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$M1$ and $E2$ strength functions of barium from thermal neutron capture

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Thermal-neutron-capture gamma rays from natural barium have been studied at the tangential facility of a reactor using a pair spectrometer. Precise transition, level, and neutron separation energies of six isotopes of barium are inferred. The separation energies are $S_n(^{133}\text{Ba})=7189.96\pm0.36$, $S_n(^{135}\text{Ba})=6972.21\pm0.18$, $S_n(^{136}\text{Ba})=9107.84\pm0.04$, $S_n(^{137}\text{Ba})=6905.78\pm0.03$, $S_n(^{138}\text{Ba})=8611.75\pm0.04$, and $S_n(^{139}\text{Ba})=4723.44\pm0.04$ keV. The $M1$ strength functions of ^{136}Ba and ^{138}Ba are found to be $(27\pm7)\times10^{-9}$ and $(5.7\pm2.1)\times10^{-9}$ MeV^{-3}, the former being much higher and the latter much lower than the global average of 18×10^{-9} MeV^{-3}. The average $\overline{B(E2)}\downarrow$ of ^{136,138}Ba observed is 53 ± 35 e^2fm^{4}MeV^{-1}, which is 0.6 ± 0.4 times the value predicted by the Axel-Brink hypothesis.

I. INTRODUCTION

An investigation of the electric quadrupole strength of photons produced in neutron capture throughout the entire mass region has been underway here for some time.[1-4] Because of the small partial width of such transitions, acquisition of spectra with high statistical precision and good sensitivity is necessary if meaningful measurements are to be made. In addition, accurate energy estimation is important in complex cases where interference or placement ambiguity is possible. Possession of high quality spectral data, such as that required for quadrupole strength studies, permits extraction of additional and important structure information.

A favorable case for the study of quadrupole strength is found in the reactions $^{135}\text{Ba}(n,\gamma)^{136}\text{Ba}$ and $^{137}\text{Ba}(n,\gamma)^{138}\text{Ba}$ where a total of five $E2$ transitions are possible. These isotopes fall near the 82 neutron shell and, since there is evidence[5] for an enhancement of the $M1$ strength in such regions, an estimation of this quantity could also prove useful.

The separation and level energies for the six isotopes of barium populated via the (n,γ) reaction range from well known to meager. Isotopes which fall into this latter class[6] are ^{133}Ba, ^{135}Ba, and ^{137}Ba. The potential information that could be obtained from a study of the photon spectrum arising from thermal neutron capture by natural barium prompted us to undertake the present study.

II. EXPERIMENTAL PROCEDURE

The experiment was conducted at the tangential irradiation facility[7] of the McMaster University Nuclear Reactor. The thermal neutron flux at the sample site was 5×10^{12} cm^{-2}sec^{-1} when the reactor operated at its nominal power of 2 MW thermal. The capture gamma rays, following passage through a 1 cm^2 collimator, were detected by a pair spectrometer consisting of a high purity Ge detector (Princeton Gamma-Tech) surrounded by a quadrisected NaI(Tl) annulus. The electronic arrangement[8] permitted the acceptance of only those pair events for which two 511 keV photons were sensed in two opposite quadrants and no bremsstrahlung was present in either of the remaining quadrants. The information was encoded by a 13 bit NS-409 ADC and data were stored in an analyzer designed around a NOVA2 computer.[9] The detection system had a resolution (FWHM) which ranged from 2.1 to 5.0 keV between the energy region 2500–8300 keV. Throughout the experiment a dual point NS-635 stabilizer, which tracked two strong peaks of the (n,γ) spectrum, was used to regulate the zero and gain of the system.

Initially a 4.0 g sample of 99.999% pure BaCO$_3$ [Aldrich Chemical Company, Inc.] was placed within a graphite capsule, inserted into the irradiation position, and counted for a total time of 250 h. Following this, calibration for energy and intensity was achieved by recording the spectrum obtained for a sample of 2.602 g BaCO$_3$ and 1.179 g melamine. This second irradiation was conducted for 75 h.

III. DATA ANALYSIS

Initially the "toe" associated with each peak was removed through application of an appropriate filter.[10] The centroids and areas of the peaks were than determined using a nonlinear least-squares fitting procedure in which a simple Gaussian line shape was assumed. The energies of photons from capture by nitrogen[11] were used as primary standards to construct the relation between energy and pulse height. Energies of prominent isolated transitions in barium were then determined from this relation and used as secondary standards for calibration of the pure barium spectrum. The process was then repeated for the pure sample in order to obtain estimates for the energies of the remaining transitions. A relative efficiency curve was constructed from the melamine data using the published nitrogen intensities.[11] This was then used to calculate the relative intensities for the barium transitions. Finally absolute intensities were determined using the total cross sections of the barium isotopes[12] and the recently published value of 78.9 ± 1.4 mb for the ^{14}N cross section.[13]

TABLE I. Energy and intensity of gamma rays in the ^{135}Ba(n,γ)^{136}Ba reaction.

From Ref. 14				From this work					
Energy (keV)		Relative intensity		Energy[a] (keV)		Absolute intensity[b] (per 1000n)		Level (keV)	
								From	To
9106.5	1.3	2.9	0.3	9107.42	0.06	24.36	0.65	9108	0
8288.2	0.8	1.8	0.4	8288.98	0.05	13.40	0.30	9108	819
7554.3	1.0	0.24	0.08	7556.43	0.07	4.52	0.15	9108	1551
7526.6	2.0	0.07	0.04	7528.89	0.16	1.05	0.07	9108	1579
				7053.75	0.24	0.97	0.26	9108	2054
7026.4	0.7	0.7	0.1	7027.48	0.06	5.94	0.21	9108	2080
6978.2	0.7	0.2	0.05	6978.91	0.11	2.10	0.10	9108	2129
				6966.44	0.18	1.16	0.08	9108	2141
				6884.97	0.10	2.08	0.13	9108	2223
				6792.05	0.23	0.75	0.23	9108	2316
				6716.84	0.23	0.87	0.10	9108	2391
6707.4	0.8	0.3	0.05	6707.58	0.07	4.20	0.17	9108	2400
				6676.97	0.15	1.72	0.12	9108	2431
6574.9	0.6	0.5	0.1	6574.90	0.06	5.81	0.20	9108	2533
				6466.72	0.11	2.85	0.14	9108	2641
				6446.18	0.10	3.41	0.17	9108	2662
				6413.89	0.22	1.01	0.17	9108	2694
				6333.93	0.47	0.91	0.20	9108	2773
				6295.93	0.13	0.83	0.12	9108	2812
				6112.13	0.17	0.85	0.11	9108	2996
6087.4	0.5	0.3	0.1	6085.69	0.11	3.70	0.38	9108	3019
6063.5	0.4	3.5	0.6	6062.36	0.04	19.81	0.31	9108	3045
				5991.32	0.17	1.59	0.35	9108	3116
5673.2	0.6	0.4	0.1	5672.32	0.07	6.57	0.25	9108	3435
5340.3	0.7	0.2	0.1	5340.24	0.10	4.48	0.26	9108	3767
5311.9	0.6	3.7	0.4	5312.39	0.05	30.50	0.92	9108	3795
5141	1.7	0.4	0.2	5141.84	0.06	4.79	0.32	9108	3966
				5127.41	0.14	3.36	0.26	9108	3980
4994.1	2.4	0.4	0.2	4992.06	0.24	1.25	0.36		
4929.4	1.7	0.8	0.3	4925.13	0.06	7.57	0.51		
4731.8	2.0	0.3	0.2	4728.65	0.11	4.80	0.30		
4508.8	2	1.5	0.2	4508.64	0.09	11.41	1.05		
4429.0	2.0	2.1	0.4	4424.51	0.10	11.01	1.02		
4322.5	1.5	1.3	0.4	4318.81	0.27	4.94	0.88		
4137.2	1.4	1.4	0.4	4137.29	0.08	6.11	0.55	4137	0
3983.4	1.0			3980.41	0.09	5.62	0.38		
3967.8	2.0			3965.28[c]	0.06	10.66	0.45	3965	0
3860.7	1.5	0.7	0.2	3863.41	0.23	3.33	1.25	3863	0
3793.7	2.0	0.5	0.2	3795.24	0.18	2.09	0.67	3795	0
3739.2	3	1.1	0.3	3738.22[c]	0.07	13.55	0.84		
				3436.18[d]	0.09	20.31	3.45	3436	0
				3370.75	0.27	5.14	0.77	3371	0
				3116.42	0.47	7.64	2.54	3116	0
				3044.51	0.05	13.03	0.58	3045	0
2977.0	0.4	3.6	0.5	2976.04	0.05	69.89	1.93	3795	819
				2873.36	0.13	9.47	2.30	3692	819
				2773.32	0.11	4.76	0.79	2773	0
				2693.97	0.11	6.79	1.21	2693	0
2686.5	2.0			2689.20	0.07	12.58	1.39		
				2485.22	0.07	13.45	0.92	2485	0
				2441.55	0.19	5.55	1.12	3992	1551
				2429.63	0.31	3.26	1.02	4008	1579
				2374.16	0.18	5.59	1.36	2374	0
				2153.53	0.08	8.14	0.70	2154	0
2128.9	1.0			2128.89	0.05	44.50	2.24	2129	0
				2083.31	0.11	9.61	1.30		
				2141.35	0.06	7.43	0.64	2141	0

