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Evidence for an $M1$ giant resonance in ^{138}Ba†

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The $M1$ strength function was measured in ^{138}Ba at an excitation energy of approximately 8.6 MeV throughout the neutron energy region 9–60 keV using the threshold photoneutron technique. A method was developed for extracting the dipole strength even though the first excited state of the daughter nucleus, ^{137}Ba, is only 281 keV above the ground state. The photoneutron spectrum was measured at laboratory angles of 90° and 135° with high resolution (0.5 ns/m) using the time-of-flight spectrometer associated with the Argonne high current linac. The $M1$ strength function for ^{138}Ba was found to be anomalously large at 8.6 MeV. In addition, the $E1$ dipole strength function was estimated at this excitation energy.

[NUCLEAR REACTION $^{138}Ba(\gamma,n)$, $E=8.6$ MeV, measured $\sigma(E_n,\theta)$, deduced $\sum\Gamma_{\gamma 0}(M1)$ and $\sum\Gamma_{\gamma 0}(E1)$.]

I. INTRODUCTION

Recently, many studies[1] of radiative processes in the threshold region have been concerned with the search for giant $M1$ resonances. The interest in these studies arises from the possibility that $M1$ transitions may shed light on the spin-dependent effects in nuclei. For example, Mottelson has given[2] a simple explanation for the giant $M1$ resonance in terms of the spin-orbit interaction. He conjectures that an $M1$ giant resonance is due to transitions between the filled and empty members of a shell-model orbital split by the spin-orbit interaction. Such transitions should be favored in nuclei near closed shells where the splitting raises the empty member into the next major shell above the Fermi surface. There is evidence for this phenomenon in the case of ^{208}Pb. Bowman *et al.*[3] have observed considerable $M1$ strength at an excitation energy of 7.9 MeV using the threshold photoneutron technique. However, Toohey and Jackson[4] have demonstrated that those experimental results for the case of ^{208}Pb are, as yet, non conclusive. Gillet, Green, and Sanderson[5] and Vergados[6] have shown that the giant $M1$ state in ^{208}Pb can be explained by considering the spin-orbit splitting of the closed neutron shell, $i_{13/2}$-$i_{11/2}$, and the closed proton shell, $h_{11/2}$-$h_{9/2}$. Furthermore, one would expect similar giant $M1$ states to appear in ^{138}Ba since it is also a closed-shell nucleus in neutron number ($1h_{11/2}$ shell). In addition, the $2d_{5/2}$ and $1g_{9/2}$ proton orbitals are filled, while the $2d_{3/2}$ and $1g_{7/2}$ orbitals are vacant.

According to the shell-model calculations, the $M1$ giant resonance in ^{208}Pb is fragmented into two segments. Large concentrations of $M1$ strength are expected to occur at 7.5 MeV, while the weak component should appear at 5 MeV. A more recent shell-model calculation,[7] which utilizes a 2p-2h interaction for fragmenting the 1p-1h $M1$ giant resonance, shifts the centroid of the upper $M1$ excitation from 7.5 to 7.9 MeV. In addition, the 2p-2h mechanism causes the spreading width to increase from 0.2 to 0.4 MeV. Hence, it is possible for the upper segment of the $M1$ giant resonance to appear at a higher excitation energy than expected from the spin-orbit splitting alone.

Although the energy at which the $M1$ giant resonance should occur in ^{138}Ba is unknown, results from electron scattering measurements[8] indicate the presence of substantial $M1$ strength in other $N=82$ nuclei at an excitation of 9 MeV. The threshold photoneutron method should provide a powerful means for measuring the $M1$ strength in this energy region since the neutron binding energy in ^{138}Ba is 8.6 MeV. For these reasons, we have measured the energy spectrum of photoneutrons from the $^{138}Ba(\gamma,n)^{137}Ba$ reaction near threshold and at laboratory angles of 90° and 135°. We have used the threshold photoneutron facility associated with the Argonne high current linac. In addition, we have developed a new method for extracting dipole radiative strengths in the presence of photoneutron decay to the ground and first excited state of the daughter nucleus. This method will be shown to play an important part in deriving the ground state radiative $M1$ strength even though the first excited state in ^{137}Ba is only 281 keV above the ground state.

