed to be in coincidence with the 732.3- and 818.6-keV γ rays [see Fig. 5(e)]. In addition, the 732.3-keV transition to the first excited state was observed to be in coincidence with the 818.6-keV transition from the first excited state to the ground state [see Fig. 5(d)].

Becvar *et al.* assigned spin and parity 2+ to this level. Both 2+ and 1− spin and parity assignments are consistent with the present experimental evidence. Since the energy of the level and the branching ratio of the transitions to the ground state and first excited state are typical of two-phonon vibrational levels in even-even nuclei the 2+ assignment is strongly favored.

C. Level at 1579.2±0.4 keV

A level at this energy was proposed by Julian and Fessler[10] on the basis of their observation of the 760.6-keV transition to the first excited state following La^{136} decay. Becvar *et al.*[12] observed a weak primary transition to a level of this energy in the (n, γ) reaction as well as the 760-keV transition.

A weak primary transition of energy 7526.6 keV was observed in the singles spectrum. This peak was clearly seen in coincidence with γ rays of 818-keV energy. The 760-keV γ ray was also observed to be in coincidence with the 818.6-keV γ ray [see Fig. 5(a)], which de-excites the first excited state.

A γ ray of 1579.8-keV energy, which would fit well in

[22] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. 98, 212 (1955).