TABLE I. (*Continued*).

From Ref. 14				From this work					
Energy (keV)		Relative intensity		Energy[a] (keV)		Absolute intensity[b] (per 1000*n*)		Level (keV) From	To
2080.8	1.5	0.8	0.4	2080.03	0.05	28.89	1.77	2080	0
				1993.60	0.20	7.90	3.15	2812	819
1954.6	1.0	3.5	1.4	1955.19	0.17	12.21	2.55	3505	1551
				1874.96	0.10	10.42	1.62	2694	819
1841.1	1.0			1842.99	0.15	22.35	2.82	2662	819
1822.0	1.5	2.2	0.5	1821.90	0.12	22.15	3.34		
				1666.81	0.16	22.02	5.82	2485	819
1612.2	0.7	1.3	0.5	1613.73	0.09	66.83	7.48		
1579.8	0.4	5.4	1.7	1581.50	0.06	37.20	2.33	2400	819
1550.0	0.6	11.9	1.4	1551.04	0.08	96.49	10.61	1551	0

[a] Error in energy is due to statistics and the calibration.

[b] Error in absolute intensity is due to statistics and efficiency calibration. To this a 16% error due to the uncertainty in σ_γ of ^{135}Ba has to be added.

[c] Has interference with ^{138}Ba.

[d] May have interference with ^{138}Ba.

TABLE II. Energy and intensity of gamma rays in the ^{137}Ba$(n,\gamma)^{138}$Ba reactions.

From Ref. 15			From this work					
Energy (keV)		Relative intensity	Energy[a] (keV)		Absolute intensity[b] (per 1000*n*)		Level (keV) From	To
8614	5		8611.28	0.10	0.87	0.04	8612	0
7176	1.8	0.1	7175.57	0.06	1.36	0.04	8612	1436
6421.5	1.7	0.5	6421.49	0.05	4.57	0.12	8612	2190
			6393.81	0.13	0.64	0.04	8612	2218
			6303.69	0.11	0.40	0.05	8612	2308
			6166.23	0.13	0.87	0.07	8612	2445
6028.4	0.6		6028.48	0.04	14.62	0.33	8612	2583
5972.3	0.7		5972.35	0.05	6.64	0.13	8612	2639
			5831.06	0.11	1.33	0.10	8612	2781
			5815.77	0.15	1.01	0.08	8612	2796
5730.4	0.5	12	5730.83	0.04	98.99	2.11	8612	2881
			5694.56	0.09	1.81	0.08	8612	2917
			5680.38	0.09	1.71	0.08	8612	2931
			5620.53	0.11	1.23	0.07	8612	2991
5559.8	2	0.3	5561.80	0.06	3.74	0.19	8612	3049
			5526.63	0.09	2.85	0.28	8612	3085
			5449.19	0.05	10.74	0.28	8612	3162
			5369.15	0.20	0.95	0.10	8612	3242
			5354.20	0.15	1.10	0.11	8612	3257
5271	1.5	1.6	5272.93	0.05	11.57	0.32	8612	3339
			5244.71	0.08	1.62	0.09	8612	3367
			5169.05	0.09	2.14	0.14	8612	3443
5108.2	2	1.3	5107.35	0.05	8.83	0.25	8612	3504
5009	2	0.4	5010.92	0.07	2.97	0.17	8612	3601
4968	1	1.3	4968.39	0.06	19.10	0.73	8612	3643
			4918.13	0.13	1.05	0.14		
4881	2	0.2	4881.25	0.09	2.44	0.23		
4774.5	1.5	1.2	4739.76	0.08	2.40	0.13		
4689	1	2.2	4689.61	0.05	21.89	0.67	8612	3922
			4676.65	0.20	2.63	0.28	8612	3935
4600	2	0.8	4599.42	0.06	5.96	0.49	8612	4012
4551.1	1.5	0.2	4551.04	0.11	2.30	0.32		

TABLE II. (*Continued*).