II. EXPERIMENTAL PROCEDURE

The essential features of the Argonne threshold photoneutron facility have been discussed[9] elsewhere and will only be summarized here. The neutron energies are determined with high resolution (0.5 ns/m) using the nanosecond time-of-flight spectrometer associated with the Argonne high current linac. An intense, pulsed beam of electrons with a precisely defined energy (20-A peak current and 4 nsec in duration produced at a repetition rate of 800 pps) is focused onto a 4-mm thick Ag converter. The electron beam is stopped in a 7.5-cm thick aluminum block which is electrically insulated from ground. The resulting current pulse provides a "time-zero" pulse for starting the time-of-flight system. The bremsstrahlung from the converter is allowed to irradiate a 1-cm thick target of ^{138}Ba, enriched to 99.9%, in the form of $^{138}Ba(NO_3)_2$.

The photoneutrons from the ^{138}Ba$(\gamma, n)^{137}$Ba reaction travel through two separate 10-m flight paths which are at laboratory angles of 90° and 135° with respect to the electron beam direction.

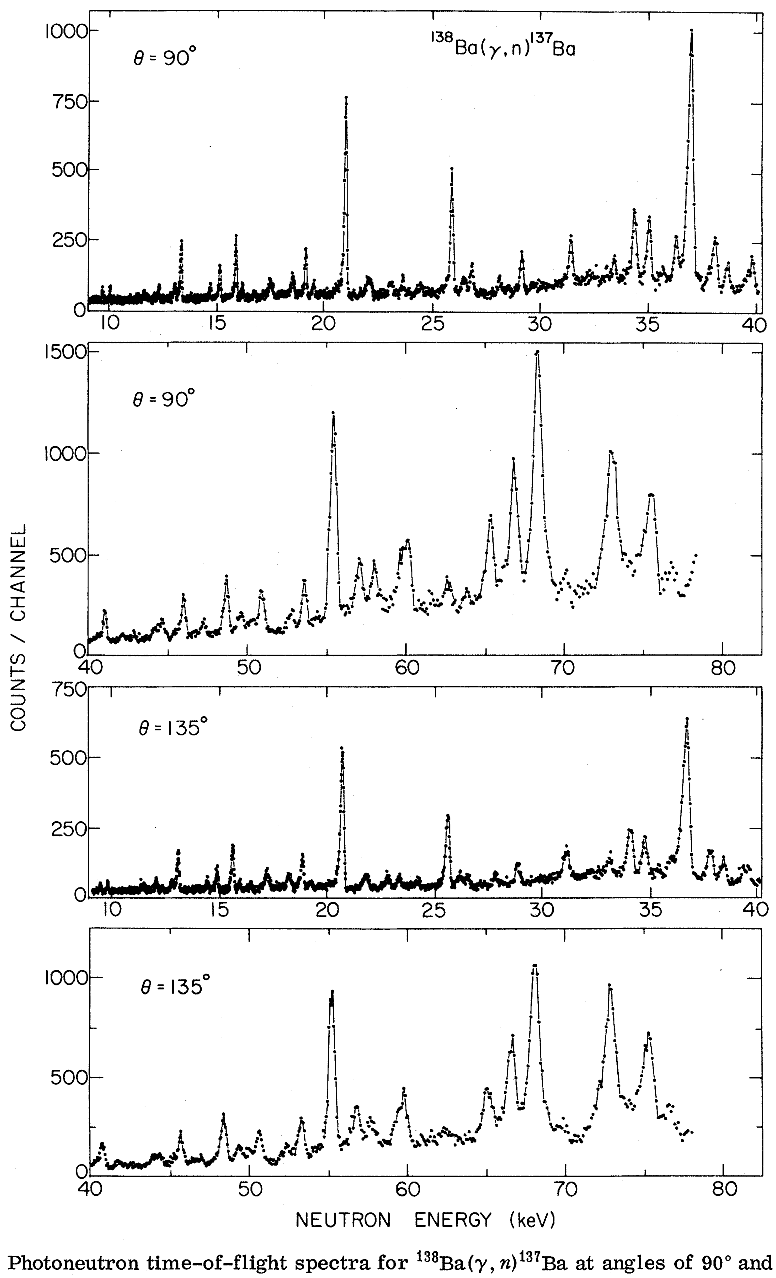

FIG. 1. Photoneutron time-of-flight spectra for ^{138}Ba$(\gamma, n)^{137}$Ba at angles of 90° and 135°.

