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$Ba^{137}(n,\gamma)$ Reaction and Level Structure of Ba^{138}†

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The γ rays from the $Ba^{137}(n,\gamma)Ba^{138}$ reaction have been studied both in singles and coincidence with a 9-cm^3 Ge(Li) detector and a Ge(Li)-NaI combination. Of a total of 91 γ rays, 15 have been identified as primary transitions de-exciting the compound nucleus. These data, together with the information obtained from coincidence spectra and from previous studies, establish 18 levels in Ba^{138} with energies 1435.7±0.2, 1893.7 ±0.5, 2189.6±0.5, 2217.6±1.0, 2307.7±0.7, 2445.6±0.5, 2582.7±0.4, 2638.8±0.5, 2880.7±0.3, 3051.4 ±2.0, 3340.0±1.5, 3503.0±2.0, 3643.4±1.5, 3921.7±1.5, 4241.9±2.0, 4280.4±2.0, 4287.5±2.0, and 4360.2±2.0 keV. In addition, six pairs of γ rays whose energies sum to equal the binding energy were found, but the order of the cascades could not be established. The neutron separation energy was found to be 8611.3±0.8 keV. The prominent 5730.4-keV primary γ ray feeds the level at 2880.7 keV, which is identified with the 3^- state seen in inelastic scattering experiments with charged particles. The level decays predominantly by the 1445.0–1435.7-keV γ-ray cascade through the 2^+ first excited state. The relation between states excited in (p,p') and (d,p) reactions and those observed in the present experiment is discussed.

I. INTRODUCTION

UNTIL now, information on the energy levels of the Ba^{138} nucleus has been obtained from studies of the β decay of Cs^{138} (32.1 min) and investigations of the inelastic scattering of charged particles on Ba^{138}.

In 1953, Langer, Duffield, and Stanley[1] measured both β-γ and γ-γ coincidences from the Cs^{138} decay. They observed γ rays of energies 0.46, 0.98, and 1.44 MeV with relative intensities 0.33, 0.43, and 1.00, respectively, and established that the 1.44-MeV transition proceeded from the first excited state to the ground state. The existence of these γ rays was later confirmed by Thulin,[2] who also found transitions at 0.128, 0.548, 2.24, and 2.68 MeV. A level scheme, which has remained essentially unchanged since then, was proposed in 1956 by Bunker, Duffield, Mize, and Starner[3] (BDMS). Both γ-ray singles and coincidence spectra were studied with NaI scintillators, and conversion electrons were observed with a 180° permanent-magnet spectrograph. In addition, the angular correlation of the 1.010–1.426-MeV γ rays (0.98–1.44 MeV, as reported by Langer *et al.*[1]) was measured. The level scheme which summarizes the results obtained by BDMS is shown in Fig. 1. The half-lives of the first and second excited states, which are included in Fig. 1, were measured by Alkhazov *et al.*[4] (Coulomb excitation) and by Currie[5] (Cs^{138} decay), respectively.

Experiments involving inelastic scattering processes were first carried out with the purpose of investigating octupole vibrations in nuclei. The (d,d') scattering experiments of Cohen and Price,[6] and later the (α,α') measurements of Hansen and Nathan,[7] yielded evidence for the existence of a 2.83-MeV state in Ba^{138}, possibly a 3^- state. Recently, Alster, Martens, and Alpert[8] repeated the (α,α') inelastic scattering experiment and reported the 3^- state at 2.89 MeV.

In recent years, the study of analog states has been a subject of extensive interest. Morrison, Williams Nolen, and von Ehrenstein[9] have investigated neutron-

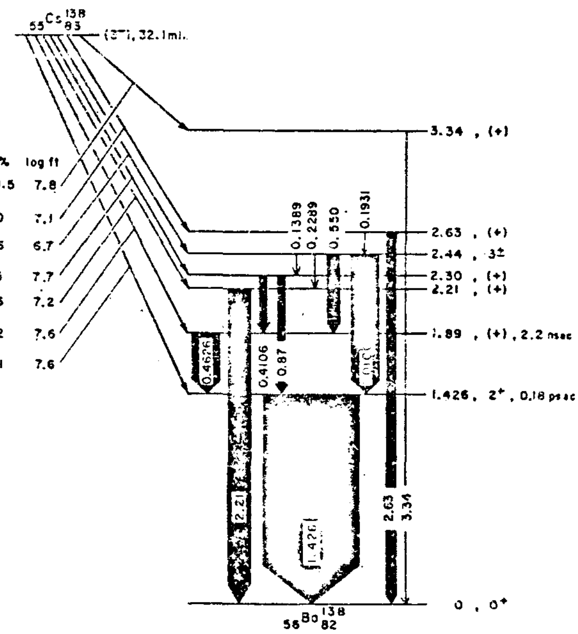

FIG. 1. Level scheme of Ba^{138} as established by Bunker *et al.* (Ref. 3). The half-lives of the first and second excited states were measured by Alkhazov *et al.* (Ref. 4) and Currie (Ref. 5), respectively.

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[9] G. C. Morrison, N. Williams, J. A. Nolen, Jr., and D. von Ehrenstein, Phys. Rev. Letters 19, 592 (1967).