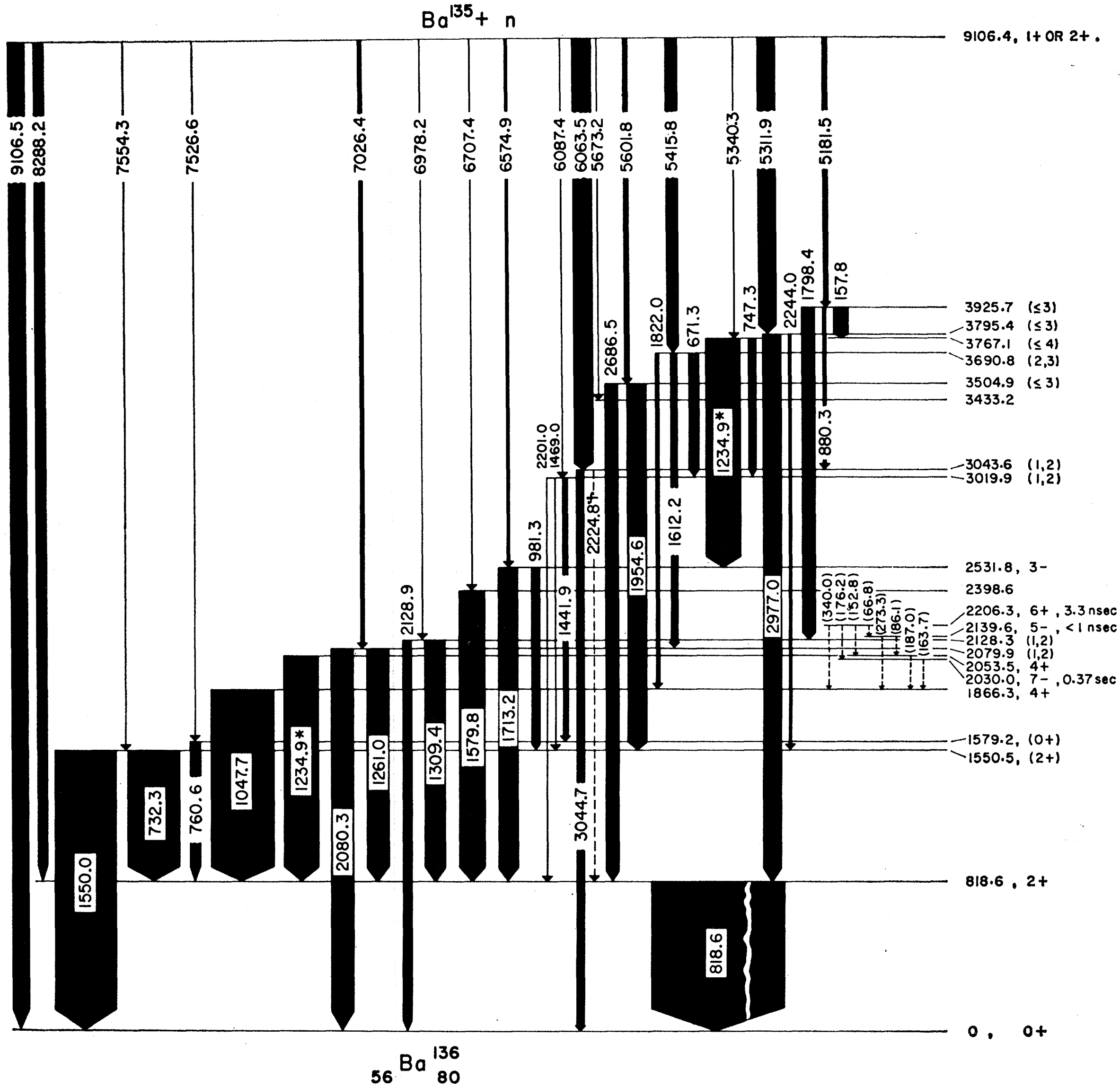

FIG. 6. Level scheme of Ba^{136} obtained from the Ba^{135}(n, γ)Ba^{136} reaction. The measured level energies (in keV), assigned spins and known half-lives are indicated on the right. The breadths of the vertical lines representing the observed transitions are proportional to the measured γ-ray intensities. The transitions shown as dashed lines on the right were not observed in the present work, but have been established by earlier radioactive decay scheme studies. Notes: * The full intensity of the 1234.9-keV transition has been placed in two positions in the level scheme. From studies of the decay of Cs^{136} a transition of this energy is well established between the 2053.5- and 818.6-keV levels. Some portion of the observed intensity may lie between the 3767.1 and 2531.8 levels. † The placing of the 2224.8-keV transition in the level scheme is only tentative since it coincides in energy with the hydrogen-capture γ ray. Hence its existence is uncertain.

energy between this level and the ground state, was observed by Becvar *et al.* and by us. Three separate pieces of evidence suggest that it should be placed elsewhere in the level scheme, namely: (i) In the present experiment the 1579.8-keV γ ray was observed to be in coincidence with the 818.6-keV γ ray de-exciting the first excited state. It appears in the coincidence spectrum with the same intensity, relative to other lines known to feed the 818.6-keV level, as in the singles spectrum. (ii) No γ ray of this energy was observed by Julian and Fessler in their study of the decay of La^{136}, although they did observe the 760.6-keV γ ray. (iii) Becvar *et al.* observed the 1578-keV γ ray in the γ-ray spectrum from the 24.5-eV (1+) neutron resonance but not from the 82- (2+) and 88-eV (2+) resonances. They observed the 760-keV γ ray in all three spectra.

Accordingly, we have placed the 1579.8-keV γ ray between the 2398.6- and 818.6-keV levels (see Sec. III J).

Julian and Fessler[10] assigned spin and parity 2+ to this level on the basis of an analogy with the known behavior of similar nuclei. Becvar *et al.* and Griffioen *et al.* assigned spin and parity 0+. Spin and parity 0+ seem probable on the basis of our knowledge[22] of the systematic behavior of even-even nuclei, but we cannot rule out spins 1, 2, and 3 on present experimental evidence.

D. Level at 1866.3±0.4 keV

This level was firmly established in earlier decay scheme studies and it has been assigned 4+ spin and parity from γ-γ angular correlation measurements.[3] The failure to observe a primary transition to this level in the present study is consistent with this spin and parity.

The strong 1047.7-keV transition proceeds from this level to the first excited state at 818.6 keV. The level energy given here, which is based on the energy sum 1047.7+818.6=1866.3 keV, is in good agreement with other recent measurements.[9,12]

E. Level at 2030.0±0.5 keV

Ruddy and Pate[7] established this level as the 0.37-sec isomeric level. No transitions to or from this level were observed in the present experiment.

This level is known[7] to decay to the 1866.3-keV level by an E3 transition of 163.7-keV energy.[9] The level energy given here is based on the energy sum 1866.3+163.7=2030.0 keV.