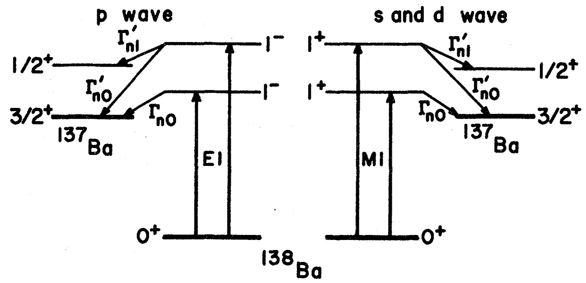

FIG. 2. Dipole photoexcitation of ^{138}Ba. The neutron decay can proceed by ground and first excited state transitions.

The neutrons are observed in an array of ^{6}Li-loaded glass detectors located at the end of each flight path. The neutron energies are determined by measuring the time interval between the time-zero pulse and the neutron detection in the ^{6}Li glass. The measured time-of-flight spectra at reaction angles of 90° and 135° are shown in Fig. 1. The ratio of the yield observed at 90° to that at 135° was calibrated with respect to the well-known 7.63-MeV state in ^{208}Pb. This level emits s-wave neutrons, and hence, provides a known isotropic angular distribution of 254-keV neutrons. The ^{208}Pb target was in the form of natural PbO with rectangular dimensions of 1 cm×5 cm×5 cm.

A schematic diagram of the photoexcitation process in ^{138}Ba is shown in Fig. 2. In the standard procedure for measuring threshold photoneutron spectra, the bremsstrahlung endpoint is adjusted so that the only neutron decay to the ground state of the daughter nucleus is possible. However, the first excited state of the daughter nucleus ^{137}Ba occurs at 281 keV above the ground state. Instead of adjusting the endpoint energy so that it is energetically impossible for neutron decay to the 281-keV state, in the present measurement the machine endpoint was raised in order to include transitions to this state. No attempt was made to distinguish the ground state and excited state transitions directly. Instead, the contribution to the radiative strength of transitions to the ground state was determined statistically in a manner described in the following section.

III. TREATMENT OF DATA

The spins and parities of the excited states were determined from the angular distributions of the photoneutrons by comparing the measured and calculated values of the ratio $R = \sigma(E, 90°)/\sigma(E, 135°)$ as a function of neutron energy. The expected values of R are given in Table I. Here, neutron transitions to the ground state and first excited state are summarized. Excited states which are induced by $M1$ and $E1$ photons decay by s- or d-wave neutrons and p-wave neutrons, respectively, where contributions from neutron decay with orbital angular momentum of 3 or larger have been ignored. If only $M1$ excitations are present and s wave is the dominant neutron decay mode, then the ratio R is expected to be 1.0. This approximation is good for emitted neutrons with energy less than 60 keV as shown in Fig. 3. The number of observed photoneutron resonances (Fig. 1) is plotted as a function of the angular distribution ratio R and in appropriate energy bins: 9–40 keV and 40–60 keV. s-wave neutron decay predominated the energy region 9–40 keV, and hence $M1$ excitations can easily be recognized in Fig. 3 as those producing isotropic neutron emission. In the energy region 40–60 keV, p-wave neutron decay becomes important and produces competition between $E1$ and $M1$ excitations.

For $E1$ excitations which undergo neutron decay to the ground state, the most probable value of R, deduced by assuming equal mixing of the two neutron channel spins in the final state, is expected to be 0.8. This value has indeed been observed in the 40–60-keV region as shown in Fig. 3. It should be pointed out that the $E1$ excitations ob-

TABLE I. Expected ratios of cross sections at 90° and 135° for the reaction ^{138}Ba$(\gamma, n)^{137}$Ba.