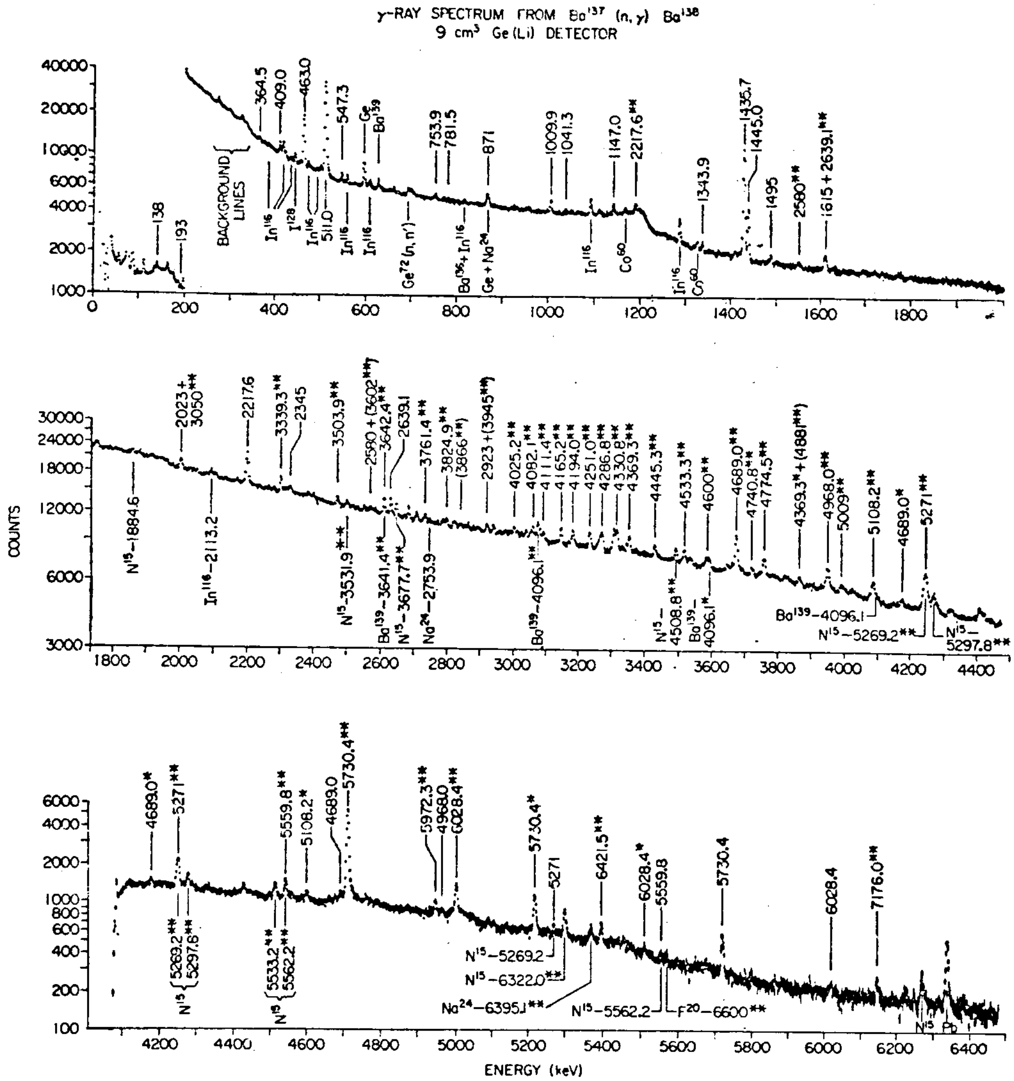

FIG. 2. γ-ray spectrum from $Ba^{137}(n,\gamma)Ba^{138}$ from 0 to 6.4 MeV. Most of the lines assigned to Ba^{138} are labeled above the peaks. Background lines are indicated below the peaks (with the exception of the 596- γ ray of Ge and the 627.26-keV γ ray of Ba^{139}). Single and double asterisks indicate one- and two-escape peaks, respectively. The energies shown in parentheses represent γ rays which are doubtful.

particle-hole states in Ba^{138} by means of reactions involving isobaric analog resonances. From this work the configurations of several states between 3.5 and 4.2 MeV were deduced.

The present work consists of an investigation of the thermal-neutron-capture reaction on Ba^{137} leading to levels in Ba^{138}. Since the ground state of Ba^{137} has spin and parity $\frac{3}{2}^+$, low-lying low-spin states (spins 0 to 3), which may not have been seen in radioactive decay owing to spin and parity selection rules, might be expected to be observed following neutron capture. Further, more accurate information on the energy levels above 3.5 MeV is a valuable complement to the study of analog states.

In Sec. II, the experimental procedure is described and the results are presented. In Sec. III, we discuss the construction of the level scheme, and our conclusions are summarized in Sec. IV.

II. EXPERIMENTAL PROCEDURE AND RESULTS

A. Equipment and Experimental Arrangement

The target was 6 g of $Ba(NO_3)_2$, enriched to 82% in Ba^{137} and containing 0.6% Ba^{135} and 17.4% Ba^{138}.[10] For thermal neutrons the contributions of these isotopes to the capture cross section are 97.6, <0.9, and 2.2%, respectively. The target, enclosed in a Teflon capsule, was exposed to an external beam from the Brookhaven graphite research reactor with an intensity of $\sim 8\times 10^6$ neutrons/cm² sec. The neutron beam was collimated to a diameter between 5 and 10 mm in the different runs. The assignment of the numerous weak lines observed was confirmed by comparison with the γ-ray spectra of

[10] The targets have been obtained from the Stable Isotopes Division, Oak Ridge, Tenn.

a sample[10] of $BaCO_3$ (containing natural Ba) and two samples of $Ba(NO_3)_2$, enriched to 93% in Ba^{135} and 99.8% in Ba^{138}, respectively.[11] In addition, background spectra were obtained with a piece of graphite in the target position so as to enhance the scattering of neutrons.

Singles γ-ray spectra were obtained with a 9-cm^3 Ge(Li) detector.[12] The pulses from the detector and a precision pulser[13] were directed into an ORTEC preamplifier-biased amplifier system and accumulated in 4096 channels of a two-dimensional, 16 384-channel TMC analyzer.

The coincidence runs were carried out with a 3×3-in. NaI scintillator and the Ge(Li) diode in a 180° geometry. The coincident pulses were accumulated in the 16 384 channels of the TMC analyzer.

The data were recorded on magnetic tape with a Datamec D 2020 unit and analyzed in a CDC 6600 computer by means of PALMUD,[14] a program that fits Gaussian functions to the peaks after having identified them automatically.[15] This program was also used for the analysis of the two-dimensional spectra. In addition, a useful qualitative picture of the coincidence runs was obtained with a program[16] that produces three-dimensional plots of the data.

B. Energy and Intensity Measurements

Singles γ-ray spectra were taken from 0 to 8 MeV in separate runs, usually with a dispersion of ~1 keV per channel. Figure 2 shows the low-, medium-, and high-energy γ-ray spectra 0–2, 2–4, and 4–6.3 MeV. A precision pulser was employed to correct for the nonlinearity of the electronic system. The results of the energy measurements are presented in column 1 of Table I. The data shown in Fig. 2 have been chosen to give an over-all picture of the Ba^{138} low-energy γ-ray spectrum, although the many weak lines, above 800 keV, presented in Table I, were only observed in runs of much longer duration in which the low-energy end of the spectrum exceeded the analyzer memory capacity.