F. Level at 2053.5±0.6 keV

The Cs^{136} decay scheme studies[6] established a level at this energy, which decays by the strong 1234.9-keV transition to the 818.6-keV level. It was assigned spin and parity 4+ by Grabowski *et al.*[3] on the basis of their study of the 1234.9–818.6-keV γ-γ directional correlation.

As expected from this spin-parity assignment no primary transition was observed to this level in the (n, γ) reaction. The strong 1234.9-keV transition was observed in singles and in coincidence with the 818.6-keV transition.

G. Level at 2079.9±0.6 keV

Becvar *et al.*[12] reported a primary γ ray of energy 7032±5 keV to a level at this energy, and transitions of energies 2080 and 1262 keV from this level to the ground state and first excited state, respectively. Julian and Fessler[10] also reported a level at this energy based on the observation of a 1261.7-keV γ ray.

The existence of this level was confirmed in the present work by the observation of the 7026.4- (primary) and 1612.2-keV transitions to this level and the 1261.0- and 2080.3-keV transitions de-exciting it. The 7026.4-keV primary transition was observed to be in coincidence with the 818.6- and 1261.0-keV transitions. The 1261.0-keV transition was, in turn, observed to be in coincidence with the 818.6-keV transition.

The 2080.3-keV transition, which was placed in the level scheme on the basis of the energy fit, was not observed by Julian and Fessler. An examination of their γ-ray spectrum (Fig. 1 of Ref. 10) reveals that a 2080.3-keV γ ray of this intensity may have gone undetected.

Becvar *et al.* suggested that the spin of this level is 1 or 2. This assignment is consistent with the fact that the level is observed to decay by γ-ray emission to levels of spins 0 and 2 and is fed moderately strongly from neutron resonances of spins 1 and 2.

H. Level at 2128.3±0.8 keV

This level is populated by the weak 6978.2-keV primary transition and by the 1798.4-keV transition from the 3925.7-keV level. It decays to the ground state and 818.6-keV first excited state by the 2128.9- and 1308.9-keV transitions. Both the 6978.2- and 1309.4-keV transitions were observed to be strongly in coincidence with the 818.6-keV transition.

Becvar *et al.* observed both the 6978.2- and 1309.4-keV transitions in their study of the $Ba^{135}(n, \gamma)Ba^{136}$ reaction. They did not observe the 2128.9- and 1798.4-keV transitions. They observed the 6978.2-keV transition in the γ-ray spectra from neutron resonances of spins 1 and 2. Julian and Fessler observed both the 1309.4- and 2128.9-keV γ rays in their study of the decay of La^{136}.

The observation of transitions to this level from states of spins 1 and 2 and from this level to states of spins 0 and 2 suggests spin 1 or 2 for this level.

I. Levels at 2139.6±0.6 and 2206.3±0.5 keV

These levels have been firmly established in studies[1–9] of the decay of Cs^{136}. They have been assigned[3,6,8] spins and parities 5− and 6+ from measurements of γ-γ directional correlations and the multipolarities of the incoming and outgoing transitions. As expected from these spin and parity assignments neither level was observed to be populated in the (n, γ) reaction.

The level energies given here were obtained by combining the measured[9] energies of the low-energy γ-rays de-exciting these levels and the other level energies measured in the present work.

J. Level at 2398.6±0.3 keV

This level is populated by the weak 6707.4-keV primary transition and decays to the first excited state at 818.6 keV by the strong 1579.8-keV transition. As discussed in Sec. III C the 1579.8-keV transition was observed to be in coincidence with the 818.6-keV transition de-exciting the first excited state. The

6707.4-keV transition was also observed to be in coincidence with the 818.6-keV transition.

A transition of energy 1580 keV was also observed by Becvar *et al.* in their study of the $Ba^{135}(n, \gamma)Ba^{136}$ reaction, but it was not placed in their level scheme.

The observation of a weak incoming transition from the 1+ or 2+ capture state and an outgoing transition to the 818.6-keV (2+) state is consistent with this level having a spin ≤ 4.