	Transition	Neutron decay	Multipolarity	$R \equiv \frac{\sigma(E, 90°)}{\sigma(E, 135°)}$	Comments
Ground state	$0^+ \to 1^+ \to \frac{3}{2}^+$	s wave	$M1$	1.0	Good for $E_n < 60$ keV
		s wave + d wave		$0.8 \le R \le 1.4$	
	$0^+ \to 1^- \to \frac{3}{2}^+$	p wave	$E1$	$0.67 \le R \le 1.0$	Important contribution for $E_n > 40$ keV
First excited state	$0^+ \to 1^+ \to \frac{1}{2}^+$	s wave	$M1$	1.0	At least a factor of 5 lower than ground state $M1$ strength
		s wave + d wave		$0.67 \le R \le 2.0$	
	$0^+ \to 1^- \to \frac{1}{2}^+$	p wave	$E1$	$0.67 \le R \le 2.0$	Most probable value of R is 1.2

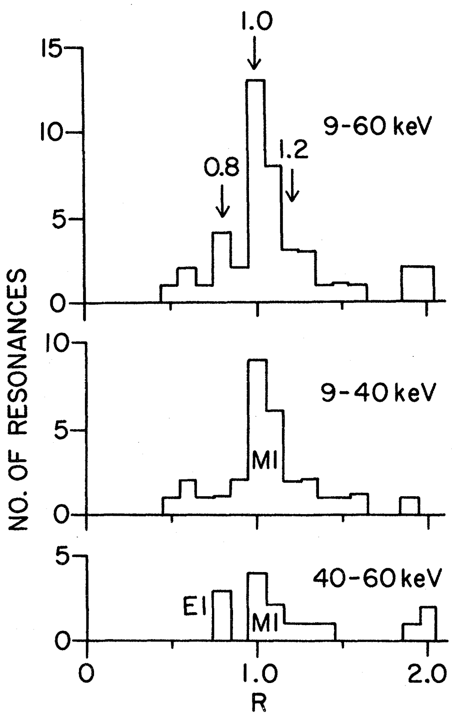

FIG. 3. The number of observed states plotted as a function of the angular distribution ratio.

served in this work are primarily characterized by neutron emission to the ground state. This is due to the fact that $\Gamma'_{n0} \gg \Gamma_{n0}$, Γ'_{n1} for p-wave neutron emission to the first excited state as shown in Sec. III. Here Γ'_{n0}, Γ_{n0}, and Γ_{n1} are neutron decay widths for the processes defined in Fig. 2. A value of 1.2 for the ratio R is expected for $E1$ excitations which decay to the excited state with equal mixing of the two possible p-wave channel spins in the final state. However, in the energy region 40–60 keV where the p-wave neutron decay width is expected to be comparable to the s-wave neutron decay width, no particular strength is observed at $R = 1.2$. At neutron energies above 60 keV, the energy resolution of the spectrometer becomes comparable with the average spacing of the states (~0.6 keV) and the individual states can no longer be resolved.

The neutron yield Y from a state of total width $\Gamma = \Gamma_{n0} + \Gamma_\gamma$ is given by

$$Y_0 = 2\pi^2 \lambda\!\!\!^{-}{}_0^2 g_J \Gamma_{\gamma 0} \Gamma_{n0} / (\Gamma_{n0} + \Gamma_\gamma) \,,$$

where $g_J = \frac{1}{2}(2J+1)/(2I+1)$ is the statistical factor. Here, $\Gamma_{\gamma 0}$ is the radiative width for direct γ-ray decay to the ground state, Γ_{n0} is the ground state neutron decay width, $\Gamma_\gamma = \sum_i \Gamma_{\gamma i}$, and λ is the reduced photon wavelength. However, in the present case there is also a yield which could appear at the observed neutron energy which is due to neutron decay to the first excited state (see Fig. 2):

$$Y_1 = 2\pi^2 \lambda\!\!\!^{-}{}'^2 g_J \Gamma'_{\gamma 0} \Gamma'_{n1} / (\Gamma'_{n0} + \Gamma'_{n'} + \Gamma'_\gamma) \,,$$

where Γ'_{n1} is the neutron decay width to the first excited state and Γ'_{n0} is the ground state neutron decay width from the more highly excited level. Hence, the total observed yield Y at a given neutron energy below 281 keV is merely the sum of the yields