From Ref. 15			From this work					
Energy (keV)		Relative intensity	Energy[a] (keV)		Absolute intensity[b] (per 1000n)		Level (keV) From	To
			4535.93	0.06	3.85	0.15	4536	0
4533.3	2	0.7	4531.67	0.05	4.79	0.18	8612	4080
			4469.25	0.25	2.39	0.50	8612	4142
4445.3	1.5	0.8	4445.38	0.05	5.86	0.33	4445	0
4369.3	1.5	0.8	4369.47	0.05	8.36	0.33	8612	4242
4330.8	1.5	1.8	4332.21	0.06	13.51	0.59	8612	4279
4323.7	1.5	1.8	4323.39	0.07	10.41	0.62	4324	0
4286.8	2	1.6	4288.03	0.06	8.63	0.42	8612	4324
4278.8	2	0.7	4280.28	0.08	4.77	0.35	4280	4279
4251	1.5	1.2	4252.10	0.06	9.06	0.35	8612	4360
4165.2	1.5	1	4166.19	0.05	7.43	0.23	8612	4445
			4142.15	0.20	0.84	0.16	4142	0
4111.4	1.5	0.2	4114.76	0.10	5.19	0.36		
			4103.28	0.52	1.46	0.71	8612	4508
4082.1	2	0.8	4082.95	0.06	6.59	0.43		
			4076.10	0.09	3.18	0.38	8612	4536
			4061.42	0.09	4.74	0.57		
4025.2	0.4		4025.85	0.07	6.44	0.45	4026	0
3963.8	1.5	0.5	3965.28	0.06[c]	4.31	0.18	8612	4646
3945	3	0.3	3945.81	0.08	5.98	0.64		
3920	3		3923.81	0.09	1.36	0.27		
3866	3		3868.54	0.17	1.81	0.53		
3824.9	1.5	0.3	3823.56	0.18	1.67	0.20		
			3826.54	0.15	1.93	0.21		
3813.7	1.5	0.2	3815.59	0.08	3.45	0.26		
3737.4	1.5	0.5	3738.22	0.07[c]	5.48	0.34		
3713.7	1.5	0.2	3714.65	0.06	8.26	0.44		
3642.4	1.5	1	3643.61	0.31	4.07	1.48	3643	0
3602	3	0.2	3600.53	0.17	1.85	0.29	3601	0
3503.9	1.5	0.9	3504.02	0.06	8.27	0.51	3504	0
			3442.34	0.13	3.70	1.32	3443	0
			3436.18	0.09[d]	8.21	1.39	3436	0
			3366.74	0.09	5.80	0.45	3367	0
339.3	1	1.3	3338.60	0.05	16.80	0.84	3339	0
			3209.75	0.10	2.11	0.35	4646	1436
			3085.43	0.17	1.78	0.26		
			3074.29	0.11	2.01	0.21	4508	1436
3050	3	0.9	3049.28	0.05	5.28	0.22	3049	0
			2931.69	0.21	1.92	0.33	2932	0
2923	3	0.5	2923.37	0.14	2.47	0.48	4360	1436
			2916.86	0.18	2.38	0.43	2917	0
			2795.68	0.14	2.14	0.54	2796	0
2639.1	1	2.2	2639.27	0.04	32.21	0.77	2639	0
			2609.56	0.16	1.13	0.30	4508	1899
2580	3	0.45	2582.86	0.08	7.31	1.30	2583	0
2217.6		2	2217.73	0.05	79.90	2.84		
2023		2	2023.55	0.07	15.70	1.25	3922	1899
2060	3	0.5	2061.12	0.18	2.69	0.68		
1780	3	1.5	1778.60	0.13	16.41	7.50		
1705	3		1708.10	0.29	4.06	1.29		
1495	1.5	2.5	1495.82	0.15	23.13	5.45	2931	1436
1445	0.2	25	1444.99	0.06	84.62	4.31		
1435.7	0.2	100	1435.88	0.04	398.65	10.48	1436	0

[a] Error in energy is due to statistics and the calibration.

[b] Error in absolute intensity is due to statistics and efficiency calibration. To this an 8% error due to the uncertainty in σ_γ of ^{137}Ba has to be added.

[c] Has interference with ^{136}Ba.

[d] May have interference with ^{136}Ba.

TABLE III. Energy and intensity of gamma rays in the ^{138}Ba$(n,\gamma)^{139}$Ba reactions.

From Ref. 16				From this work					
Energy (keV)		Relative intensity		Energy[a] (keV)		Absolute intensity[b] (per 100n)		Level (keV) From	To
4096.1	0.7	60	7	4096.14	0.04	56.9	1.2	4724	627
3641.4	0.7	20	3	3641.47	0.05	20.8	0.4	4724	1082
3432.0	2.0	1		3432.40	0.33	0.5	0.1	4724	1291
2594.1	1.0	8	1	2594.29	0.04	6.8	0.2	4724	2129
2567.0	2.0	3	1.5	2564.61	0.08	2.1	0.1	4724	2185
2537.0	1.5	3	1	2537.88	0.06	4.6	0.3	4724	2185
2522.5	1.5	8.5	1.5						
				2480.68	0.12	0.5	0.1	2481	0
				2288.28	0.08	2.5	0.2	472	2435
2242.0	1.0	5	1	2242.67	0.06	3.5	0.2	4724	2481
				2173.96	0.23	0.6	0.2	2174	0
1952.3	1.0	3	2	1951.53	0.15	1.2	0.4	1951	0
1854.0	1.0	3	2	1853.31	0.09	3.2	0.3	2481	627
1558.0	1.0	2.5	1.5	1558.10	0.33	1.3	0.5	2186	627
1500	2	1		1501.52	0.16	4.01	1.32	2129	627
1420.1	1.0	5	2	1420.01	0.33	1.9	0.52	1420	0

[a] Error in energy is due to statistics and the calibration.

[b] Error in absolute intensity is due to statistics and efficiency calibration. To this a 10% error due to the uncertainty in σ_γ of ^{138}Ba has to be added.

The energies and intensities of the transitions observed for barium are listed in Tables I–VI. The energy errors were estimated by combining the uncertainty in the centroid with that from the calibration. The same procedure was used for relative intensity error estimates using the area uncertainty with that of the efficiency curve. For absolute intensities, errors must be adjusted to include the additional contributions arising from the uncertainty in the barium and nitrogen cross sections.

The high sensitivity and precision of the present measurements resulted in the detection of many more transitions than were previously observed, even when enriched targets had been used. Isotopic and decay mode assignment were made where possible through use of previous studies.[6,14–16] In addition, precise level energy data from compilations[17–23] was employed when available. Because of the number of transitions observed and the multitude of levels associated with the contributing isotopes, misassignment is possible. To minimize this, duplicate placement ambiguities were resolved by using energy precision and intensity information. Possible interference from any impurity was checked with the help of the compilation of Lone *et al.*[24]

IV. RESULTS AND DISCUSSIONS

A. Photon transitions in barium

Using the thermal-neutron-capture cross sections and natural abundances[12] of barium isotopes, it is calculated that about 44% of the primary gamma radiation results from capture in ^{137}Ba, whereas 29% and 20% should be ascribed to capture in ^{135}Ba and ^{138}Ba, respectively. The remaining 7% is due to captures in ^{132}Ba, ^{134}Ba, and ^{136}Ba.

In total 67 transitions have been identified to be due to ^{136}Ba and of these, 34 are new. The number of primary transitions is 28, which is more than twice that previously reported.[14] Among the transitions, 55 could be placed in a decay scheme. The energies and absolute intensities of ^{136}Ba transitions are presented in Table I and the decay modes indicated. Energies and relative intensities from Ref. 14 are also displayed. Although the energies agree in general within error, there has been a significant improvement in precision.

Eighty-five transitions have been attributed to ^{138}Ba. Among these 38 are primary, thus doubling the number of such transitions observed in the past.[15] The energy, intensity, and assignment of the transitions along with those in the literature are presented in Table II.

The level structure of ^{139}Ba is very simple because of the influence of the 82 neutron closed shell. Therefore there are relatively few transitions expected and this has been borne out by the fact that only 15 have been observed. These are presented in Table III along with those from the literature.[16] Ground state transitions from the

TABLE IV. Energy and intensity of gamma rays in the ^{132}Ba$(n,\gamma)^{133}$Ba reactions.

Energy[a] (keV)		Relative intensity[b]	Level (keV) From	To
7189.85	0.26	0.38	7190	0
6327.44	0.12	6.39	7190	863
5656.70	0.18	1.55	7190	1532
5608.64	0.30	0.96	7190	1581

[a] Error in energy is due to statistics and the calibration.

[b] Error in relative intensity is due to statistics and efficiency calibration.

TABLE V. Energy and intensity of gamma rays in the ^{134}Ba$(n,\gamma)^{135}$Ba reactions.

From Ref. 6 Energy (keV)	From Ref. 6 Relative intensity	From this work Energy[a] (keV)		From this work Relative intensity[b]		Level (keV) From	Level (keV) To
		6972.39	0.25	0.7	0.1	6972	0
		6751.64	0.22	0.5	0.1	6972	221
5389	6.0	5387.57	0.07	6.0	0.4	6972	1584
4895	1.7	4895.03	0.22	3.8	1.3	6972	2075
4520	5.1	4524.00	0.10	3.2	0.4	6972	2448
		2447.80	0.18	4.9	0.9	2448	0

[a] Error in energy is due to statistics and the calibration.

