Electric dipole and quadrupole ground state transitions in ^{138}Ba from ^{138}Ba(γ,γ) and ^{138}Ba(γ,γ')

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Twelve ground state transitions up to about 5 MeV have been observed by the resonant scattering of bremsstrahlung from natural barium. Six of the first seven lines are from 2^+ states in ^{138}Ba as evidenced by the angular distribution measurements and the correspondence of the energies with known levels in ^{138}Ba. Presumably these arise from proton configurations. Of the remaining five lines four have distributions expected for spin 1 levels. The linear polarization of the scattered radiation for the first of these, at 4027 keV, suggests a negative parity. It is likely that this state is derived from the superposition of the one phonon quadrupole and octupole transitions in ^{138}Ba. Comparison with the results of other studies indicates that the other three lines are from neutron particle-hole states in ^{138}Ba. Widths in terms of the ground state branching ratios and the partial widths for decays to the ground state are given for the identified levels.

[NUCLEAR REACTIONS ^{138}Ba(γ,γ), (γ,γ'); bremsstrahlung $E=1.5-5.1$ MeV; measured $\sigma(96°)$ and $\sigma(126°)$, LP; deduced J,π,Γ. Natural targets.]

The character of the low lying levels of ^{138}Ba have been investigated extensively through the inelastic scattering of protons[1] and α particles,[2] through the ($d,^3$He) reaction[3] and through electromagnetic decay in (β,γ) (Ref. 4) and (n,γ) (Ref. 5) experiments. Because of the closed neutron shell ($N=82$) these low lying levels are presumed to arise from proton configurations, i.e., protons moving in the $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, $s_{1/2}$, and $h_{11/2}$ orbitals outside the $Z=50$ closed shell. The results of the before mentioned experiments and shell model calculations confirm this picture up to about 3.6 MeV where the first neutron particle-hole state appears.

Transition strengths for many of the levels below 3.4 MeV have been extracted from the (p,p') (Ref. 1) and (α,α') (Ref. 2) experiments and the agreement between the two is good. $B(E2)$ values for the first 2^+ state as obtained from Coulomb excitation[6] and (e,e') (Ref. 7) studies are consistent with each other but significantly larger than those obtained from the charged-particle inelastic scattering measurements. This discrepancy is also true for the first 2^+ state of ^{144}Sm.[1]

Higher lying states in ^{138}Ba up to about 5 MeV, have been studied through the (d,p) reaction and by the inelastic scattering of protons through isobaric analog resonances.[8] In these latter measurements both proton and neutron particle-hole excitations can occur. The neutron particle-hole states will have negative parities and are expected to decay predominantly by electric dipole transitions; this suggests that 1^- states will show strong ground state transitions. The positive parity states arising from proton excitations are not expected to compete with the neutron particle-hole states in the higher energy region.

In addition to the negative parity neutron particle-hole states one may also have for vibrational nuclei a negative parity multiplet formed by the superposition of the one phonon quadrupole and octupole excitations.

The resonance fluorescence techniques is ideally suited for measuring the properties of ground state transitions from states of even-even nuclei with $J^\pi=1^\pm$ and 2^+. States with $J^\pi=2^-$ and $3^\pm$ or higher will not be observed in general; consequently many ambiguities are removed. Furthermore, the angular distribution of the radiation for dipole and quadrupole transitions to the ground state of even-even nuclei are unique and very different making the choice between the two possible spins a simple matter. For spin 1 states the selection of the parity can be made through the measurement of the linear polarization of the scattered radiation. The success of such measurements depends on the statistics; this limits the cases to rather strong ground state transitions.

In this paper we present the results of resonance fluorescence measurements on ^{138}Ba; a preliminary report on a few of the levels studied has already appeared.[9] A bremsstrahl beam with energies up to about 5 MeV was used as the source of exciting radiation. Since normal barium served as the scatterer an ambiguity exists as to the isotope responsible for some of the higher energy lines. For all the levels attributable to ^{138}Ba, spin and parity assignments were made, and the level widths were extracted using, generally, the branching ratio of others.