$$Y = Y_0 + Y_1 \,.$$

An estimate of the contribution to the intensity of neutron decay to the ground state from the higher energy group of excited levels can be obtained by the following argument. Consider the ratio of the yields from this group to the group of ground state transitions

$$r = \frac{Y_1}{Y_0} = \frac{\Gamma'_{\gamma 0} \Gamma'_{n1}}{\Gamma_{\gamma 0} \Gamma_{n0}} \frac{(\Gamma_{n0} + \Gamma_\gamma)}{(\Gamma'_{n0} + \Gamma'_{n1} + \Gamma'_\gamma)} \,. \tag{1}$$

One can readily see from the last expression and Fig. 2 that the ratio r will be decreased by the presence of a large value of Γ'_{n0} in the denominator. It is expected that Γ'_{n0} will be larger than Γ_{n0} or Γ'_{n1} at a given neutron energy E_n by the factor $[(E_n + 281 \text{ keV})/E_n]^{1/2}$ for s-wave neutrons. That is, as the neutron energy E_n becomes smaller, then the ratio r also becomes smaller. An estimate of the average value of r was obtained in the neutron energy region 9–60 keV using a Monte Carlo analysis in which sets of the reduced widths of 1000 levels in Eq. (1) were chosen from a Porter-Thomas distribution. In this analysis, it was assumed[10] that

$$\langle \Gamma_\gamma \rangle = \langle \Gamma'_\gamma \rangle = 0.1 \text{ eV}$$

and

$$\langle \gamma_{n0}^2 \rangle = \langle \gamma'^2_{n1} \rangle = \langle \gamma'^2_{n0} \rangle = 5.0 \text{ eV} \,,$$

where the γ_{n0}^2, γ'^2_{n1}, and γ'^2_{n0} are the reduced widths associated with the neutron widths Γ_{n0}, Γ'_{n1}, and Γ'_{n0}, respectively. These assumptions are reasonable since the single-particle spreading widths[11] are of the order of a few MeV and the strength function is slowly varying over an energy interval of 300 keV. The neutron reduced widths were obtained from known strength functions and level spacings for $A = 138$, while the average ground state radiation width was determined from the present measurement.

Using this method, the average value of r was found to be 0.4 in the energy range 9–60 keV. Because of the shape of the bremsstrahlung spectrum, the photon intensity required to excite the high energy group of levels is only 1/1.7 as intense as that required for the lower energy group of levels.

Therefore, r is also diminished by a factor of 1.7, so that the true value of r is found to be 0.24. Hence, the yield of true ground state transitions observed in the present measurement is estimated to be 80% of the total observed yield. By randomly choosing the neutron reduced widths and the radiative width $\Gamma_{\gamma 0}$ from a Porter-Thomas distribution and using the analysis described in Ref. 12, the value $\langle \Gamma_{\gamma 0}\Gamma_{n0}/\Gamma\rangle/(\langle\Gamma_{\gamma 0}\rangle\langle\Gamma_{n0}/\Gamma\rangle)$ was found to be 0.8. Then the expression for the average $M1$ ground state radiation width becomes

$$\langle\Gamma_{\gamma 0}(M1)\rangle = \frac{\langle Y(M1)\rangle}{1+r}\langle\Gamma/\Gamma_{n0}\rangle/(1.6\pi^2 g_J \lambda\!\!\!^{-}_{M1}{}^2) . \quad (2)$$

The average radiation width for the γ-ray transitions to the states of energy $E+281$ keV is given by

$$\langle\Gamma'_{\gamma 0}(M1)\rangle = \langle Y(M1)\rangle B\frac{[r/(1+r)\langle\Gamma/\Gamma_{n0}\rangle]}{(1.6\pi^2 g_J \lambda\!\!\!^{-}_{M1}{}^2)} ,$$

where B is the bremsstrahlung shape factor and is 1.7 in this case. Here it is assumed that the yield is measured at a laboratory angle of 90°. A similar expression for the $E1$ ground state radiation width can be written