[b] Error in relative intensity is due to statistics and efficiency calibration.

excited states at 2481 and 2174 keV were observed for the first time in the present study.

No information regarding the ^{132}Ba$(n,\gamma)^{133}$Ba reaction has been published. We observed four transitions which may be due to ^{133}Ba. The photon energies and relative intensities of these are presented in Table IV.

In the present study, six transitions are observed in ^{135}Ba, of which all but one are primary. Three of the transitions, including the one from the capture to ground state, were not reported in the past. The energy and intensity of transitions for ^{135}Ba found in this work and those of Ref. 6 are presented in Table V.

The energies and relative intensities of the transitions for ^{137}Ba along with those from the literature[6] are given in Table VI. The energies of transitions observed here differ significantly from the published values.

The unassigned transitions are presented in Table VII. These transitions could not be fitted unambiguously within any of the level structures of the barium isotopes as presently known. In some case energy imprecision has restricted placement.

B. Neutron separation energies

To determine the neutron separation energy of ^{136}Ba, recoil-corrected energies of 27 primary transitions have been added to the corresponding known energy levels[17] or to secondary transitions, if observed. In the case of ^{138}Ba, in total 32 primary transitions have been used. For ^{139}Ba and ^{137}Ba, a least-squares fit[11] was performed to determine level energies as well as the neutron separation energies. For ^{133}Ba and ^{135}Ba, the level energies,[18,19] and three and four primary transitions, respectively, have been utilized to estimate the separation energy.

The values of the separation energies of the six isotopes of barium obtained in this work are presented in Table VIII along with those from the compilation of Wapstra and Audi.[20] The present values for ^{133}Ba, ^{136}Ba, ^{138}Ba, and ^{139}Ba agree well and show a marked increase in precision. The $S_n(^{135}\mathrm{Ba})=6972.21\pm0.18$ keV of this work is slightly lower than the reported value of 6973.2 ± 0.4 keV.[20] For ^{137}Ba, the present S_n value of 6905.78 ± 0.03 keV, on the other hand, is higher than the 6899 ± 3 keV quoted by Wapstra.[20]

C. Energy levels

Energy levels inferred for the six isotopes of barium, along with those reported previously, are given in Tables IX–XIV. The values for ^{136}Ba exhibit general agreement with those in the literature,[17] although there is a substantial improvement in precision. There is evidence for a new level at 3863 keV.

In ^{138}Ba the level at 3162 keV differs slightly from that in the literature,[21] while the other levels agree within er-

TABLE VI. Energy and intensity of gamma rays in the ^{136}Ba$(n,\gamma)^{137}$Ba reactions.

From Ref. 6 Energy (keV)	From Ref. 6 Relative intensity	From this work Energy[a] (keV)		From this work Relative intensity[b]		Level (keV) From	Level (keV) To
		6906.02	0.11	1.2	0.1	6906	0
6610	4	6621.81	0.06	5.3	0.2	6906	283
4716	55	4723.37	0.04	55.0	1.1	6906	2182
4245	20	4242.72	0.05	19.3	0.6	6906	2663
		3583.81	0.19	2.1	0.4	6906	3323
		3322.95	0.13	1.7	0.2	3323	0
		2662.66	0.06	9.5	0.6	2663	0
		2379.10	0.07	9.0	1.0	2663	284
		2182.00	0.26	2.8	0.3	2182	0
1898	45	1898.58	0.05	60.7	2.2	2182	284

[a] Error in energy is due to statistics and the calibration.

[b] Error in relative intensity is due to statistics and efficiency calibration.

TABLE VII. Unassigned transitions observed in neutron capture by natural barium.

Photon energy[a] (keV)		Relative intensity[b]		Photon energy (kev)		Relative intensity	
7790.10	0.23	0.61	0.11	4925.13	0.06	7.08	0.48
7040.43	0.31	0.53	0.09	4876.69	0.08	6.17	0.57
6894.11	0.23	0.66	0.11	4861.02	0.29	1.10	0.37
6773.94	0.20	0.76	0.13	4855.11	0.14	3.59	0.68
6663.20	0.27	0.73	0.09	4799.43	0.17	2.61	0.36
6643.55	0.40	0.54	0.10	4812.07	0.11	3.58	0.34
6563.45	0.23	0.74	0.09	4820.38	0.17	2.28	0.27
6487.56	0.22	1.18	0.24	4786.16	0.07	6.28	0.26
6387.54	0.14	1.35	0.06	4766.82	0.22	1.60	0.22
6290.24	0.41	0.20	0.07	4755.92	0.06	11.14	1.74
6210.58	0.22	0.67	0.09	4739.76	0.08	5.55	0.29
6206.16	0.31	0.47	0.09	4728.65	0.11	4.48	0.28
6181.19	0.17	1.29	0.14	4711.89	0.23	1.67	0.21
6129.41	0.06	8.93	0.49	4707.21	0.11	3.96	0.24
6085.69	0.11	3.46	0.36	4664.12	0.11	2.28	0.25
5998.79	0.27	0.82	0.29	4655.12	0.11	2.84	0.32
5951.33	0.08	2.12	0.17	4638.44	0.15	4.66	0.67
5920.46	0.25	1.28	0.51	4609.36	0.09	7.77	0.77
5888.40	0.18	3.53	1.24	4604.66	0.15	4.98	0.79
5840.75	0.33	0.89	0.14	4592.69	0.15	4.10	0.64
5767.85	0.74	0.83	0.28	4551.04	0.11	5.32	0.74
5756.16	0.77	0.87	0.29	4501.72	0.29	2.56	0.75
5583.83	0.29	1.04	0.15	4495.50	0.17	4.98	0.77
5556.53	0.16	2.55	0.36	4482.84	0.49	2.79	0.81
5539.57	0.23	2.44	0.45	4414.42	0.22	5.26	0.86
5432.75	0.22	1.50	0.55	4349.16	0.08	6.23	0.79
5401.72	0.15	1.66	0.15	4341.93	0.22	2.24	0.55
5376.04	0.13	3.27	0.25	4318.81	0.27	4.62	0.83
5363.35	0.59	0.68	0.19	4313.81	0.46	2.24	0.76
5308.14	0.33	2.70	0.35	4273.72	0.42	1.46	0.46
5256.89	0.14	1.82	0.15	4258.30	0.22	3.05	0.42
5235.71	0.08	3.59	0.20	4230.89	0.27	2.42	0.42
5225.18	0.09	2.86	0.19	4207.69	0.07	7.15	0.42
5177.84	0.06	11.43	0.48	4220.20	0.07	6.06	0.59
5146.22	0.35	0.72	0.14	4200.68	0.05	15.85	0.62
5135.08	0.16	1.27	0.31	4189.49	0.13	3.61	0.41
5092.49	0.10	6.73	0.39	4148.89	0.17	1.99	0.34
5044.76	0.09	3.31	0.38	4127.13	0.31	2.90	0.49
5040.76	0.08	4.57	0.43	4068.72	0.18	4.10	0.63
4992.06	0.24	1.16	0.33	4057.13	0.54	1.98	1.01
4051.64	0.22	3.18	1.26	3120.55	0.93	3.90	1.66
4046.62	0.13	5.90	1.05	3110.47	0.28	7.76	2.02
4036.82	0.16	5.19	0.56	3095.31	0.09	8.20	0.80
4031.88	0.13	7.14	0.71	3061.98	0.14	3.74	0.46
4017.27	0.11	7.62	0.79	3032.35	0.11	4.52	0.44
4011.54	0.20	3.94	0.59	2966.48	0.18	6.24	0.78
4001.37	0.08	13.79	1.47	2928.60	0.20	5.04	0.90
3993.86	0.35	3.17	1.11	2913.88	0.30	3.55	0.83
3988.95	0.40	3.03	1.01	2901.97	0.25	2.16	0.52
3940.02	0.39	3.50	1.31	2895.67	0.09	7.67	0.74
3933.84	0.22	5.14	2.04	2886.02	0.20	2.92	0.56
3905.24	0.16	5.08	2.82	2828.00	0.04	13.67	0.58
3891.39	0.08	6.68	0.50	2806.14	0.06	11.49	1.04
3881.43	0.35	1.39	0.35	2773.32	0.11	4.45	0.74
3853.68	0.20	2.20	0.45	2762.34	0.08	8.76	0.97
3845.53	0.22	1.81	0.47	2748.10	0.14	4.00	0.84
3799.98	0.09	3.98	0.82	2679.64	0.08	10.24	1.56
3785.57	0.21	2.45	0.78	2614.96	0.20	1.77	0.55
3778.75	0.24	1.99	0.88	2577.45	0.22	6.46	2.08