Because of the relatively low thermal-neutron-capture cross section of Ba^{137}, many background lines were observed. Careful comparisons with the spectra obtained with a graphite scatterer in the target position and with samples of enriched Ba^{135} and Ba^{138} have allowed us to distinguish between the lines from the $Ba^{137}(n,\gamma)$ reaction and those in the background. In the energy region between 1.5 and 3 MeV, where escape peaks are difficult to distinguish from full-energy peaks, the possibility still remains that some of the weakest lines (e.g., those de-exciting the high-energy levels) have been incorrectly assigned to Ba^{138}.

As an energy calibration in the low-energy region, the 1173.23±0.04- and 1332.48±0.05-keV γ rays[17] of Co^{60} were superimposed on the Ba^{138} γ-ray spectrum. At intervals during the measurement the same spectrum was routed into a separate section of the analyzer memory together with a set of pulser peaks to correct for short-term drifts and nonlinearities. Since the Co^{60} lines lie close to the 1435.7–1445.0-keV doublet, precise energy values were obtained for these two γ rays of Ba^{138}, the first of which defines the energy of the first excited state. As shown in Table I, this value has been determined to within 0.2 keV and is approximately 10 keV higher than the previously reported value.[3]

In the high-energy region the following procedure, which makes the use of several energy standards unnecessary, was applied. As in the low-energy region, the neutron-capture γ-ray spectrum was recorded together with a set of pulser peaks flanking the γ-ray peaks. The separations between the strong 5.74-MeV γ ray[18] and the other high-energy lines (including the prominent 6322.0-keV γ ray[19] following neutron capture in the N^{14} present in the target) were then determined in units of the pulser. This step assumes linearity within the short intervals defined by pairs of pulser peaks flanking each γ ray. The pulser units were converted into energy units by using the well-known energy difference between two-escape, one-escape, and full-energy peaks. In our case, the three peaks corresponding to the 5.74-MeV γ ray were strong enough (Fig. 2) to provide a precise measure of this scale factor. Moreover, these three peaks also allowed us to obtain three semi-independent determinations for each γ ray involved in this measurement. The final results are shown in Table II. Column 1 enumerates the γ rays observed and column 2 gives the separation in energy between the 5.74-MeV γ ray and the other γ rays. The γ-ray energies, given in column 3 (and also in Table I), are derived from the values in column 2 and the energy value of 6322.0±0.4 keV reported[19] for the N^{15} γ ray, which was adopted here. Finally, the accurate determination of the 1435.7–1445.0-keV γ-ray cascade defines a precise value for the energy of the level fed by the 5730.4-keV transition. This value, in turn, is combined with the results in column 2 to establish the other level energies shown in column 4.

The high density of lines between 2 and 4 MeV (Fig. 2) makes the measurement of energies in this

[11] The results from the $Ba^{135}(n,\gamma)$ and $Ba^{138}(n,\gamma)$ reactions will be published elsewhere.

[12] This detector was fabricated by H. Kraner of the Brookhaven National Laboratory Instrumentation Department.

[13] The pulser has been designed by A. Z. Schwarzschild; its main component is a Kelvin Varley Voltage Divider: Dekapot (Electro Scientific Industries, Inc., Model CA 1463).

[14] M. A. J. Mariscotti, Brookhaven National Laboratory Report No. BNL-10904 (unpublished).

[15] M. A. J. Mariscotti, Nucl. Instr. Methods 50, 309 (1967).

[16] The computer program to produce these tridimensional plots was written by P. Thieberger.

[17] G. Murray, R. L. Graham, and J. S. Geiger, Nucl. Phys. 63, 353 (1965).

[18] This line was observed in the natural Ba spectrum by B. B. Kinsey and G. A. Bartholomew, Can. J. Phys. 31, 1051 (1953).

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TABLE I. Energies, relative intensities, and assignments of γ rays observed in the $Ba^{137}(n,\gamma)Ba^{138}$ reaction. Those cases where pairs of γ rays have energies which sum to equal the binding energy but the order of the cascade remains uncertain are indicated with a capital letter in parentheses on the right of the energy value. *W* indicates very weak transitions ($I_\gamma \lesssim 0.1$).