K. Level at 2531.8±0.5 keV

The one-escape peak of the strong 6063.5-keV transition lies at 5552.5 keV. From our knowledge of the one-escape–two-escape peak ratio for the ~9-cm^3 Ge(Li) detector it is clear that this peak is too intense by a factor of 3 to be due to the one escape peak alone. Accordingly, the remainder of the line intensity was assigned to a 6574.9-keV primary transition, which feeds a level at 2531.8 keV. This level decays to the 818.6- and 1550.5-keV levels via the 1713.2- and 981.3-keV transitions.

The coincidence results shed little light on the properties of this level. There is some evidence that the two-escape peak of the 6574.9-keV transition is in coincidence with peaks at 820 and 730 keV in the spectrum from the NaI counter. This evidence is weak.

This level may be identified with the 2.50-MeV (3−) state observed by Alster *et al.*[13] in their studies of the inelastic scattering of 31-MeV α particles on Ba^{136}. The observed decay pattern is consistent with the 3− assignment, although no positive evidence for this spin assignment was obtained here.

L. Level at 3019.9±0.5 keV

This level is fed by the weak 6087.4-keV transition from the capture state, and by the 747.3- and 671.3-keV transitions from the levels at 3767.1 and 3690.8 keV. It decays via the 2201.0-, 1469.0-, and 1441.9-keV transitions to the 818.6-, 1550.5-, and 1579.2-keV levels. All of these γ rays were placed on the strength of the energy fits alone.

The observation of a transition from the capture state to this level and transitions from this level to states of spins 0 and 2 is consistent with spin 1 or 2 for this level. It should be noted that this restriction on the spin value only applies if the 0+ assignment to the level at 1579.2 keV is correct.

M. Level at 3043.6±1.4 keV

This level is fed by the strong 6063.5-keV primary transition and by the 880.3-keV transition from the level at 3925.7 keV. It decays to the ground state by the 3044.7-keV transition.

The energy difference $3043.6-818.6=2225.0$ keV coincides in energy with the hydrogen-capture γ ray. The absolute intensity of this line was observed to be six or seven times greater in the $Ba^{135}(n, \gamma)Ba^{136}$ reaction than in the $Ba^{137}(n, \gamma)Ba^{138}$ and $Ba^{138}(n, \gamma)Ba^{139}$ reactions. Accordingly, the transition, of measured energy 2224.8 keV, has been tentatively placed in the level scheme. Hence the dashed line in Fig. 6. Some support for the placing of this transition comes from the improved intensity balance for this level if this transition is placed here. Further support was obtained from the observation of the 6063.5-keV transition in coincidence with the 818.6-keV transition de-exciting the first excited state.

As noted in Sec. III K the difference in energy of the 3043.6- and 2531.8-keV levels is 511 keV. It was not possible in the present experiment to determine whether a transition of this energy exists in Ba^{136}.

The observation of the strong primary transition to this level and the de-exciting transition to the ground state is consistent with spin 1 or 2 for this level.

N. Level at 3433.2±0.5 keV

A level at approximately this energy was reported by Becvar *et al.*[12] on the basis of an observed 5675±5-keV transition in their resonance neutron-capture γ-ray studies. A weak primary transition (of energy 5663.2± 0.6 keV) belonging to the $Ba^{135}(n, \gamma)Ba^{136}$ reaction was observed in the present work. No other evidence for the existence of such a level was found.

O. Level at 3504.9±1.1 keV

A level at 3504 keV was reported by Becvar *et al.*[12] on the strength of an observed 5602±5-keV transition. A moderately strong primary transition of energy 5601.8 keV was observed to feed this level in the present work. The level decays to the 818.6- and 1550.5-keV levels by transitions of 2686.5- and 1954.6-keV energy. These transitions were placed in the level scheme on the basis of energies alone.

The assignment of spin ≤ 3 to this level appears to be consistent with the observed mode of decay and the assumption that the strong primary transition to this level is a dipole transition.

P. Level at 3690.8±1.5 keV

This level is populated by the strong 5415.8-keV primary transition. It decays to the 1866.3- (4+), 2079.9- (1, 2), and 3019.9-keV (1, 2) levels by transitions of 1822.0-, 1612.2-, and 671.3-keV energy.