EXPERIMENTAL PROCEDURE

Much has been reported concerning the resonance fluorescence technique.[10-12] Involved in the present measurements were all of the various ramifications of the method necessary for extracting the parameters of nuclear levels. The source of existing radiation was the bremsstrahl beam produced by passing analyzed electrons from the Bartol Van de Graaff accelerator through a 35 mg cm^2 Au foil. Measurements of the scattered radiation were made using a 55 cm^3 and a 45 cm^3 Ge(Li) detector positioned at 96° and 126°, respectively, with respect to the incident photons. The scatterer consisted of 116.5 gm of $BaCO_3$ powder of normal isotopic abundance packed into a Lucite container 7.62 cm in diameter by 2.54 cm in depth.

The yield curve established previously for the studies of the levels in ^{59}Co (Ref. 11) was used in obtaining the scattering cross section. However, to assure that changes with time had not taken place, to remove the uncertainty at 4 MeV, and to calibrate the two detector system, several additional measurements were undertaken. The scattered radiation for the 1436 keV 2^+ state of ^{138}Ba was compared directly with that for the 1368 keV 2^+ state of ^{24}Mg using as the scatterer a disk of Mg 1 cm thick sandwiched with the $BaCO_3$ scatterer. The width of the 4087 keV 2^+ level of ^{208}Pb was measured in a self-absorption experiment and compared with the scattering results. Since it is highly probable that this level of ^{208}Pb decays predominantly to the ground state and since the angular distribution of the quadrupole radiation is known, this comparison results in a calibration of the two detectors. Finally, the scattering through the 3562 keV 0^+ state of ^{6}Li was observed; since the angular distribution of this radiation must be isotropic, a further check of the relative efficiency of the two detectors was obtained.

For the one case of the 4027 keV level of ^{138}Ba two additional measurements beyond that of simple scattering were made. First, a self-absorption experiment was performed. The absorber was a disk of metallic barium 4.45 cm in diameter by 1.148 cm thick; a tin absorber was used for comparison. In the second experiment, the linear polarization was measured using the two-slab Ge(Li) detector system described previously.[12]

RESULTS

Typical spectra for 96° and 126° scattering are given in Figs. 1 and 2. It is quite clear from the results of Fig. 1 that the angular distributions for the 3338 and 3365 keV lines are the same and very

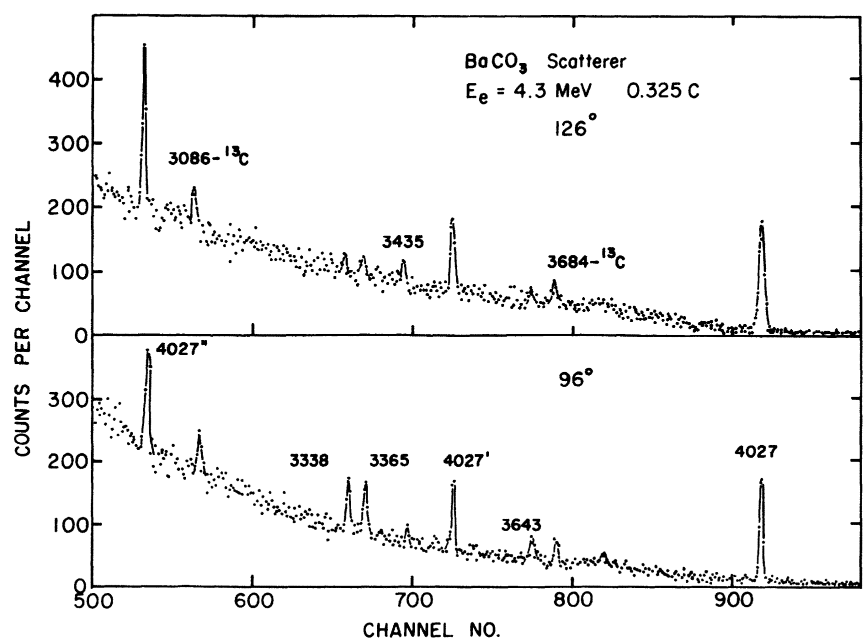

FIG. 1. Pulse height distributions for mean scattering angles of 126° and 96° as obtained with the 45 and 55 cm^3 Ge(Li) detectors, respectively. The end-point γ-ray energy was 4.3 MeV and the total electron charge was 0.325 C. The labeled lines in the 96° spectrum are from ^{138}Ba; those in the 126° spectrum are from ^{13}C and some other isotope of Ba. Note the difference in the distribution of the 3338 and 3365 keV doublet and the 4027 keV line.

