MASTER

LOCATING GIANT RESONANCES WITH PHOTONEUTRONS

by

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Abstract: Recent studies of collective magnetic dipole resonances in heavy nuclei will be reviewed with an emphasis on photoneutron experiments. In particular, the nuclear mass regions of 120, 140 and 208 will be discussed in detail. New very high resolution photoneutron studies of ^{208}Pb will be presented. Applications of the photoneutron polarization method to the $^{208}\text{Pb}(\gamma, n_0)$, ^{207}Pb and $^{119}\text{Sn}(\gamma, n_0)$, ^{118}Sn reactions will be reviewed.

1. INTRODUCTION

Interest in the search for giant magnetic dipole resonances (GMDR) in heavy nuclei has been renewed recently. The level of enthusiasm can be gauged by the burgeoning collection of both experimental and theoretical studies of the GMDR region of ^{208}Pb . Since the next paper specifically treats the question of M1 excitations in the ^{208}Pb nucleus, I shall focus only on what we have learned from photoneutron experiments. The ^{208}Pb nucleus should provide an ideal demonstration of a GMDR since it is believed that both proton ($h_{11/2}^{-1} \rightarrow h_{9/2}$) and neutron ($i_{13/2}^{-1} \rightarrow i_{11/2}$) spin-flip transitions contribute. Theoretical calculations¹⁻⁵ place the isovector component of the GMDR between 7.5 MeV and 9.2 MeV of excitation. Moreover, interest in the M1 transition strength in ^{208}Pb was rekindled when Brown et al⁵ speculated that the resonance should occur at high excitation energy (~ 9.2 MeV) due to the effects of rho-meson exchange on the effective N-N potential. Experimentally, photoneutron, fast neutron capture and neutron scattering studies have provided more information concerning the GMDR in ^{208}Pb than any other reaction process. Unfortunately, there are very few studies

of other heavy nuclei in the mass regions of 90, 120, and 140, which also are expected to exhibit a GMDR. Of these cases positive evidence for a GMDR was reported only in the mass-140 region. The enhanced M1 transition strength in this mass region is believed to be due to $(g_{9/2}^{-1} \rightarrow g_{7/2})_{\pi}$, $(h_{11/2}^{-1} \rightarrow h_{9/2})_{\nu}$ and, possibly, $(d_{5/2}^{-1} \rightarrow d_{3/2})_{\pi}$ transitions. Mass-140 nuclei were studied in both inelastic electron scattering⁶ and photoneutron⁷ experiments. The mass-120 nuclei are particularly interesting since the GMDR would be predominately due to $(g_{9/2}^{-1} \rightarrow g_{7/2})$ proton spin-flip transitions. New photoneutron data for the $^{119}\text{Sn}(\gamma, n)^{118}\text{Sn}$ reaction will be presented in this discussion.

Most simply, a collective M1 resonance for a spin-zero nucleus, say, can be thought of as a combination of both proton and neutron spin-flip excitations. The wave function for the isovector component can be written as $|1^+\rangle_v = a|p^{-1}p\rangle - b|n^{-1}n\rangle$ and for isoscalar, $|1^+\rangle_s = a|p^{-1}p\rangle + b|n^{-1}n\rangle$, where $a^2 + b^2 = 1$. The reduced transition probability is then given by

$$B(M1; 1^+ \rightarrow 0^+) = \frac{\mu_o^2}{2\pi} \left\{ (g_{sp} - g_{lp}) \left[\frac{l_p(l_p+1)}{2l_p+1} \right]^{1/2} a + (g_{sn} - g_{ln}) \left[\frac{l_n(l_n+1)}{2l_n+1} \right]^{1/2} b \right\}^2$$

where l is the orbital angular momentum of the proton or neutron shell, g is the spin or orbital g -factor and μ_o is the nuclear magneton. Clearly, the M1 transition probability increases with l and one would expect heavy nuclei to have the strongest M1 excitations. In contrast, a single-particle M1 excitation does not have this l -dependence. For example, a single-particle neutron transition can be written as