The strength of the primary transition indicates that it is probably a dipole transition, which restricts the spin of the level to ≤ 3. The level decays to states of spins 4 and 1 or 2. Since an octupole transition of 1822-keV energy is unlikely to compete strongly with a dipole or quadrupole transition of energy 1612 or 671 keV the spin of the 3690.8-keV level must be 2 or 3.

Q. Level at 3767.1±1.0 keV

This level is populated by the weak 5340.3-keV transition from the capture state and by the 157.8-keV transition from the level at 3925.7 keV. It decays to the 3019.9-keV level by the 747.3-keV transition, which was observed to be in coincidence with the 157.8-keV transition [see Fig. 5(c)].

The 1234.9-keV transition also fits well in energy between this level and the 2531.8-keV level, but this transition is already well established (see Sec. III F) between the 2053.5- and 818.6-keV levels. Some small fraction of the observed 1234.9-keV line intensity may belong to a transition from the 3767.1-keV level.

No other transitions to or from this level were observed in the present work.

The observed feeding and decay pattern is consistent with this level having a spin ≤ 4.

R. Level at 3795.4±0.9 keV

The strongest primary transition of energy 5311.9 keV feeds this level. It decays strongly to the first 2+ state at 818.6 keV via the 2977.0-keV transition, and by a weaker 2244.0-keV transition to the probable 2+ level at 1550.5 keV. No other transitions to or from this level were observed.

The strength of the primary transition indicates that it is probably of dipole character. This is consistent with a spin ≤ 3 for this level.

S. Level at 3925.7±1.2 keV

This level is populated by the 5181.5-keV primary transition, and decays via the 1798.4-, 880.3-, and 157.8-keV transitions to the levels at 2128.0, 3043.6, and 3767.1 keV. The 1798.4- and 880.3-keV transitions were placed here on the basis of the energy fits alone.

The placing of the 157.8-keV transition, which is an unusual one since it implies that this transition is greatly enhanced compared with all the other possible transitions de-exciting this level, is mainly based on the energy fit. The observation of the 671.3- and 747.3-keV γ rays in coincidence with a peak at $\sim$160 keV, which can not be interpreted as arising from a back-scattered peak since such a peak would also appear in coincidence with the 732.3- and 760.6-keV γ rays, is also consistent with this assignment although it does not prove that it is correct.

It should be pointed out that the energy 157.8 keV agrees within the errors with the differences in energy of several pairs of γ rays assigned to Ba^{136} (see Table I). There is no other evidence to suggest that these pairings are significant except in the case of the 5758.9- and 5601.8-keV pairing. In this case the latter is the primary γ ray feeding the level at 3504.9 keV. If we assume that the 5758.9-keV γ ray is also a primary transition then it would feed a level at 3347.4 keV. A careful search failed to reveal any further evidence of a level at this energy.

In summary we may say that the placing of the 157.8-keV transition is the only one consistent with the information available to us at present. Since the level scheme shown in Fig. 6 is clearly incomplete it remains possible that the 157.8-keV transition may belong in one or more of several other positions in the level scheme.

If we assume that the primary transition is a dipole transition then these observations are consistent with a spin ≤ 3 for this level.

T. Possible Levels Not Included in the Level Scheme

There is some evidence from the neutron-capture γ-ray studies to suggest the existence of levels in Ba^{136} at 2222.0 and 2859.8 keV. We did not include these levels in the level scheme of Fig. 6 because of the weakness of the available evidence. Comments on the evidence available on these levels follow:

Level at 2222.0±0.7 keV. Becvar *et al.*,[12] in their study of resonance neutron capture in Ba^{135}, suggested a level in Ba^{136} at 2222 keV based on the observation of the 1404- and 671-keV transitions, which would fit in energy between such a level and the 818.6- and 1550.5-keV levels. They did not include this level in their level scheme. They also reported a weak 641-keV transition, which would fit in energy between a 2222-keV level and the level at 1579.2 keV. The transitions of 1403.6- and 671.3-keV energy were observed in the present study of thermal neutron capture in Ba^{135}. No 641-keV transition was observed. In addition, a weak 1469.0-keV transition was observed, which fits in energy between the 3690.8-keV level and a level at 2222.0 keV. Both the 671.3- and 1469.0-keV transitions have been placed elsewhere in the level scheme.