TABLE VII. (*Continued*).

Photon energy[a] (keV)		Relative intensity[b]		Photon energy (keV)		Relative intensity	
3733.23	0.14	5.47	0.56	2569.55	0.23	5.99	1.90
3718.94	0.42	1.99	0.54	2531.05	0.28	5.54	1.38
3705.60	0.25	3.00	0.59	2517.14	0.14	4.78	1.13
3590.49	0.13	6.40	0.75	2512.02	0.08	10.62	1.37
3562.52	0.16	3.35	0.71	2500.27	0.32	13.09	7.46
3451.58	0.20	6.72	1.77	2470.84	0.10	6.82	0.92
3412.81	0.09	3.51	0.49	2436.68	0.31	3.02	0.98
3397.12	0.09	7.54	0.99	2422.54	0.18	5.57	0.99
3380.46	0.14	2.50	0.95	2402.10	0.08	9.72	1.17
3359.88	0.34	2.64	0.74	2278.71	0.54	7.15	3.32
3350.71	0.20	4.84	0.72	2275.89	0.65	5.61	2.42
3333.70	0.30	2.59	1.01	2164.96	0.22	6.56	1.67
3320.52	0.13	3.14	0.44	2040.61	0.29	14.14	6.58
3304.08	0.11	6.57	0.72	1961.50	0.16	9.96	2.13
3294.61	0.17	4.53	0.68	1940.55	0.07	15.62	2.29
3230.01	0.09	6.47	1.60	1869.54	0.12	6.62	1.29
3224.79	0.09	6.26	1.86	1832.05	0.23	12.51	2.73
3219.96	0.15	3.81	1.28	1727.09	0.19	13.39	4.62
3197.11	0.17	3.02	0.73	1718.84	0.30	8.37	2.97
3148.13	0.22	3.44	1.04	1572.59	0.07	21.91	1.80
3144.28	0.21	4.55	1.10	1532.64	0.12	72.64	9.97
3141.03	0.18	4.85	0.99	1507.17	0.24	26.70	10.35
3129.53	0.67	3.57	1.77				

[a] Error in energy is due to statistics and the calibration.

[b] Error in relative intensity is due to statistics and efficiency calibration.

ror. There are two possible new levels at 3085 and 3601 keV. The levels in ^{139}Ba agree in general with those in the literature[22] but again there has been marked improvement in precision.

Three levels of ^{133}Ba were determined in the present study and agree within error with the values in the literature.[18] Because the statistics were poor, the precision obtained is worse than for the published data. The levels of ^{135}Ba agree with those previously reported.[19]

The four energy levels in ^{137}Ba obtained in the present study differ by 5–18 keV from the values adopted in the latest compilation[23] as is apparent in Table XIV. There is a discrepancy in the literature regarding the first excited state in ^{137}Ba. A study of the $(\alpha,3n\gamma)$ reaction[25] gave a value of 279.2±0.3 keV, while a value of 283.65±0.15 was obtained from a study of the $(n,n'\gamma)$ reaction.[26] The present study gives a vale of 283.76±0.04 keV, thus supporting the value obtained from the $(n,n'\gamma)$ reaction and disagreeing with the other value which was incidentally adopted in the compilation.[23] The other common levels from the two reactions[25,26] exhibit general agreement. The level at 2182.33 keV in the present work is higher than 2173±2 keV quoted by Peker in the compilation.[23] Peker used the corresponding primary transition reported by Groshev *et al.*[6] It should be mentioned at this point that out of the four transitions in the ^{136}Ba$(n,\gamma)^{137}$Ba reaction that Groshev *et al.* reported, the two with higher energy differ substantially from our values while the lower two are in agreement. The separation energy of ^{137}Ba was previously found to be 6891 keV,[6] in contrast with our value of 6905.78 keV. This problem has been compounded by the fact that in the report of Groshev *et al.*, the same transition energy is erroneously given two values, e.g., 4712 and 4716 keV. The compiler used 4716 keV which, in combination with his adopted S_n value of 6889 keV, gave the level at 2173±2 keV. Groshev *et al.*, on the other hand, used 4712 keV which, in combination with their deduced S_n value of 6891 keV, gave the level at 2179 keV. If the other data of Groshev *et al.*, e.g., the transition energy 1898 keV and the level energy 281 keV, are used the level energy is found to be 2179 keV. This value is close to the present value of 2182.33 keV. Our value also agrees with 2180±20 keV found in the (d,p) reaction.[27] The level at 2662.87 keV differs from the adopted value of 2644±5 keV,[24] which is again readjusted from the value of 2646 keV of Groshev *et al.* The corresponding primary transition at 4245 keV,[6] when used in conjunction with the present S_n value of 6906 keV, gives a level energy of 2661

TABLE VIII. Neutron separation energies of barium isotopes.

Final nucleus	Neutron separation energy			
	This work[a]		Ref. 20	
^{133}Ba	7189.96	0.36	7190	7
^{135}Ba	6972.21	0.18	6973.2	0.4
^{136}Ba	9107.84	0.04	9107.1	0.8
^{137}Ba	6905.78	0.03	6899	3
^{138}Ba	8611.75	0.04	8611.3	0.8
^{139}Ba	4723.44	0.04	4723.41	0.30

[a] Based on a ^{15}N Q value of 10 833.30±0.02 keV (Ref. 20).

TABLE IX. Level energies of ^{136}Ba.

This work Energy (keV)		Ref. 17 Energy (keV)	
818.59	0.06	818.515	0.012
1551.12	0.06	1550.97	0.03
1578.73	0.17	1579.02	0.05
2053.89	0.25	2053.876	0.02
2080.09	0.04	2080.07	0.05
2128.88	0.05	2128.81	0.05
2141.35	0.06	2141.28	0.07
2222.69	0.11	2222.73	0.06
2315.61	0.23	2315.43	0.09
2356.03	0.22	2356.46	0.07
2390.82	0.23	2390.77	0.08
2400.08	0.08	2399.86	0.09
2430.70	0.15	2430.98	0.06
2485.25	0.07	2485.44	0.17
2532.77	0.07	2532.46	0.07
2640.95	0.11	2640.71	0.21
2661.50	0.11	2661.63	0.10
2693.96	0.10	2693.64	0.17
2773.37	0.11	2772.4	0.3
2777.69	0.14	2778.5	0.8
2811.75	0.13	2811.73	0.20
2976.08	0.05	2975.7	0.5
2995.56	0.18	2994	5
3044.87	0.04	3045.6	0.5
3116.39	0.17	3114	1
3179.72	0.08	178.9	0.7
3370.80	0.26	3370	1
3435.39	0.08	3436	1
3767.49	0.11	3767.1	0.5
3795.34	0.07	3795.5	0.4
3863.09	0.08		
3965.90	0.08	3965.0	0.5
3980.43	0.08	3983.5	2.0

keV which agrees with our value. The present value also agrees with 2663±20 keV obtained from the (d,p) reaction.[27] The level at 3322.65 keV may be compared with 3319±20 keV.[27] It appears that the uncertainty quoted in the (d,p) study is overestimated.