E_γ (keV)	I_γ (relative)	Level (keV) from – to	$\Delta L - E_\gamma$[a] (keV)
138.9[b]		2445.6–2307.7	−1
193 ±2	0.7	2638.8–2445.6[c]	0.2±2
228.9[b]		2445.6–2217.6	−0.9
364.5±1	1.2	2582.7–2217.6	0.6±1.4
		4287.5–3921.7	1.3±3
393 ±2[d]	*W*	2582.7–2189.6	0.1±2
409.0±0.5	3	2307.7–1898.7	···
463.0±0.5	18	1898.7–1435.7	···
547.3±0.5	2	2445.6–1898.7	−0.4±1
753.9±0.6	1.5	2189.6–1435.7	0 ±0.8
765 ±2	0.3	3643.4–2880.7	−2.3±3
773 ±2	0.5		
781.5±1.5	1	2217.6–1435.7	0.4±1.6
834 ±1.5	0.5	3051.4–2217.6	−0.2±2
871 ±1.5	4.8	2307.7–1435.7	1 ±1.6
920 ±2[d]	*W*	3503.0–2582.7	0.3±3
1009.9±0.3	4	2445.6–1435.7	···
1041.3±0.3	1.1	3921.7–2880.7	−1 ±1.6
1060 ±2	0.6	3503.0–2445.6	−2.6±3
		3643.4–2582.7	0.7±3
1147.0±0.3	3.5	2582.7–1435.7	0 ±0.6
1343.9±0.4	2		
1413 ±2	2		
1435.7±0.2	100	1435.7–0	···
1445.0±0.2	25	2880.7–1435.7	···
1478 ±2	0.8	3921.7–2445.6	−2 ±3
1495 ±1.5	2.5		
1615 ±2	4	3051.4–1435.7	0.7±3
		3921.7–2307.7	−1 ±3
1698 ±3	*W*	4280.4–2582.7	0.3±4
1705 ±3	*W*	3921.7–2217.6	−1 ±3
		4287.5–2582.7	−0.2±3
1745 ±3	*W*	3643.4–1898.7	−0.3±3
1780 ±3	1.5	4360.2–2582.7	−2.5±3
2023 ±2	1.5	3921.7–1898.7	0 ±3
		4241.9–2217.6	1.3±3
2050 ±3	0.5	4241.9–2189.6	2.3±3
		4360.2–2307.7	2.5±3
2060 ±3	0.5	4280.4–2217.6	2.8±3
2070 ±3	0.6	3503.0–1435.7	−2.7±3
		4287.5–2217.6	−0.1±3
2095 ±3[d]	*W*	4287.5–2189.6	3 ±3
2140 ±3[d]	*W*	4360.2–2217.6	2.6±3
2152 ±3	*W*		
2188 ±2	0.7	2189.6–0	1.6±2
2208 ±3[d]	0.5	3643.4–1435.7	−0.3±3
2217.6±0.5	2	2217.6–0	···
2345 ±2	0.6	4241.9–1898.7	−1.8±3
2580 ±3	0.45	2582.7–0	2.7±3
2639.1±1	2.2	2638.8–0	−0.2±1
2845 ±3	0.5	4280.4–1435.7	−0.3±3
2923 ±3	0.5	4360.2–1435.7	1.5±3
3050 ±3	0.9	3051.4–0	1.4±3
3339.3±1	1.3	3340.0–0	0.7±1.7
3503.9±1.5	0.9	3503.0–0	−0.9±2.5
3602 ±3[d] (*A*)	0.2		
3642.4±1.5	1	3643.4–0	1 ±2.5
3713.8±1.5	0.9		
3737.4±1.5	0.5		
3761.4±1.5	0.5		
3813.7±1.5	0.2		
3824.9±1.5	0.3		
3866 ±3[d] (*B*)	*W*		
3920 ±3[d]	*W*	3921.7–0	1.7±3
3945 ±3[d]	0.3		
3963.8±1.5	0.5		
4025.2±1.5	0.4		
4060.2±1.5 (*C*)	0.3		
4082.1±2 (*D*)	0.8		
4111.4±1.5 (*E*)	0.2		
4165.2±1.5 (*F*)	1		
4194.0±1.5	1.2		
4251.0±1.5	1.2	8611.3–4360.2	···
4278.8±2	0.7	4280.4–0	1.2±3
4286.8±2	1.6	4287.5–0	0.7±3
4323.7±1.5	1.8	8611.3–4287.5	···
4330.8±1.5	1.8	8611.3–4280.4	···
4369.3±1.5	0.8	8611.3–4241.9	···
4445.3±1.5 (*F*)	0.8		
4500 ±3[d] (*E*)	*W*		
4533.3±2 (*D*)	0.7		
4551.1±1.5 (*C*)	0.2		
4600 ±2	0.8		
4689.0±1.0	2.2	8611.3–3921.7	···
4740.8±1.5 (*B*)	0.4		
4774.5±1.5	1.2		
4881 ±2[d]	0.2		
4968.0±1	1.3	8611.3–3643.4	···
5009 ±2 (*A*)	0.4		
5108.2±2	1.3	8611.3–3503.0	···
5271 ±1.5	1.6	8611.3–3340.0	0.4±2
5559.8±2	0.3	8611.3–3051.4	···
5730.4±0.5	12	8611.3–2880.7	···[e]
5972.3±0.7	1	8611.3–2638.8	···
6028.4±0.6	2.3	8611.3–2582.7	···[e]
6421.5±1.7	0.5	8611.3–2189.6	···[e]
7176.0±1.8	0.1	8611.3–1435.7	−0.6±1
8614 ±5[d]	*W*	8611.3–0	−4 ±5

[a] ΔL denotes the difference in energy of the levels between which the transition takes place minus the recoil energy. A dashed line in this column indicates that the γ-ray energy has been used to determine the level energy.
[b] Energy value from Ref. 3, indicated in parentheses in the level scheme.
[c] See Sec. III H.
[d] γ ray doubtful; indicated by dashed line in the level scheme.
[e] Energies of these transitions were used to determine the binding energy.

region difficult. Since the majority of the lines appear as members of unresolved multiplets, the determination of their positions and areas was carried out graphically. Furthermore, the pulser was not employed in this section of the spectrum. Instead, we adopted the following lines as energy references to calculate the energy of the remaining lines, and we assumed linearity in the intermediate regions: 2217.6±0.5 keV (Ba^{138} line; the two-escape-peak energy was obtained from the low-energy spectrum); 2509.9±0.25, 2655.7±0.25, 3486.8 ±0.30, and 4275.8±0.35 keV (two-escape peaks of N^{15} lines, Ref. 19); 2753.9±0.12 keV (Na^{24} full-energy peak, Ref. 17); 3074.1±0.7 keV [two-escape peak of the strong line from the $Ba^{138}(n,\gamma)Ba^{139}$ reaction, Ref. 11]; and 3667.0 and 3946.0 keV (two-escape peaks of lines seen in the high-energy spectrum of Ba^{138}).