$$B(M1, l - \frac{1}{2} \rightarrow l + \frac{1}{2}) = \frac{3\mu_o^2}{4\pi} (g_{sn} - g_{ln})^2 \left[\frac{l+1}{2l+1} \right]$$

and consequently, does not depend strongly on the neutron orbital. In addition, Bohr and Mottelson⁸ have provided a simple expression for predicting the excitation energy of the collective M1 resonance:

$$E_R = V_{so} \left[1 + \frac{k \sum}{V_{so}} \right]^{1/2}$$

where $k = 40/A$, V_{so} is the spin-orbit splitting in MeV, and

$$\sum = \frac{16}{3} \left[\frac{l_n(l_n+1)}{2l_n+1} + \frac{l_p(l_p+1)}{2l_p+1} \right]$$

The regions of expected enhanced M1 strength were calculated with this formula. These regions are shown as the shaded areas in fig. 1. The location of the E1 resonance is shown for reference. The

threshold photoneutron method should be ideal for studies of the GMDR since the neutron separation energy for many of these nuclei is near the expected energy of the GMDR.

Fig. 1. The expected excitation energies for the GMDR are shown as shaded areas. The curve represents the location of the E1 giant resonance.

2. GIANT M1 RESONANCE IN THE MASS-140 REGION

Thus far, evidence for the existence of a collective M1 resonance in heavy nuclei is most convincing for the mass-140 region. Broad resonances in Ce, La and Pr nuclei were first observed in inelastic electron scattering studies⁶ at excitation energies of 9 MeV and 12 MeV. These results are shown for Ce in fig. 2. At that time the multipolarities of these resonances were tentatively assigned as M1 at 9 MeV and M2 at 12 MeV. It is now believed that the 12-MeV resonance is a collective E2 excitation. The location and strength of the 9-MeV resonance are in good agreement with the prediction⁸ of the simple collective model. The threshold photoneutron method is ideal for investigating a possible M1 resonance centered at approximately 9 MeV, since the neutron separation energies in ¹³⁸Ba and ¹⁴⁰Ce are 8.58 MeV and 9.06 MeV, respectively. Both of these nuclei were studied⁷ at the Argonne threshold photoneutron facility. The parities of the levels were assigned on the basis of photoneutron angular distribution measurements.

Fig. 2. The results of an inelastic electron scattering experiment at Darmstadt for the mass-140 region. The arrow points to the location of the expected GMDR.

An electron accelerator of high current and a spectrometer of high resolution must be employed in order to study the angular distribution of individual levels in these nuclei. Fortunately, the neutron time-of-flight spectrometer and the Argonne high-current linac are ideal for this purpose. Typically, energy-analyzed electron pulses of 10-A peak current, 4-ns duration and 800 Hz repetition rate can be extracted from the ANL linac. The spectra observed for the $^{138}\text{Ba}(\gamma, n)^{137}\text{Ba}$ reaction are shown in fig. 3. The resolution of the spectrometer ranges between 30 eV and 300 eV in this energy region. Analysis of the data was restricted to that below 60 keV since the resolution of the

Fig. 3. High resolution photoneutron spectra for the $^{138}\text{Ba}(\gamma, n)^{137}$ reaction at 90° and 135° .

spectrometer is comparable with the level spacing at this energy. In the ^{138}Ba and ^{140}Ce nuclei M1 excitation decay by s-wave neutrons and E1 resonances, by p-wave neutrons. Thus the signature for an M1 excitation is an isotropic angular distribution. Assuming equal mixtures of the two p-wave channel spins, the most likely angular distribution ratios, $R \equiv \sigma(90^\circ) / \sigma(135^\circ)$, for E1 excitations are 0.8 for neutron decay to the ground state and 1.2 for transitions to the first excited state. A total of 44 resonances in ^{138}Ba were analyzed between $E_n = 9$ and 60 keV. The number of observed resonances is plotted as a function of the angular distribution ratio in fig. 4. Clearly, a relatively large number of resonances exhibit an isotropic angular distribution. Since only a small energy interval could be spanned with this method, the criterion for enhanced M1 strength was the magnitude of the average M1 photon reduced width k_{M1}^2 .