The observation of these transitions may imply the existence of a level at 2222.0±0.7 keV. The ground-state transition from a level at this energy would coincide in energy with the hydrogen capture γ ray at 2223 keV. The evidence available from the present work (see Sec. III M) indicates that a 2224.8±2.0-keV γ ray may be present in the $Ba^{135}(n, \gamma)Ba^{136}$ spectrum. It can be placed between the 3043.6- and 818.6-keV levels as well as here.

No primary transition to a level at this energy was observed. We feel that further evidence is required before this level can be included in the level scheme.

Level at 2859.8±0.8 keV. A level at this energy is suggested by the observation in the present work of transitions of 1309.4-, 993.4-, and 732.3-keV energy, which fit in energy between a level at this energy and the levels at 1550.5, 1866.3, and 2128.0 keV. Both the 1309.4- and 732.3-keV transitions are well established elsewhere in the level scheme (see Secs. III H and III B) but some portion of the observed intensity of these transitions may belong to other transitions of the same energies.

Becvar *et al.*[12] did not observe the 993.4-keV transition in the γ-ray spectrum from the 24.5-keV neutron resonance, but this transition is weak and may have been missed in their spectrum. These authors did observe a moderately strong 2040-keV transition, which would fit between the 2859.8- and 818.6-keV levels. Such a transition was not observed in the thermal neutron-capture γ-ray spectrum. Hence it is unlikely that it deexcites the same level as the 1308.9- and 732.3-keV transitions.

Again the above evidence is too weak to establish the existence of a level at this energy.

No evidence was found for the existence of levels at 2141.0, 2284.5, 2315.6, 2485.4, 2609.9, and 2770 keV, which were reported in studies[10,11] of the decay of 9.87-min La^{136}. Since La^{156} has spin and parity 1+ we expect these levels to have low spin. The neutron capture reaction also populates low-spin levels in Ba^{136} and hence we might expect these levels to be populated directly or indirectly in this reaction. A search of the γ-ray singles spectrum failed to reveal any transition between these levels and any other known level. In addition Becvar *et al.*[12] did not report any of these levels in their study of resonance neutron capture on Ba^{135}. However, the known Porter-Thomas fluctuations in the decay of the capture state prevent us from drawing any positive conclusion about the existence of these levels from our failure to observe their population in the (n, γ) reaction.

Alster *et al.*[13] reported levels at 0.83 (2+), 2.10, 2.50 (3−), 2.8, 3.1, 3.50, and 3.65 MeV in their study of α-particle scattering on Ba^{136}. With the exception of the level at 2.8 MeV, levels close to these energies were observed in the present work. The two sets of levels cannot be equated because of the limited energy resolution of 130–150 keV in the charged-particle scattering experiments.

IV. DISCUSSION

An examination of the Ba^{136} level scheme (Fig. 6) reveals two striking features, namely the cluster of high-spin levels at ~2-MeV excitation energy and the vibrational pattern of the first four excited states.

The group of high-spin levels has been described[6,8] in terms of the shell model as arising from the two-particle configurations $p(g_{7/2})_{J=6,4}{}^2$, $n(h_{11/2})_{J=6,4}{}^{-2}$, and $p(d_{5/2})_{J=4}{}^2$ for the 6+ and 4+ states, $n(h_{11/2}{}^{-1}, d_{3/2}{}^{-1})$ for the 7− state, and $n(h_{11/2}{}^{-1}, d_{3/2}{}^{-1})$ or $n(h_{11/2}{}^{-1}, s_{1/2}{}^{-1})$ for the 5− state. As expected from the low spin of the neutron capture state these states are either not populated or are very weakly populated in the (n, γ) reaction. Consequently, the present experiment provides little new information on the properties of these levels.