Column 3 of Table I shows the initial and final levels between which the γ-ray transition occurs. Column 4 of Table I gives the difference between the γ-ray energy and the expected transition energy (i.e., the energy deduced from the difference in the level energies) to show the degree of agreement obtained. A dashed line in

TABLE II. Results from the high-energy spectrum.

i	$\Delta_\gamma(i)$[a] (keV)	$E_\gamma(i)$[b] (keV)	Level energy[c] (keV)
1	-460.3 ± 0.7	5270.1 ± 0.9	...[d]
2	0	5730.4 ± 0.5	2880.7 ± 0.3[c]
3	241.9 ± 0.4	5972.3 ± 0.7	2638.8 ± 0.5
4	298.1 ± 0.2	6028.4 ± 0.6	2582.6 ± 0.4
5 (N^{15})	591.6 ± 0.3	6322.0 ± 0.4[e]	(N^{15})
6	691.1 ± 0.4	6421.5 ± 0.7	2189.6 ± 0.5
7	1445.6 ± 0.6	7176.0 ± 0.8	...[f]

[a] Separation in energy between the ith and $i=2$ γ rays. The results shown in this column represent the weighted average of the values obtained when the two-escape, one-escape, and full-energy peaks of the $i=2$ γ ray were taken as references (see text).
[b] Values derived from the energy of the N^{15} line ($i=5$) (Ref. 19).
[c] The accurate determination of the 1435.7–1445.0-keV γ-ray cascade (Table I) defines a precise value for the energy of the level fed by the 5730.4-keV transition. This value in combination with the $\Delta_\gamma(i)$ from column 2 was used to obtain the other level energies.
[d] See Sec. III J for the determination of this level energy.
[e] Reference 19.
[f] Level energy fixed by the energy of the 1435.7-keV γ ray.

this column implies that the γ-ray energy has been used to establish the level energy.

The γ-ray cascades 5730.4–1445.0–1435.7, 6028.4–1147.0–1435.7, and 6421.5–753.9–1435.7 keV were used to find the weighted average value 8611.3 ± 0.8 keV for the neutron separation energy (recoil-energy correction for each case is $\sim$0.2 keV).

The relative intensities of the γ rays are given in column 2 of Table I. These were obtained with the use of an efficiency curve which was determined for our Ge(Li) detector according to a method described elsewhere.[20]

C. γ-γ Coincidences

Measurements of γ-γ coincidences were made in three separate runs with the 9-cm^3 Ge(Li) detector and a 3×3-in. NaI scintillator. Pulses from both counters were stored in the TMC analyzer in a 256×64-channel format. γ rays of energies 0–2, 1–3, and 4.2–6.2 MeV, which were detected in the Ge diode, were studied in coincidence with γ rays of 0–1.6 MeV detected by the NaI scintillator.

For the analysis of the spectrum in coincidence with each γ ray we used the program PALMUD[14] 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 3 shows the spectra corresponding to coincidences with the 463.0-, 1435.7-, 5730.4-, and 6028.4-keV γ rays. In the present experiment, only the strongest cascades in the de-excitation of the compound nucleus appear clearly in the coincidence data. In the low-energy–low-energy runs the great number of transitions makes the interpretation of the coincidence results difficult. Conversely, in the high-energy run, where there are fewer transitions, it is difficult to accumulate sufficient counts to establish weak lines because of the relatively low efficiency of the Ge(Li) detector at these energies and the low thermal-neutron-capture cross section of Ba^{137}. The results obtained from the coincidence experiments are summarized in Table III.

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

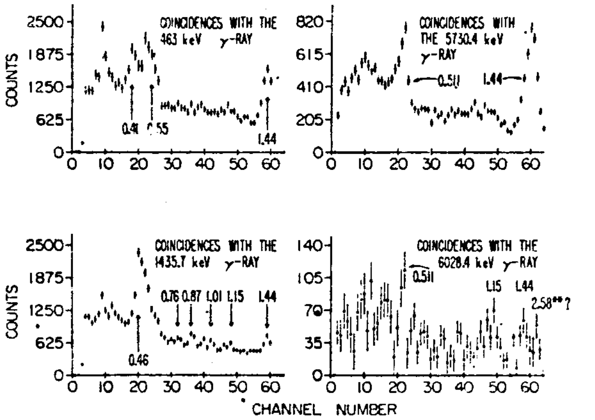

FIG. 3. Net coincidence spectra from the 3×3-in. NaI detector gated with the 463.0-, 1435.7-, 5730.4-, and 6028.4-keV γ rays, which were detected in the Ge(Li) diode. Each spectrum was obtained as a computer output from the program PALMUD (Ref. 14), which summed the spectrum slices associated with the gating γ ray and subtracted an equal number of background slices.

III. CONSTRUCTION OF LEVEL SCHEME

The data in Tables I and III together with the information available from previous investigations were used to construct the level scheme shown in Fig. 4. Because it was possible to obtain only limited information from the coincidence studies, most of the level scheme rests on the use of the energy-combination principle and on the assignment of certain γ rays as primary transitions. The latter assignments are supported in each case by the existence of more than one transition depopulating the level fed by the primary γ ray, except in the cases of the 2638.8- and 3340.0-keV levels, the existence of which is additionally supported by the results of BDMS, and the 2880.7-keV level, where the strengths of the two transitions involved and the energy fit leave little doubt about this state. Six two-step γ-ray cascades, whose energies sum to equal the

TABLE III. Results of γ-γ coincidence measurements.

γ ray (keV)	Coincident peaks (MeV)
409.0	0.46
463.0	0.41, 0.55, 1.44
547.3	0.46
871	1.44
1009.9	(1.06), 1.44
1147.0	1.44
1435.7	0.46, (0.76), 0.87, (1.01), (1.15), 1.44
1445.0	1.44
1615	0.41, 0.46, 0.87, 1.44
2025 or 3050**	(0.46), (1.44)
5730.4	1.44
6028.4	0.36–0.39, 1.15, 1.44
6421.5	0.75