D. Magnetic dipole strength function

The magnetic dipole strength function is defined as[28]

$$k=\langle \Gamma_{\gamma_i} D^{-1} E_{\gamma_i}^{-3} \rangle \ , \tag{1}$$

where Γ_{γ_i} is the partial $M1$ radiative width of the capture state for transition i, D the average spacing of accessible neutron resonances at the neutron binding energy, and E_{γ_i} denotes the transition energy. To determine k, the quantities $(\Gamma_{\gamma_i} D^{-1} E_{\gamma_i}^{-3})$ were determined separately for 17 and 16 transitions in ^{136}Ba and ^{138}Ba, respectively. Corrections were made for the fractional spin contribution (F) to the capture. The values of F, Γ_γ, and D were calculated using the data of Ref. 12. The calculated values for ^{136}Ba and ^{138}Ba are given in Table XV.

In ^{136}Ba, levels with spins 1^+ and 2^+ are populated by

TABLE X. Level energies of ^{138}Ba.

This work Energy (keV)		Ref. 21 Energy (keV)	
1435.91	0.03	1435.795	0.010
2190.10	0.06	2189.8	0.2
2217.75	0.05	2217.97	0.06
2307.90	0.12	2307.66	0.07
2445.38	0.13	2445.72	0.07
2583.04	0.05	2583.18	0.08
2639.29	0.03	2639.59	0.07
2779.93	0.12	2779.5	0.09
2795.78	0.10	2795.68	0.14
2880.79	0.06	2880.98	0.14
2917.02	0.09	2916.86	0.18
2931.24	0.10	2931.52	0.21
2991.09	0.12	2991.24	0.09
3049.49	0.04	3049.99	0.17
3085.12	0.09		
3162.44	0.06	3163.61	0.12
3242.49	0.20	3242.66	0.12
3257.43	0.15	3257.72	0.25
3338.67	0.04	3339.07	0.19
3366.86	0.06	3367.02	0.25
3436.22	0.09	3437.5	0.6
3442.52	0.08	3442.6	0.6
3504.17	0.05	3505.1	2
3600.71	0.07		
3643.29	0.07	3643.3	0.4
3922.06	0.07	3922.61	0.18
3935.01	0.20	3935.27	0.15
4012.25	0.07	4012.3	0.4
4025.91	0.07	4027.0	1.5
4061.18	0.07	4061.42	0.09
4080.00	0.06	4080.1	0.5
4142.29	0.16	4142.15	0.2
4242.21	0.07	4242.51	0.18
4279.47	0.07	4278.8	2.0
4323.56	0.05	4346	2
4359.58	0.07	4360.2	2.0
4445.47	0.04	4445.3	0.2
4508.41	0.52	4508.11	0.15
4535.90	0.05	4538	2
4646.41	0.07	4645.7	2.5

TABLE XI. Level energies of ^{139}Ba.

This work Energy (keV)		Ref. 22 Energy (keV)	
627.28	0.04	627.318	0.022
1081.92	0.05	1082.04	0.05
1420.02	0.33	1420.67	0.04
1951.55	0.15	1952.3	1.0
2129.11	0.04	2129.3	0.9
2158.80	0.08	2158.87	0.16
2173.98	0.23	2173.95	0.05
2185.53	0.06	2185.9	0.8
2435.14	0.08	2433	10
2480.70	0.05	2481.4	0.7

TABLE XII. Level energies of ^{133}Ba.

This work Energy (keV)		Ref. 18 Energy (keV)	
862.36	0.38	862.77	0.09
1533.13	0.40	1532.38	0.08
1581.19	0.47	1581	10

TABLE XIII. Level energies of ^{135}Ba.

This work Energy (keV)		Ref. 18 Energy (keV)	
220.39	0.28	220.95	0.13
1584.53	0.19	1584.36	0.10
2077.09	0.31	2075.46	0.17
2447.98	0.14	2447	15