The properties of the first four excited states in Ba^{136} suggest strongly that this nucleus can be considered a vibrational nucleus.[22] The even-even vibrational or near-harmonic nuclei are characterized by a triplet of quadrupole vibrational states with spins 0+, 2+, and 4+ at an excitation energy twice that of the first excited state. (We denote by 2+′ the second excited 2+ state.) In these nuclei the 2+→0+, 4+→2+, 0+′→2+, and the $E2$ part of the 2+′→2+ transitions are all enhanced with respect to single-particle transitions. The $M1$ part of the 2+′→2+ transition is retarded, and the 2+′→0+ transition is observed to be weak compared with the 2+′→2+ transition. The vibrational or spherical model[22] successfully describes these properties of even-even, near-spherical nuclei. It is less successful in describing some other features of these nuclei. First, it fails to predict the order of the two-phonon triplet. Various attempts[23–28] to explain the observed excitation sequence of the triplet and the energy intervals between the members of the triplet by including anharmonic terms in the vibrational Hamiltonian have met with limited success. Secondly, the model predicts

$$B(E2;\, 2+'\rightarrow 2+)/B(E2;\, 2+\rightarrow 0+) = 2,$$

whereas the experimental values[29] are found to be smaller. Thirdly, the model predicts $E_{2+}'/E_{2+} \geq 2$, whereas this ratio is found to be less than 2 for several of the Pt nuclei. Finally, the results of recent experiments[30] indicate that some vibrational nuclei have sizable intrinsic quadrupole moments contrary to the predictions of the model.

In Ba^{136}, as in $Pt^{192,194,196}$, we find that the ratio of the excitation energies $E_{2+}'/E_{2+} = 1.89$, which is lower than both the value 2.0 predicted by the vibrational model and the average experimental value[22] 2.2. However, the mean excitation energy of the two-phonon triplet (1665.5 keV) is 2.03 times the energy of the first excited state. The ratio

$$B(E2;\, 2+'\rightarrow 0+)/B(E2;\, 2'+\rightarrow 2+) = 0.029 \pm 0.006$$

is in good agreement with measured values for other similar nuclei. A fuller comparison with this and other models requires further experimental information on such properties as the $M1$-$E2$ mixing in the 2+′→2+ transition and the lifetimes of the 2+′ and 2+ states. Gerschel, Pautrat, Ricci, Teillac, and Van Horen-

[23] L. Wilets and M. Jean, Phys. Rev. **102**, 788 (1956).
[24] B. J. Raz, Phys. Rev. **114**, 1116 (1959).
[25] T. Tamura and L. G. Komai, Phys. Rev. Letters **3**, 344 (1959).
[26] A. K. Kerman and C. M. Shakin, Phys. Letters **1**, 151 (1962).
[27] D. M. Brink, A. F. R. De Toledo Piza, and A. K. Kerman, Phys. Letters **19**, 413 (1965).
[28] K. H. Bhatt, Phys. Letters **24B**, 22 (1967).
[29] P. H. Stelson and F. K. McGowan, Phys. Rev. **121**, 209 (1961); F. K. McGowan and P. H. Stelson, Phys. Rev. **126**, 257 (1962); F. K. McGowan, R. L. Robinson, P. H. Stelson, and J. L. C. Ford, Jr., Nucl. Phys. **66**, 97 (1965); W. T. Milner, F. K. McGowan, R. L. Robinson, P. H. Stelson, and R. O. Sayer, Bull. Am. Phys. Soc. **12**, 1201 (1967); F. K. McGowan, R. L. Robinson, P. H. Stelson, and W. T. Milner, Nucl. Phys. **A113**, 529 (1968).
[30] See J. de Boer and J. Eichler, Advan. Nucl. Phys. **1**, 1 (1968).