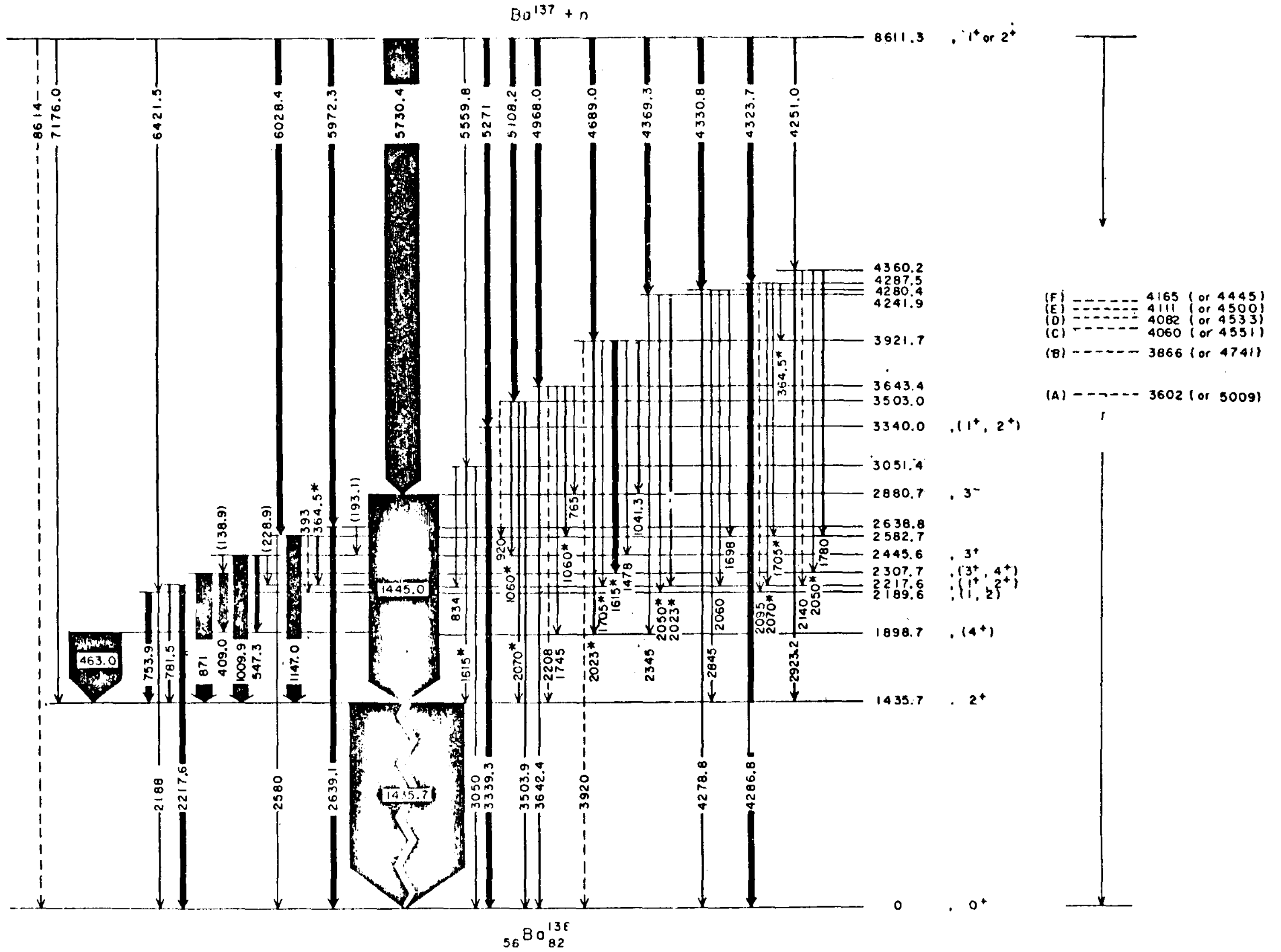

FIG. 4. Level scheme of Ba^{138} obtained from the $Ba^{137}(n,\gamma)$ reaction. Tentative assignments are indicated by dashed lines. γ-rays placed more than once are shown with an asterisk. The 138.9-, 228.9-, and 193.1-keV γ rays are shown in parentheses to indicate that their assignment was mainly based on the results of Bunker *et al.* (Ref. 3). The levels shown as dashed lines on the right-hand side are implied by the observation of two-step γ-ray cascades, whose energies equal the binding energy *but the order of which could not be established.* The capital letters are included to identify these γ rays in Table I.

neutron binding energy, were found, but the order in which these γ-rays proceed could not be established. Accordingly, they were not included in the level scheme, although reference to them is made on the right of Fig. 4. The capital letters in parentheses are used to identify these γ rays in Table I. Comments on the properties of the individual levels follow.

A. Level at 1435.7±0.2 keV

This state, the first excited state, was originally established by Langer *et al.*[1] As a result of the present work, a much more precise value has been obtained for the energy of this state. It is approximately 10 keV higher than the value reported earlier.[3] Spin and parity 2^+ have been assigned to this level on the basis of the systematics of even-even nuclei.[21] This level is fed from the capture state by the 7176.0-keV transition.

B. Level at 1898.7±0.5 keV

BDMS established the existence of this level in their study of the Cs^{138} decay. The strong 463.0-keV transition proceeds from this level to the first excited state. Since a transition to the ground state has not been seen, the level spin is probably either 0 or ≥3. A 4^+ assignment would be supported by the following: (a) The *ft* value of the β decay to this level indicates even parity,[3] and considering the close analogy with the La^{140} decay, it favors spin 4 rather than 0. On the basis of the similarity between the Ba^{138} and Ce^{140} level schemes, a 4^+ assignment was also suggested by Currie,[5] after he determined the half-life of this state to be comparable with that of the first 4^+ state in Ce^{140} at 2083 keV. (b) No primary transition from the capture state has been observed to populate this state in the present investigation. (c) A theoretical calculation based on the quasiboson treatment of the pairing force[22] predicts the 4^+ state in Ba^{138} at a slightly lower energy than in Ce^{140} (the opposite trend is expected for the 0^+ states according to this calculation).

C. New Level at 2189.6±0.5 keV

The 6421.5-keV primary transition populates this state. Two transitions, with energies of 753.9 and 2188 keV, are placed as de-exciting this state on the basis of their energies. The 753.9-keV γ ray was also observed to be in coincidence with both the primary 6421.5- and the 1435.7-keV γ rays. Because of the existence of both the primary and ground-state transitions, the spin of this level is probably 1 or 2.

D. Level at 2217.6±1 keV

We have identified the strong 2217.6-keV γ ray of our spectrum with the ground-state transition de-exciting the 2.21-MeV level proposed by BDMS. The weak 781.5-keV transition to the first excited state has been assigned on the basis of its energy.

The presence in the background of the 6395.1-keV line of Na^{24} precludes the identification of a possible 6394-keV primary transition to this state. Comparisons with the intensities of other background lines and an examination of the coincidence results indicate that the primary transition in Ba^{138}, if present, is very weak.

The existence of the 2217.6-keV transition to the ground state implies spin 1 or 2 for this level. The even parity is deduced from the *ft* values obtained by BDMS.