$$\langle\Gamma_{\gamma 0}(E1)\rangle = \frac{\langle Y(E1)\rangle}{1+r}\frac{\langle\Gamma'/\Gamma_{n1}\rangle}{(1.5\pi^2 g_J \lambda\!\!\!^{-}_{E1}{}^2)}\frac{4(1+\eta^2)}{3(1+\frac{7}{5}\eta^2)} ,$$

where η is the ratio of the amplitude for a p-wave neutron with channel spin = 1 to that with channel spin = 2. The above correction factor involving η arises from the fact that the $E1$ photoneutron yield has an angular dependence. In terms of the measured neutron angular distribution ratio for $E1$ photons, η^2 can be written

$$\eta^2 = \tfrac{3}{8}(3R_{E1}-2)/(1-R_{E1}) .$$

In the present case the most likely value of R_{E1} is 0.8 and hence, has a negligible effect on $\langle\Gamma_{\gamma 0}(E1)\rangle$. Finally, a similar expression can be obtained for the non-ground state neutron decay scheme. However, in this case the anisotropic neutron decay does not significantly affect the value of $\langle\Gamma_{\gamma 0}(E1)\rangle$ observed at an angle of 90°. In principle, the value of $\Gamma_{\gamma 0}$ can be determined from a measurement at a particular angle only after correcting for the nonisotropy in the angular distribution.

IV. RESULTS AND DISCUSSION

The reduced width for the electric dipole transitions was calculated from the expression[13]

$$\bar{k}_{E1} = \sum_{E1}\Gamma_{\gamma 0}/(E_\gamma{}^3 A^{2/3}\Delta E) \quad (3)$$

while the reduced width for magnetic dipole transitions was calculated[13] from

$$\bar{k}_{M1} = \sum_{M1}\Gamma_{\gamma 0}/(E_\gamma{}^3\Delta E) ,$$

where $\bar{k}$ is the average reduced width and ΔE is the energy interval in which states used in the analysis were found. Here, $\Gamma_{\gamma 0}$ is in eV while E_γ and ΔE are in MeV. In the present work, the neutron ground state and first excited state transitions were not individually sorted out. Instead, all observed $M1$ strength was integrated and corrected for non-ground state neutron decay according to expression 2. The amount of $E1$ strength which occurs in the angular distribution ratio range of 0.9 to 1.1, and hence represents a contamination of the true $M1$ strength, was found to be small. Using the average value of $E1$ strength found in the ratio intervals 0.5 to 0.9 and 1.1 to 2.0 (Fig. 3), the $E1$ contamination to the $M1$ strength was estimated to be 0.3 eV.

With the above corrections in mind, the value of the integrated $M1$ strength in the neutron energy range 9 to 60 keV was found to be $\sum\Gamma_{\gamma 0}(M1) = 3.0$ eV. Hence, the value of the $M1$ reduced width was calculated to be $\bar{k}_{M1} = 90 \pm 35\times 10^{-3}$. This value is considerably larger than the average reduced width[14] of 18×10^{-3} found for most nuclei in the atomic mass range $A = 80$ to 250. This anomalously large value of $\bar{k}_{M1}$ provides further evidence that an $M1$ giant resonance exists at an excitation roughly 9 MeV in the $N = 82$ nuclei.

Indeed, by assuming that this anomalous $M1$ strength is due to 1p-1h spin-flip excitations, it is possible to compute an upper limit for the integrated $M1$ strength. The ^{138}Ba nucleus is closed in neutron and proton number in the $1h_{11/2}$ and $2d_{5/2}$, $1g_{9/2}$ shells, respectively. The total $M1$ strength for ^{138}Ba can be calculated by assuming that the $M1$ spin-flip transitions proceed by $h_{11/2} \to h_{9/2}$, $g_{9/2}\to g_{7/2}$, and $d_{5/2}\to d_{3/2}$. The width of the $M1$ strength is related to the reduced matrix elements[15] by the expression:

$$\sum_{I_f a_f}\Gamma_{M1} = 0.011\,58 E_\gamma{}^3 \sum_{I_f a_f}\Lambda(M1) ,$$