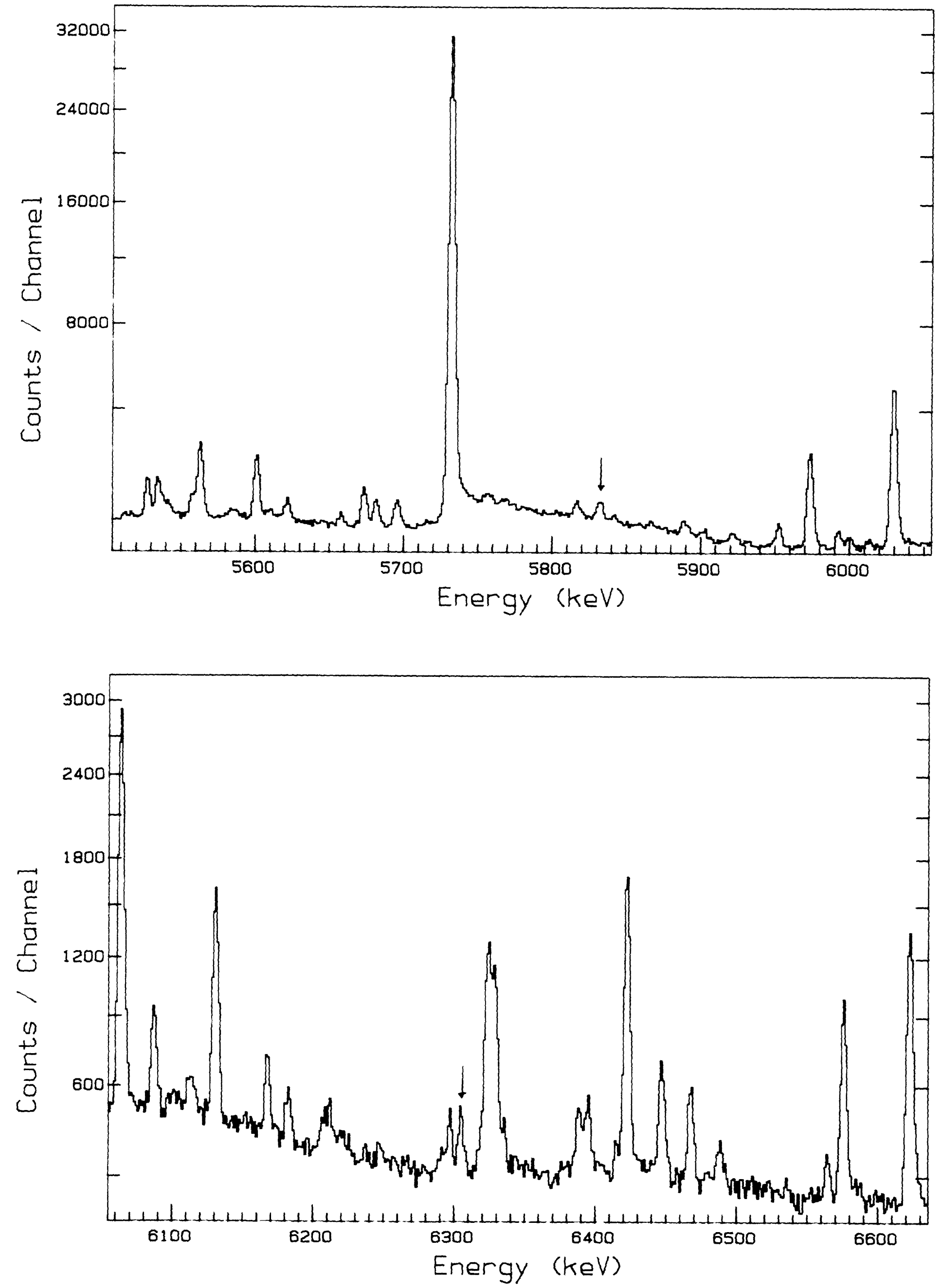

FIG. 1. The upper portion of the Ba(n,γ) spectrum containing three primary $E2$ transitions. The $E2$ transitions at 5832, 6304, and 7054 keV are indicated. The ordinate is the square root of the counts per channel thus yielding a constant precision.

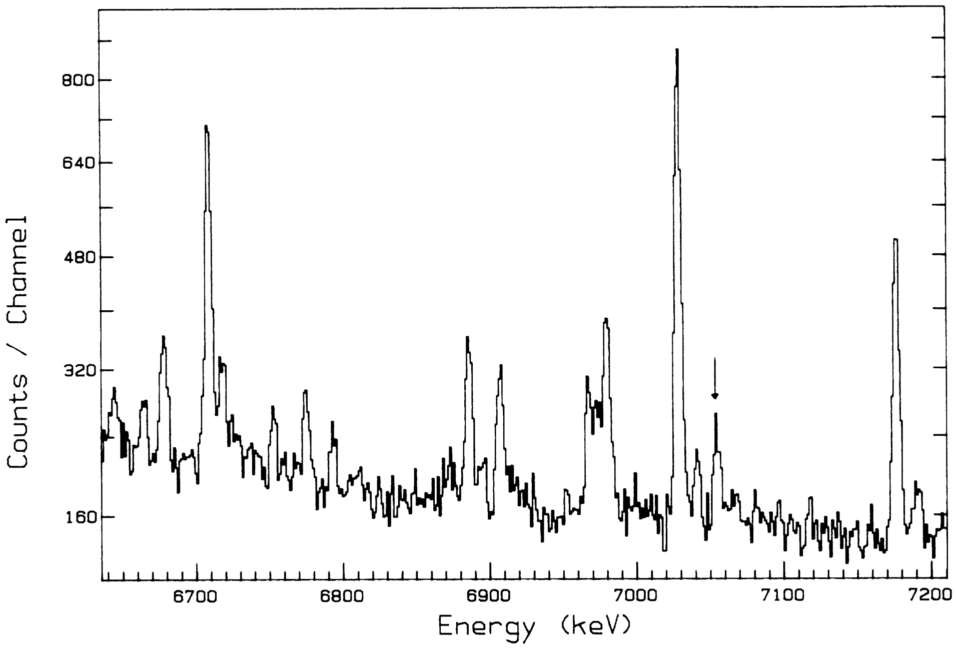

FIG. 1. (*Continued*).

$M1$ transitions from both possible capture states which also are formed with spin 1^+ and 2^+. For the populated level 0^+ (or 3^+), the contribution is entirely from the 1^+ (or 2^+) capture state. In ^{138}Ba, the levels with spins 1^+, 2^+, and 3^+ are contributed to by only the 2^+ capture state, which dominates the thermal capture cross section.

The quantities $\Gamma_{\gamma i} D^{-1} E_{\gamma i}^{-3}$ for ^{136}Ba and ^{138}Ba and the averages for these are presented in Tables XVI and XVII. The magnetic strength function for ^{136}Ba using 16 primary transitions is found to be $(27\pm7)\times10^{-9}$ MeV^{-3}. This value agrees with that of $(20\pm7)\times10^{-9}$ MeV^{-3} obtained from this nucleus from discrete neutron resonance capture[29] but does not support the value 50×10^{-9} MeV^{-3} reported by Bollinger[30] from average resonance capture. This value may be compared with the global average of the $M1$ strength function which is reported[5,30] to be $(30\pm4)\times10^{-9}$ MeV^{-3} and 18×10^{-9} MeV^{-3}.

The quantity $\langle \Gamma_{\gamma i} D^{-1} E_{\gamma i}^{-3} \rangle$ for $E1$ radiation, using four transitions, is found to be $(69\pm39)\times10^{-9}$ MeV^{-3}. This agrees within error with the value $(39\pm19)\times10^{-9}$ MeV^{-3} obtained from a resonance capture experiment.[29]

The strongest primary transitions in ^{136}Ba is at 5312 keV and populates a level at 3795 keV. The reduced strength of the transition is 346×10^{-9} MeV^{-3}. The tentative spins and parity of the level[17] are 0(+),1,2,3(+). If the level has a positive parity, the primary transition can be $M1$ and, if included in the average, will yield an $M1$ strength function of $(46\pm15)\times10^{-9}$ MeV^{-3}. If the parity of the level is negative, the corresponding primary transition would be $E1$. Inclusion of this transition would make the $E1$ strength function $(124\pm70)\times10^{-9}$ MeV^{-3}. Considering the Porter-Thomas distribution[31] and performing an analysis, there appears to be a 20:1 chance that the transition is $E1$ and therefore that the level at 3795 keV has a negative parity. Since we have observed the deexcitation of the level to the ground state which is 0^+, a $J=0$ or 3 assignment can be ruled out. Thus this level has possible $J^\pi = 1(-)$, $2(-)$. But as the deexcitation to the ground state rules out $2(-)$ in favor of $2(+)$, it is likely that the spin is $1(-)$.

After the exclusion of the unconfirmed $M1$ transition, most of the strength in the thermal spectrum is due the ground state transition of the capture state at 9108 keV. The strength of this transition is found to be more than 10 times the average of the rest. The question arises if this ground state transition is following a semidirect capture. The semidirect capture only occurs for $1_n=0$ states.[32] In the target nucleus ^{135}Ba, $l_n=2$ states are partially empty, but s states are full and very little $l_n=0$ strength is expected. In fact for the 9108 keV transition,

TABLE XIV. Level energies of ^{137}Ba.

This work Energy (keV)		Ref. 23 Energy (keV)		Ref. 27 Energy (keV)		Ref. 26 Energy (keV)	
283.76	0.04	279.2	0.3			283.65	0.15
2182.33	0.04	2173	2	2180	20		
2662.69	0.04	2644	5	2663	20		
3322.65	0.11			3319			

TABLE XV. Values of F, Γ_γ, and D for ^{136,138}Ba calculated from Ref. 12.

Final nucleus	Resonance spins	F	$\langle \Gamma_\gamma \rangle$ (eV)	D (eV)
^{136}Ba	1^+	0.19	0.106	99
	2^+	0.81	0.132	67
^{138}Ba	1^+	0		
	2^+	1	0.08	486

TABLE XVI. Magnetic dipole strength in ^{136}Ba. Average: $(27\pm7)\times10^{-9}$ MeV^{-3}.