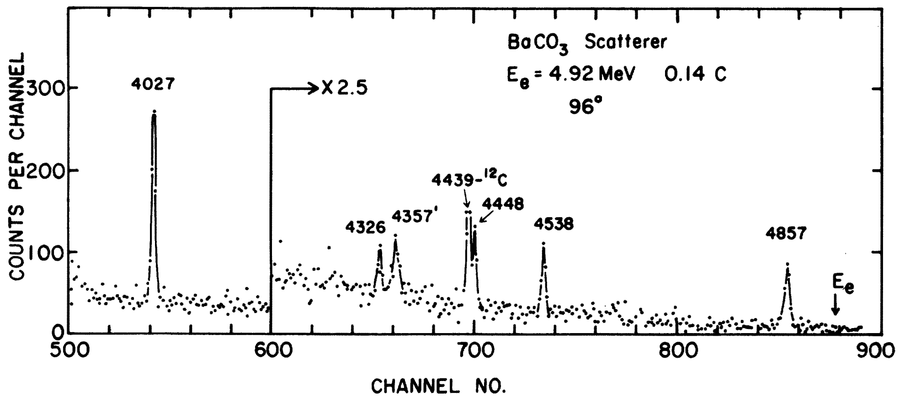

FIG. 2. Pulse height distribution for a mean scattering angle of 96° and an end-point energy of 4.92 MeV. All but the 4439 keV line are attributed to spin 1 levels in ^{138}Ba. The 4439 keV line is from ^{12}C.

different from that for the 4027 keV line. These are as expected for ground state transitions from spin 2 and spin 1 levels, respectively. The two lines labeled ^{13}C in Fig. 1 are the result of resonant scattering from the 1% of ^{13}C present in the carbon of the scatterer. The 4439 keV line seen in Fig. 2 is from the 2^+ state in ^{12}C.

The results of this investigation are summarized in Table I. Except for the 3435 keV line all the lines up to and including that at 3643 keV are clearly from ^{138}Ba as evidenced by the agreement with previous studies.[1,4] The origin of the 3435 keV line is not clear but is presumably from one of the other isotopes of barium. A level reported to be at 2190 keV from (n,γ) studies[5] with a spin of 1 or 2 and a ground state branching ratio of 32% was not observed in these studies nor in the (β,γ) (Ref. 4), (p,p') (Ref. 1), and (α,α') (Ref. 2) measurements. On the basis of the statistics our results give a limit on the partial width of 0.6 meV for decays to the ground state assuming a spin of 2. One may suggest that the 2190 keV level is an unnatural parity state, i.e., $J^\pi = 1^+$ or 2^-.

The relatively large width obtained for the 4027 keV level and the presence in the spectra of a line at 2591 keV, which results from a branching to the 1436 keV level, places this level in ^{138}Ba. The intensity of the 2591 keV line corresponds to a branching ratio of $(16 \pm 4)\%$. For the higher energy lines the conclusions are more speculative. The possibility of seeing branches to the 1436 keV level of ^{138}Ba from the 4448 and 4857 keV states was

TABLE I. Properties of states observed in barium.

E_γ [a] (keV)	$N_{SC}(126°)/N_{SC}(98°)$ [b]	A	J^π	Γ_0^2/Γ (meV)	Γ_0/Γ [c]	Γ_0 (meV)
1435.50(25)	0.51(5)	138	2^+	2.33(17)	1.00	2.33(17)
2218.0(10)	0.46(6)	138	2^+	4.02(41)	0.98	4.10(41)
2639.7(10)	0.79(23)	138	(2^+)	2.9(11)	0.89	3.3(12)
3338.4(15)	0.47(9)	138	2^+	12.3(14)	0.78	15.8(17)
3365.4(15)	0.49(8)	138	2^+	14.5(15)	1.00	14.5(15)
3434.7(15)	2.18(41)			$75(9)/ga$ [d]		
3642.7(15)	0.31(15)	138	2^+	7.5(8)	1.00	7.5(8)
4027.0(15)	1.28(7)	138	1^-	208(10)	0.58(9)	$360(^{+48}_{-33})$
4326(2)	1.22(19)	(138)	(1^-)	14.4(25)		
4448(2)	1.29(23)	(138)	(1^-)	43.5(66)		
4538(2)	1.20(20)			$32(4)/ga$ [d]		
4857(2)	1.50(22)	(138)	(1^-)	196(20)		

[a] The energies and uncertainties are based on: 1368.53(4)(^{24}Na) (Ref. 13), 1460.75(6)(^{40}K) (Ref. 13), 2614.47(10)(ThC″) (Ref. 13), 3562.0(10)(^{6}Li), and 4087.0(10)(^{208}Pb). The higher energies were obtained from the 4439 keV line of ^{12}C with the aid of the one and two escape peaks.