beeck[31] and Sakai[32] have examined systematically the level structure of the Ba isotopes. Only the 2+ and 4+ members of the two-phonon triplet are known in the lighter Ba isotopes. The discovery of the 0+ member in Ba^{136} suggests that we may expect to find the third member of the triplet in the other Ba isotopes. The excitation energies of these levels vary smoothly as we go from the rotational structure of the neutron-deficient Ba nuclei to the near-harmonic Ba^{136} and semimagic Ba^{138}. Sakai,[32] following Sheline,[33] examined the correlation of level structure between vibrational and rotational nuclei, and by simple phenomenological arguments showed that the 4+, 2+, and 0+ states of the two-phonon quadrupole triplet tend to the 4+ state of the ground-state rotational band, the 2+ head of the γ-vibrational band, and the 0+ head of the β-vibrational band, respectively. Unfortunately, our knowledge of the level structure of Ba^{136} is still too limited to provide a test of this hypothesis. Further information on the properties of the levels at 2398.6 and 3433.2 keV might be of particular interest since a β-vibrational band built on the 1579.2-keV level would have a 2+ level at $\sim$2398 keV and a 4+ level at $\sim$3445 keV, and a γ-vibrational band built on the 2+ level at 1550.5 keV would have a 3+ member at $\sim$2370 keV and a 4+ member at $\sim$3417 keV.

Recently, it has been found[34] that the first excited 2+, 4+, 6+, etc. levels in even-even, near-spherical nuclei such as Ba^{136} can be described as members of a ground-state rotational band. In this model, the "Variable Moment of Inertia" (VMI) model, each nucleus is described by two adjustable parameters, the ground-state moment of inertia parameter $\mathcal{I}_0$ and the softness parameter σ, which are determined by a least-squares fit to all known levels. This model has been shown to be valid over the range $2.23 \leq E_{4+}/E_{2+} \leq 3.33$. From the measured ratio $E_{4+}/E_{2+} = 2.28$, which lies within the range of applicability of this model, we find $\sigma \approx 200$ and $\mathcal{I}_0 = 0.0005$ for Ba^{136}, as compared with $\sigma \sim 0.01$ and $\mathcal{I}_0 \sim 0.03$ for a typical deformed nucleus in the rare-earth region. Since this model successfully describes ground-state bands in many nuclei as "soft" as Ba^{136}, it again points to a smooth change from "spherical" to "deformed" nuclei. The model predicts the 6+ member of the ground-state band in Ba^{136} at 3115 keV. Because of the high spin this level was not observed in the (n, γ) reaction. At the same time the predicted level energy is greater than the decay energy of both Cs^{136} and La^{136}. Hence it is not observed in the radioactive decay of these isotopes. A test of this prediction must await charged-particle reaction studies. This prediction and the fact[8] that the 340-keV $E2$ transition to the 4+ level at 1866.3 keV is weakly hindered with respect to the single-particle estimate clearly suggests that the 6+ state at 2206.3 keV is not related to the ground-state band.

[31] G. Gerschel, M. Pautrat, R. A. Ricci, J. Teillac, and J. Van Horenbeeck, *Proceedings of the International Conference on Nuclear Physics, Paris, 1964* (Éditions du Centre National de la Recherche Scientifique, Paris, 1965), Vol. II, p. 501.

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

[33] R. K. Sheline, Rev. Mod. Phys. **32**, 1 (1960).

[34] M. A. J. Mariscotti, G. Scharff-Goldhaber, and B. Buck, Phys. Rev. **178**, 1864 (1969).

The strong similarity between the level schemes of Ba^{136}, Ce^{138}, and Xe^{134} has been previously pointed out by Fujioka *et al.*[8] The most striking feature of this analogy is the occurrence of the group of high-spin states at $\sim$2-MeV excitation in all three nuclei. The ratio E_{4+}/E_{2+} is very similar for these nuclei. It seems very likely that we can expect to observe the remaining members of the "two-phonon triplet" in Xe^{134} and Ce^{138}.

The level scheme presented in Fig. 6 is obviously incomplete. For most of the levels populated in the (n, γ) reaction the total outgoing intensity exceeds the total incoming intensity, indicating the presence of many levels and weak transitions as yet unobserved. In addition, our knowledge of the spins, parities, and lifetimes of the known levels is very limited. It will be of particular interest to determine the nature of the group of states between 3 and 4 MeV which appear to prefer to decay to the levels at $\sim$3 MeV rather than to the lower excited states.

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