E (keV)	I (%)	$\Gamma_{\gamma_i} D^{-1} E_{\gamma_i}^{-3}$ (MeV^{-3})$\times10^{8}$
9107	2.44	18.2
7529	0.10	1.3
6966	0.12	2.0
6792	0.07	1.3
8289	1.34	4.0
7556	0.45	1.8
7027	0.59	2.9
6979	0.21	1.0
6885	0.20	1.0
6717	0.09	0.7
6708	0.42	2.4
6467	0.28	1.8
6446	0.34	2.2
6414	0.10	0.6
6334	0.09	0.6
5991	0.16	1.3

TABLE XVII. Magnetic dipole strength in ^{138}Ba. Average: $(5.7\pm2.1)\times10^{-9}$ MeV^{-3}.

E (keV)	I (%)	$\Gamma_{\gamma_i} D^{-1} E_{\gamma_i}^{-3}$ (MeV^{-3})$\times10^{9}$
7175	0.14	0.6
6394	0.06	0.4
6165	0.09	0.6
6028	1.46	10.0
5972	0.66	5.1
5680	0.17	1.5
5620	0.12	1.1
5562	0.37	3.6
5449	1.07	1.1
5369	0.10	1.0
5272	1.16	13.0
5245	0.16	1.8
5169	0.21	2.5
4968	1.91	25.6
4676	0.26	4.2
4532	0.48	8.5

$l_n=2$ (d,p) strength, but no $l_n=0$ strength is observed.[17] Thus the transition is not semidirect. It may be mentioned here that virtually no $l_n=0$ (d,p) strength is observed for the other transitions in ^{136}Ba as well.

The $M1$ strength function for ^{138}Ba, obtained using 16 primary transitions, is $(5.7\pm2.1)\times10^{-9}$ MeV^{-3}. This value is much lower than that of ^{136}Ba. This is also lower than the global average.[5,30] This low value of the magnetic strength for a closed shell nucleus is contrary to what is expected.[5]

E. $E2$ strength in neutron capture

Since the spin of the target nuclei ^{136,138}Ba is 0^+, s-wave neutron capture produces only $\frac{1}{2}^+$ states. Thus a primary transition populating a $\frac{5}{2}^+$ level will be a pure $E2$ transition, provided that the p-wave capture contribution is negligible. Using data of Ref. 12, the ratio of $E1$ transitions arising from p-wave capture to $E2$ transitions is found to be less than $\frac{1}{200}$ in the present instance. A list of four $\frac{5}{2}^+$ levels in the two isotopes are given in Table XVIII. Primary $E2$ transitions to three of these levels were observed in the present study for the first time. An upper limit for the intensity of the unobserved transition was also determined. The results are presented in Table XVIII. The three cases were checked against possible interference from other isotopes of barium. A transition at 6751 keV which could be an $E2$ transition in ^{136}Ba can be better explained on the basis of energy as a transition in ^{135}Ba. A portion of the Ba(n,γ) spectrum containing the primary $E2$ transitions is displayed in Fig. 1.

To compare the experimental $E2$ strength with that expected from giant quadrupole resonances,[1,33] we estimated the reduced transition probability:[28]

$$\overline{B(E2)\downarrow}\ (\text{per MeV})=1.25\times10^{12} f_{E2}(E)\ [e^2\text{fm}^4\text{MeV}^{-1}] \tag{2}$$

where

$$f_{E2}=\langle \Gamma_{\gamma_i} D^{-1} E_{\gamma_i}^{-5} \rangle \ ,$$

Γ_{γ_i} being the partial $E2$ radiative width of the capture state for transition i, D the average level spacing of the resonances of a given spin and parity, and E_{γ_i} denotes the transition energy.

The absolute intensities of the primary $E2$ transitions are converted to radiative widths by using the Γ_γ and F values given in Table XV. The level spacings used are also given. The $B(E2)\downarrow$ values for the transitions are presented in Table XVIII. The average $\overline{B(E2)\downarrow}$ is found to be 53 ± 35 e^2fm^{4}MeV^{-1}. The uncertainty reflects the 68% limits for a χ^2 distribution with four degrees freedom.

The quadrupole strength function, on the basis of the giant resonance model, is the sum of the contribution from the isoscalar and isovector giant quadrupole resonances:[1]

$$\left\langle \frac{\Gamma_{\gamma_i}}{D} \right\rangle = \left\langle \frac{\Gamma_{\gamma_i}}{D} \right\rangle_{T=0} + 1.8 \left\langle \frac{\Gamma_{\gamma_i}}{D} \right\rangle_{T=1} \ . \tag{3}$$

TABLE XVIII. Primary $E2$ transitions in ^{136,138}Ba.

Final nucleus	Level (keV) populated	Photon energy (keV) Expected	Observed	Intensity (per $1000n$)	$\overline{B(E2)}\downarrow$ (e^2fm^4/MeV) Expt.	Calc.
^{136}Ba	1866.576(19)	7241.04(4)		<0.04	<3.1	83.8
	2053.876(20)	7053.77(4)	7053.75(24)	0.97(26)	175.0	83.8
^{138}Ba	2307.66(7)	6303.94(8)	6303.69(11)	0.40(5)	8.3	85.0
	2779.50(9)	5832.12(10)	5831.69(11)	0.93(9)	27.5	87.5
				Average	53±35	85

The enhancement of the isovector resonance is due to the effect of the exchange corrections.[34] Each of the contributions is given by[33]

$$\left\langle \frac{\Gamma_{\gamma_i}}{D} \right\rangle_{T=0,1} = 7.77\times10^{-12} E_\gamma^4 E_{0T}^2 C_T \frac{\Gamma_T}{(E_\gamma^2 - E_{0T}^2)^2 + \Gamma_T^2 E_\gamma^2} , \qquad (4)$$

where E_{OT} and Γ_T are the giant resonance energy and width, respectively, for isospin T. For $T=0$ and 1, $C=Z^2A^{-1/3}$ and $NZA^{-1/3}$, respectively. The E_0 and Γ_T were calculated from the mass number systematics compiled by Bertrand.[35] The $\overline{B(E2)}\downarrow$ values were determined using the theoretical $\langle \Gamma_{\gamma_i}/D \rangle_{\mathrm{GQR}}$ for each of the transitions. The average $\overline{B(E2)}\downarrow$ is 85 e^2fm^{4}MeV^{-1} which agrees within error with our experimental value of 53±35 e^2fm^{4}MeV^{-1}. The mean value of the experimental result, however, may also be in agreement with the finding of two surveys[1,36] in the past that note that the $E2$ strengths are on average lower by about a factor of 2 than the predictions based on the Axel-Brink[36,37] extrapolation.

V. CONCLUSIONS

A set of neutron separation energies has been determined for six isotopes of barium. Substantial improvement in precision is achieved. There is a general agreement in values with those of the literature for all but ^{137}Ba which is found to be 7 keV higher than the currently accepted value.[20] For these isotopes level energies have been deduced. The values for ^{137}Ba show significant deviation from those adopted in the latest compilation.[23] Others, in general, are in agreement with the literature. Evidences in the present study narrow down the possible spin of a level of ^{136}Ba at 3795 keV from 0(+)1,2,3(+) to 1,2. The more probable spin seems to be 1(−).

The magnetic strength functions of ^{136}Ba and ^{138}Ba have been determined. The value for ^{136}Ba agrees with the global average. The $M1$ strength function of ^{138}Ba is one-third the global average. This low value for ^{138}Ba is contrary to what is expected from the spin-flip model.[38]

Three primary $E2$ transitions are observed in ^{136,138}Ba and the upper limit for another $E2$ transition is determined. The quadrupole strength function of ^{136,138}Ba is found to be 0.6±0.4 times that expected on the basis of the giant quadrupole resonance model. Similar findings were reported in the past.[1,36]

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