[b] This ratio should be 0.49 (1.33) for ground state transitions from spin 2 (spin 1) states in even-even nuclei.

[c] Branching ratios, except for the 4027 keV state, were taken from Ref. 4.

[d] $g = (2J_{ex}+1)/(2J_{g.s.}+1)$; a = isotopic abundance/0.717.

hampered by the presence of the two escape peaks from the 4027 and 4448 keV lines of ^{138}Ba and the 4439 keV line from ^{12}C. For the remaining two lines at 4326 and 4538 keV no such branching was observed.

As mentioned in the previous section additional measurements were made on the radiation from the 4027 keV state. The measurement of the linear polarization of the scattered radiation resulted in a value for $C_{\parallel} - C_{\perp}/C_{\parallel} + C_{\perp}$ of $(+4.50 \pm 2.88)\%$ which strongly suggests a negative parity for the state. The self-absorption experiment gave a value of $(37.7 \pm 3.7)\%$ for the absorption; this corresponds to the partial width for decays to the ground state as given in Table I. The value for Γ_0^2/Γ was obtained by comparing the scattering with that for the 4087 keV 2^+ state of ^{208}Pb. The self-absorption for this ^{208}Pb level resulted in a value for Γ_0 of 0.43 ± 0.03 eV and the value for Γ_0/Γ was taken as 1 on the basis of previous studies.[10] Γ_0/Γ for the 4027 keV level of ^{138}Ba therefore becomes 0.58. A comparison with the 16% observed branch to the 1436 keV, 2^+ level suggests additional branching to higher lying levels. The observation of these branch γ rays, however, would be impossible because of the relatively low energies and the high background resulting from the nonresonant scattering of the bremsstrahlung beam at these low energies.

DISCUSSION

A comparison of the present results for the transition rates with those of Coulomb excitation,[6] (p,p') (Ref. 1) and (α,α') (Ref. 2) experiments in terms of single particle units is given in Table II. The agreement with the Coulomb excitation result[6] for the first excited state is good. The charged particle studies give a significantly smaller value for this state, whereas for the higher lying 2^+ states the agreement is varied. The charged particle studies, however, give only the isoscalar part of the transition rate which is formally equal to the electromagnetic rate only for $N=Z$. To the extent that the vibrational collective model is a good description of ^{138}Ba the two should be equal; it is clear that this is not the case. For a more detailed discussion of this general problem, reference is made to the studies of Larson, Austin, and Wildenthal,[1] Barker and Hiebert,[2] and Bernstein.[14]

In Table III are shown the results of the calculation of Waroquier and Heyde[15] for the first three 2^+ states along with the experimental work. There is a question as to the second 2^+ state. Mariscotti *et al.*[5] report to have observed a spin 2 state at 2190 keV; however, as pointed out above no such level was observed in all the other studies. In Table III it has been assumed that the second and third 2^+ states are at 2218 and 2640 keV, respectively. The theory predicts a large enhancement for the $B(E2)$ of the first 2^+ state and much less strength for the second and third 2^+ states; also the prediction is for predominant ground state transitions for these latter two states. The experimental results show reasonable agreement with these predictions. This calculation performed in the framework of the BCS model and the shell model calculations of Larson *et al.*[16] only considers protons moving outside the $Z=50$ closed shell. States involving neutron excitations would not be predicted.

Inelastic proton scattering through isobaric analog resonances in neutron magic nuclei leads predominantly to neutron particle-hole excitations. Along with (d,p) studies one can extract information concerning the states observed. A comparison of states resulting from the decay of the $p_{3/2}$ and $p_{1/2}$ analog resonances, with $ln=1$ in the neutron transfer experiments[8] and observed in the present (γ,γ) measurements is given in Table IV. It appears very likely that the levels observed in the present study at 4027, 4326, 4448, and 4857 keV are the same as those seen in the reaction studies. These states are assumed to be, therefore, in ^{138}Ba, and on the basis of the angular distributions shown in Table I [and ln = odd in (d,p)]

TABLE II. Comparison of reduced transition strengths in single particle units with results of other studies.