where

$$\sum_{I_f a_f}\Lambda(M1) = \sum \mu\,|M^1_\mu\psi(^{138}\mathrm{Ba})|^2 .$$

I_f and a_f are the spins of the final particle states, μ is the projection of the final 1^+ state, and M^1_μ is the magnetic dipole operator. In terms of the proton and neutron contributions to the strength, the matrix elements become

$$|M^1_\mu\psi(^{138}\mathrm{Ba})|^2 = \tfrac{4}{3}B_{\pi d} + \tfrac{8}{3}B_{\pi g} + \tfrac{10}{3}B_\nu ,$$

where $B_{\pi d}$, $B_{\pi g}$, and B_ν are the reduced transition probabilities for protons in the d and g orbitals and neutrons, respectively. Hence, the integrated strength for ^{138}Ba is found to be

$$\sum \Gamma_{M1} = (28\ \text{eV})_{\pi d} + (54\ \text{eV})_{\pi g} + (36\ \text{eV})_\nu = 118\ \text{eV}\ .$$

This integrated value represents an upper limit and is not inconsistent with the observed $M1$ strength, 3.0 eV, over an energy range of 50 keV. The spreading width of single-particle states is expected to be the order of a few MeV. Furthermore, a width of approximately 1 MeV for the $M1$ state in $N = 82$ isotopes other than ^{138}Ba has been observed[8] using electron scattering techniques. If the 118 eV were assumed to be spread over a 1-MeV interval then one would expect ≈6 eV in the interval studied in this measurement. Thus our result exhausts half of the sum rule strength expected under such assumptions.

The contribution of the neutron excitation ($h_{11/2} \to h_{9/2}$) to the integrated strength is significantly larger than that of the proton transition ($d_{5/2} \to d_{3/2}$). This is primarily due to the fact that the population of neutrons in the $1h_{11/2}$ orbital and the number of vacancies in the $1h_{9/2}$ orbital is greater than the number of protons and vacancies in the $2d_{5/2}$ and $2d_{3/2}$ orbitals, respectively. In addition, the total $M1$ strength is sensitive[16] to isospin effects. For example, consider the role of protons and neutrons, separately, in the $1h_{11/2} \to 1h_{9/2}$ transitions. A $1h_{11/2}$ filled proton and a $1h_{9/2}$ vacant orbital can contribute $\sum \Gamma_{M1} = (52\ \text{eV})_\pi$ at most, while an analogous neutron configuration can contribute only $\sum \Gamma_{M1} = (36\ \text{eV})_\nu$.

In order to check the self-consistency of the measurements, the observed $E1$ strength was compared with the expected value. Axel has shown[17] that the electric dipole strength function is given by

$$\bar{\Gamma}/D = (6.1 \times 10^{-15}) E_\gamma{}^5 A^{8/3}\ .$$

In terms of the reduced width, this expression becomes

$$\bar{k}_{E1} = (6.1 \times 10^{-9}) E^2 A^2\ .$$

For the ^{138}Ba nucleus, the Axel formulation yields $\bar{k}_{E1} \times 10^3 = 9$. The integrated $E1$ strength in the energy region 9–60 keV was observed to be 2.1 eV. Using the method described in Sec. III, the neutron decay to ground state and first excited states were separated and the integrated radiation widths were found to be 3.3 and 6.0 eV, respectively. Using these values and Eq. (3), the average photon reduced widths for the ground state and first excited state neutron transitions were computed to be $\bar{k}_{E1} \times 10^3 = 4 \pm 1$. These results are in good agreement with other observations[18] which indicate that the Axel estimate consistently overestimates the reduced $E1$ width.

V. CONCLUSIONS

In conclusion, it has been demonstrated that the threshold photoneutron technique is a powerful method for extracting the dipole radiation strengths even in those cases where the first excited state of the daughter nucleus is near the ground state. In particular, the $M1$ strength from the ^{138}Ba(γ, n)-^{137}Ba reaction has been measured throughout the neutron energy interval 9–60 keV. The average photon reduced width was found to be more than four times the average value ($\bar{k}_{M1} \times 10^3 = 18$) for most nuclei. This anomalously large width provides evidence for a giant $M1$ resonance in ^{138}Ba at an excitation near 8.6 MeV.

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