E. Level at 2307.7±0.7 keV

Our data confirm the results of BDMS regarding this level. Two transitions with energies 409.0±0.5 and 871±1.5 keV were identified as originating in this level. This was confirmed by the observation of the 871–1435.7- and 409.0–463.0-keV γ-γ coincidences. The presence of background γ rays from Ge, Na, and F near 870 keV hindered the determination of the energy and intensity of the 871-keV transition. Accordingly, the level energy was obtained solely from the energy sum 409.0+1898.7 keV.

From the de-excitation pattern of this level and the *ft* value of the β decay leading to it (which favors even parity), the most probable assignment would be 3^+ or 4^+. Spin $I=0$ would not be in agreement with the *ft* value and $I^\pi=1^\pm$, and 2^+ is improbable because of the absence of the ground-state transition. In addition, if the 1898.7-keV state is 4^+, the existence of the 409.0-keV transition supports $I\geq 2$. On the other hand, $I\geq 5$ is not in accord with the presence of the transition to the first 2^+ state.

F. Level at 2445.6±0.5 keV

This level has been found by BDMS. We have not observed a primary transition to this state. Our coincidence data support the placing of both the 1009.9- and 547.3-keV transitions. The 228.9-keV γ ray appears weakly in singles and is not seen in coincidence with the full-energy peak of the 2217.6-keV γ ray. (The two-escape peak of the latter transition lies on the Compton edge of the 1435.7-keV line and a strong coincidence is observed between pulses of this energy and a line at ~230 keV which is identified with the backscattered radiation.) Both the 228.9- and 138.9-keV transitions have been placed in the level scheme of Fig. 4 mainly on the basis of the results of BDMS. BDMS assigned spin 3 to this state from their angular-correlation results and even parity is supported by their *ft* values. The similarities between the properties of this level and those of the 2412-keV 3^+ state[23] in Ce^{140} furnish additional evidence for the close correspondence of excitations in the two nuclei.

[21] G. Scharff-Goldhaber, Phys. Rev. 90, 587 (1953).
[22] D. Bes (private communication); D. Bes and C. J. Veje, quoted in Ref. 25.
[23] C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967).

G. New Level at 2582.7±0.4 keV

The 6028.4-keV primary transition populates this state, which decays predominantly through the 1147.0-keV transition to the first excited state. The 364.5-, 393-, and 1147.0-keV transitions are seen in coincidence with the 6028.4-keV γ ray (Fig. 3).

H. Level at 2638.8±0.5 keV

The 5972.3-keV γ ray is assumed to populate this level. The level energy is then derived from the values in Table II. The existence of the strong 2639.1-keV line led us to identify this level with the 2.63-MeV level previously reported by BDMS. A 193.1-keV transition found by BDMS was assigned by them as originating from the 2638.8-keV level. Their coincidence results, however, did not confirm this assignment, but the precise level-energy values obtained here tend to support their placing of this γ ray in the level scheme (2638.8−2445.6 =193.2). In the present work, a 193-keV γ ray is observed. Its intensity relative to that of the 2639.1-keV γ ray, on the other hand, appears to be about three times stronger than in the Cs^{138} decay.[3] Moreover, this line was not observed in coincidence with the 547.3- or 1009.9-keV γ rays. In view of these apparent contradictions, (a) doubt remains about the origin of the 193-keV transition, and (b) the possibility that the 193-keV peak in the neutron-capture spectrum may have more than one component must be considered.

I. Level at 2880.7±0.3 keV

This level, which is fed by the strongest primary transition (5730.4 keV), is probably that which has been seen in inelastic scattering experiments first by Cohen and Price[6] at 2.83 MeV and more recently by Alster *et al.*[8] at 2.89 MeV. The latter confirmed the previous tentative 3^- assignment[7] for this level. Hansen and Nathan,[7] who also performed inelastic scattering experiments, observed a single peak at 1.4 MeV in the de-excitation spectrum of this level, and, in order to be consistent with the work of Cohen and Price, postulated the existence of a 1.4–1.4-MeV cascade. This has now been confirmed (the 1445.0–1435.7-keV cascade) by the improved energy determination in the present work and the coincidence results. The strong 5.73–1.44- and 1.44–1.44-MeV γ-γ coincidences are shown in Fig. 3.

J. Level at 3340±1.5 keV

We have observed the 3.34-MeV γ ray seen by BDMS in the Cs^{138} decay which led them to assume the existence of this level. In addition, a two-escape peak corresponding to a 5270.1±0.9-keV γ ray is present in the high-energy spectrum (Fig. 2). This energy agrees well with the expected value for a primary transition to this level but, at the same time, coincides, within the errors, with the value 5269.2±0.35 keV reported for a N^{15} line.[19] Intercomparison of the spectra from $Ba^{135}(NO_3)_2$, $Ba^{137}(NO_3)_2$, and natural $BaCO_3$ targets confirmed the assignment of a primary transition of this energy to Ba^{135} and yielded its energy and intensity. The existence of a ground-state transition indicates spin 1 or 2 for the 3340-keV level. Even parity is deduced from the ft values[3] of the Cs^{138} β decay.

K. Other Levels above 3 MeV

Levels in this energy region, other than that at 3340.0 keV, have not been observed in the radioactive-decay studies, but a number of them have recently been excited in (p,p') and (d,p) reactions.[8,9]

We have observed a large number of γ rays which may populate energy levels in this region. In addition to the level at 3340.0 keV, eight other levels were established and their decay modes determined. Six other levels whose energies, however, could not be established are implied by the existence of two-step γ-ray cascades de-exciting the compound nucleus (shown on the right-hand side of Fig. 4). Further investigations, with a wider range of techniques, will be needed to unravel the decay modes of these levels.

The level at 3051.4 keV is fed by the 5560-keV γ ray. This γ ray appears in the spectrum unresolved from the 5562.2-keV line[19] of N^{15} but it has been identified as a Ba^{138} γ ray in the same manner as in the case of the 5271-keV γ ray (see Sec. III J).