E_γ (keV)	Coul. exc.[a] $G(E2)$	p,p' [b] $G(\mathrm{IS},2)$	α,α' [c] $G(\mathrm{IS},2)$	Present $G(E2)$
1436	10.4(4)	6.1	5.6	11.2(8)
2218		1.7	1.2	2.2
2640		0.2		0.7
3338		0.7	1.0	1.1
3365		1.0		1.0

[a]See Ref. 6. [b]See Ref. 1. [c]See Ref. 2.

TABLE III. Comparison of experimental $B(E2)$'s with calculation of Waroquier and Heyde for first three 2^+ states in ^{138}Ba.

E_γ (keV)	J^{π} [a]	Experimental $B(E2)\downarrow$ (e^2 fm^4)	Experimental Γ_0/Γ	Theoretical $B(E2)\downarrow$ (e^2 fm^4)	Theoretical Γ_0/Γ
1436	2_1^+	474	1.00	427	1.00
2218	2_2^+	94.5	0.98	48.1	0.96
2640	2_3^+	31.9	0.89	8.45	1.00

[a]It is assumed that the 2190 keV state designated as 2^+ by Waroquier and Heyde (Ref. 15) is not a 2^+ state.

TABLE IV. Comparison of the (p,p') analog resonance, (d,p) and (n,γ) results with the present observations for levels above 4 MeV.

(γ,γ) (keV)	(n,γ) [b] (keV)	$(d,p)(ln=1)$ [a] (keV)	(p,p') [a] $p_{3/2}$ [c] (keV)	$p_{1/2}$ (keV)
4027		4027	4027	
	4280	4279	4279	
4326	4325	4325	4325	
4448	4446	4445	4445	4445
4538	4536	4536		
	4564	4555		
		4571	4563	4563
	4645	4645	4652	4652
	4745	4737	4743	4743
	4799	4791	4791	4791
4857	4876	4863		4856
		5020		5030

[a] The energies given here were taken from Fig. 2 of Ref. 8. Those above 4.5 MeV are not all consistent with those of Ref. 18 which were obtained from a private communication.

[b] These energies were taken from Ref. 18.

[c] Levels which also show an $f_{7/2}$ component have not been listed since such levels would have J^π values resulting in level widths too small to be observed in the present experiments.

would have a 1^- character. Following the study of the systematics by Mudersback, Hensler, and Wurm[17] one suggests that the 4326, 4448, and 4857 keV states are rather pure neutron particle-hole states, the first two arising from the $p_{3/2}$ resonance and the last from the $p_{1/2}$ resonance. A second 1^- state resulting from the decay of the $p_{1/2}$ resonance would also be expected; however, no other lines were observed in the present studies up to 5.1 MeV.

The character of the 4027 keV, 1^- level appears to be quite different. This state is only weakly excited in the (d,p) and analog resonance experiments and is the lowest 1^- state in ^{138}Ba observed in this study. Pancholi and Martin[18] suggest a possible 1^- assignment for the 3503 keV state. However, no such line was observed in the present study, the observable limit for $g\Gamma_0^2/\Gamma$ being about 10 meV. Assuming that the 4027 keV line is from the lowest 1^- state in ^{138}Ba a comparison with the equivalent 1^- states in ^{140}Ce and ^{142}Nd at 3644 and 3426 keV, respectively, shows an energy shift as a function of Z which is quite different from that expected for a pure neutron particle-hole state.[17] It is probable that these states are members of the two phonon excitations resulting from the superposition of the first 2^+ and 3^- states. The energy of 4027 keV for the ^{138}Ba 1^- level is somewhat below the sum of $E(2_1^+)(1436\text{ keV}) + E(3_1^-)(2881\text{ keV})$ in agreement with the observation of Metzger[19] for other nuclei in this region. The value for $B(E1,1^- \rightarrow 0^+)/B(E1)_{\text{s.p.}}$ of $(3.04 \pm 0.42)\times 10^{-3}$ is also consistent with the results for ^{140}Ce and ^{142}Nd.[20]

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