The complexity of the level scheme above 3 MeV gives rise to many unresolved multiplets in the γ-ray spectrum and to ambiguities in the assignment of transitions. A typical example is the 1615-keV γ ray, whose full-energy peak coincides with the two-escape peak of the 2639.1-keV γ ray. Its existence and intensity were deduced from the area of the full-energy peak of the 2639.1-keV transition together with the known two-escape full-energy peak efficiency ratio for our detector.[20] Furthermore, a transition with this energy may be placed in the level scheme as de-exciting both the 3051.4- and 3921.7-keV states. The 3642.4-keV γ ray was unresolved from the 3643-keV line from the $Ba^{138}(n,\gamma)$ reaction[11]; its intensity was determined in comparison with the strong 4096.1-keV γ ray of Ba^{135}, clearly seen in our spectrum (Fig. 2).

IV. DISCUSSION

The results of the present investigation support the conclusions arrived at by previous authors and at the same time add considerable new information to our knowledge of the level structure of Ba^{138}. The fact that Ba^{138} is a semimagic nucleus with 82 neutrons makes model calculations of some of its level properties relatively simple. It is hoped that the data presented here will stimulate further theoretical studies.

A prominent property of the compound nucleus is its preference to de-excite into the 3^- state at 2880.7 keV believed to be an octupole vibration[7]), which in turn strongly decays into the first 2^+ state.

This behavior is typical of nuclei lying near closed neutron shells, for which strong primary transitions to 3^- states are usually observed. The 5730.4-keV transition to the 3^- state, which is the strongest primary transition in Ba^{138}, provides the most striking evidence for this trend.

In Sec. III, the similarity between the level schemes of Ba^{138} and Ce^{140} has been mentioned. One observes, for example, that both nuclei display a large gap ($\sim$0.15 MeV smaller in Ba^{138} than in Ce^{140}) between the ground and first excited states, which is typical of magic and semimagic structures. The 1.9-MeV state in Ba^{138} believed to be 4^+ (see Sec. III B) also appears at about 0.15 MeV lower than the 4^+ state in Ce^{140}. In both nuclei, 3^+ states are observed at about 2.4 MeV. These and other similarities suggest the existence of a 0^+ state in Ba^{138}, since such a state has been found in Ce^{140} at 1.9 MeV.

Christensen and Yang[24] have carried out a search for 0^+ states in $N=82$ nuclei via the inelastic scattering of protons and deuterons on targets of Ba^{138}, Ce^{140}, Nd^{142}, and Sm^{144}, measuring $E0$ transitions with a six-gap β-ray spectrometer. They succeeded in exciting 0^+ states in all these nuclei save for Ba^{138}, and reached the conclusion that if a 0^+ state exists in this nucleus, the cross section of this reaction must be very small. A calculation of 0^+ states in these nuclei, already mentioned in Sec. III B, carried out by Bés and Veje,[22] agrees fairly well with the experimental results in Ce^{140}, Nd^{142}, and Sm^{144} and predicts a 0^+ state in Ba^{138} at $\sim$1.9 MeV. Another theoretical calculation, based on the exact treatment of the pairing force, is now in progress.[25] Since this state plays a particularly important role in testing any theoretical description, we have searched for evidence for its excitation in the (n,γ) reaction. No conclusive evidence was found.

It is of considerable interest to consider the upper levels found in the present investigation in relation to the results recently reported by Morrison *et al.*[9] These authors have studied (p,p') and (d,p) reactions leading to the excitation of neutron-particle-hole states in Ba^{138}. The configurations of these states involve the $2f_{7/2}$, $3p_{3/2}$, and $3p_{1/2}$ shells for the particle excitations and the $2d_{3/2}$ and $3s_{1/2}$ shells for the hole excitations. The former are identified by the resonances in $Ba^{138}+p$ scattering, whereas a predominant $(d_{3/2})^{-1}$ component is expected in states populated in the (d,p) reaction, since this is the target-ground-state configuration. As a result of combining the information obtained in both reactions, the configuration of several states in Ba^{138} was inferred. The energy (in MeV) of these states and the spin and parity assigned to them are the following: 3.56, 3^-; 3.64, 4^-; 3.86, 5^-; 3.92, 3^-; 4.08, 2^-; and 4.16, 4^-. Results of the present experiment pertaining to these levels are as follows:

(a) No level in the vicinity of 3.56 MeV is populated following thermal neutron capture.

(b) A level at 3643.4 keV is populated by a strong primary transition. Five transitions to levels with spins and parities ranging from 0^+ to 4^+ may be fitted as deexciting this level. The strongest of these is to the ground state. The most probable assignment would appear to be 2^+.

These results, taken at face value, stand in contradiction to the 4^- assignment for this level deduced from the (p,p') and (d,p) reaction studies.[9] Three possible explanations for this discrepancy suggest themselves. First, since the five transitions presumed to de-excite the 3643.4-keV level are placed on energy considerations alone, the possibility exists that some of them originate elsewhere in the level scheme. Second, the 3643.4-keV level may not be identical with the 3.64-MeV level excited in the charged-particle reactions. Third, if the present results are correct and if the levels observed in the neutron capture and charged-particle reactions are the same, then this level would appear to have a character different from that previously suggested.[9]

(c) The 3866-keV state is implied by a two-step γ-ray cascade. Such a two-step cascade, however, would not be expected to proceed through a 5^- intermediate state. The levels observed in the two reactions are therefore assumed to be different.

(d) A 3921.7-keV level is populated by a strong primary transition and is de-excited, in turn, principally by transitions to the 4^+ state at 1898.7 keV, the 2307.7-keV state with probable spin and parity 3^+ or 4^+, and the 3^- octupole vibrational state at 2880.7 keV. These results are all in agreement with the 3^- spin and parity assignment of Morrison *et al.*[9]

(e) As in the case of the 3866-keV level, the existence of the 4082- and 4165-keV levels is implied only by two-step γ-ray cascades. In the case of the 4082-keV level, the existence of a two-step cascade through an intermediate 2^- state appears improbable but cannot be ruled out. This state, therefore, may be identical with that observed by Morrison *et al.*[9] In the case of the 4165-keV level, a two-step cascade clearly would not proceed through a 4^- intermediate state. The 4165-keV state, therefore, cannot be identical with that excited in the (p,p') and (d,p) reactions.[9]

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[24] P. R. Christensen and F. Yang, Nucl. Phys. 72, 657 (1965).
[25] A. Zuker (private communication).