Fig. 4. The number of resonances observed in the $^{138}\text{Ba}(\gamma, n)^{137}\text{Ba}$ reaction as a function of the angular-distribution ratio.

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

where $\sum_{M1} \Gamma_{\gamma 0}$ is the sum of the observed ground-state radiative

widths in the energy interval ΔE . Bollinger⁹ has shown that $\bar{k}_{M1} \approx 18 \times 10^{-3}$ for most nuclei. If we assume that this value represents an M1 "background" level in nuclei, then a value of $\bar{k}_{M1}$ which is significantly larger than the background value would satisfy our criterion for enhanced M1 strength. For ^{138}Ba the value of $\bar{k}_{M1}$ was found to be approximately four times greater than the background level. In the case of ^{140}Ce the reduced width was observed to be twice the background value. Clearly, the photoneutron studies are consistent with a collective M1 resonance in the mass 140 region. This is the only situation in heavy nuclei where two independent experiments involving different reaction processes show a positive indication of a GMDR.

3. STUDIES OF M1 EXCITATIONS IN ^{208}Pb

3.1 THRESHOLD PHOTONEUTRON POLARIZATION STUDIES IN ^{208}Pb

There is great interest in the search for a collective M1 resonance in ^{208}Pb at many laboratories. Later in this session S. Raman will be speaking in detail on this subject, thus I shall focus only on the photoneutron experiments. Evidence for a giant M1 resonance in ^{208}Pb was first reported¹⁰ by the

Livermore photoneutron group. The alleged group of M1 resonances was centered at approximately 7.9 MeV and exhausted more than half of the sum rule. The spins and parities of the resonances were assigned on the basis of the observed photoneutron angular distribution ratios. Later, Toohey and Jackson¹¹ demonstrated that J^π could not be assigned uniquely in ^{208}Pb solely from measurements of the angular distributions. Consequently, at Argonne we observed¹² the polarization of photoneutrons from resonances near threshold in ^{208}Pb . The advantages of observing the photoneutron polarization can be seen by considering the expression for the differential polarization¹³ for the $^{208}\text{Pb}(\gamma, n_0) ^{207}\text{Pb}$ reaction:

$$\frac{d\vec{p}}{d\Omega} = \hat{k} \hat{\lambda}_\gamma^2 \left\{ \begin{aligned} & \left[-0.325 a_s(E1) a_{po}(M1) \sin\Delta_{spo} + 0.230 a_s(E1) a_{p1}(M1) \right. \\ & \quad \left. \sin\Delta_{spl} \right. \\ & \quad \left. -0.230 a_d(E1) a_{po}(M1) \sin\Delta_{dpo} - 0.325 a_d(E1) a_{p1}(M1) \right. \\ & \quad \left. \sin\Delta_{dpl} \right] \sin\theta \\ & \left. -0.199 \left[a_s(E1) a_d(E1) \sin\Delta_{sd} + a_{po}(M1) a_{p1}(M1) \sin\Delta_{popl} \right] \right. \\ & \quad \left. \sin 2\theta \right\} \end{aligned} \right.$$

Here, $\hat{k}$ is a unit vector which is perpendicular to the reaction plane, $a_{\ell s}(M1)$ are the reaction amplitudes for the emission of a photoneutron of orbital angular momentum ℓ and channel spin s . It is clear from the above expression that an E1-M1 interference gives rise to an angular dependence of $\sin(\theta)$, whereas an E1 or M1 excitation leads to a $\sin(2\theta)$ dependence. However, we make the observation that Δ_{popl} , the nonresonant phase difference for p-waves, is approximately zero; $\Delta_{popl} = \phi_{p0} - \phi_{p1} \approx 0$. If the nonresonant phase shifts are approximated by hard-sphere shifts, then $\Delta_{popl} = 0$. With this approximation the differential polarization for dipole photoexcitation becomes:

$$\frac{d\vec{p}}{d\Omega} \approx \hat{k} \hat{\lambda}_\gamma^2 \left\{ \begin{aligned} & \left[-0.325 a_s(E1) a_{po}(M1) \sin\Delta_{spo} + 0.230 a_s(E1) a_{p1}(M1) \right. \\ & \quad \left. \sin\Delta_{spl} \right. \\ & \quad \left. -0.230 a_d(E1) a_{po}(M1) \sin\Delta_{dpo} - 0.325 a_d(E1) a_{p1}(M1) \right. \\ & \quad \left. \sin\Delta_{dpl} \right] \sin\theta \\ & \left. -0.199 a_s(E1) a_d(E1) \sin\Delta_{sd} \sin 2\theta \right\} \end{aligned} \right.$$

The angular dependence of the photoneutron polarization provides a signature for the multipolarity of the excitation. A pure M1

excitation gives no polarization, a pure E1 resonance gives rise to a $\sin^2(\theta)$ angular dependence and interfering E1 and M1 excitations lead to a $\sin(\theta)$ dependence. In a region where only dipole radiation is a consideration a measurement of the photoneutron polarization at only two angles, $\theta=90^\circ$ and 135° , is necessary in order to determine the multipolarity of the photoexcitation process. It should be emphasized that an E1-E2 interference effect can give rise to $\sin(\theta)$ and $\sin^2(\theta)$ terms in the polarization and in some cases cannot be distinguished from an E1-M1 interference by observing the polarization at only two angles.

Ninety-six percent of the M1 strength reported by Livermore was thought to occur in five levels at $E_n = 180, 314, 610, 647$ and 838 keV. Unfortunately, no single polarimeter can span this entire energy range. Consequently, a variety of analyzing targets was used for these experiments. Photoneutrons were scattered from natural Mg in the energy region 170-320 keV and from ^{160}Gd between 500 and 1200 keV. Above 1.5 MeV a carbon scatterer was employed. A schematic diagram of the Argonne threshold photoneutron facility¹⁴ and polarimeter system is shown in fig. 5.

Fig. 5. Schematic diagram of threshold photoneutron facility and polarimeter system at the Argonne National Laboratory.

The energy-analyzed electron beam from the linac was converted to bremsstrahlung in a Ag target. The partially polarized photoneutrons from the $^{208}\text{Pb}(\gamma, n_0)^{207}\text{Pb}$ reaction traveled through two well-collimated flight paths, approximately 10-m in length, which were at angles of 90° and 135° with respect to the photon beam axis. A neutron spin-precession solenoid was placed along each flight path in order to minimize the effects of false asymmetries. The neutron spin-precession method is compatible with a continuous energy spectrum of photoneutrons. The neutrons which scattered at angles of $\pm \theta$ from the analyzing target were detected in plastic scintillators. The neutron energies were observed with high resolution using the time-of-flight method. The first spectra observed with the newly developed polarimeter system are shown in fig. 6.

Fig. 6. The two lower panels illustrate the raw time-of-flight data for the $^{208}\text{Pb}(\gamma, n)^{207}\text{Pb}$ reaction at an angle of 135° and after the photoneutrons are scattered from an ^{16}O analyzer. Both cases of the spin-precession solenoidal field are demonstrated. The final measured photoneutron polarizations are shown in the upper panels.

The two lower panels of fig. 6 show the raw time-of-flight spectra from the $^{208}\text{Pb}(\gamma, n_0)^{207}\text{Pb}$ reaction at 135° after the neutrons scatter from an ^{160}Gd analyzer at angles of $\pm 50^\circ$. The resonance energies are shown in units of keV and the energy scale was calibrated to that of ref. 11. The final polarizations at 90° and 135° are shown in the upper panels. Clearly, all of the resonances except for those at 603, 613 keV exhibit a $\sin(2\theta)$ dependence, and consequently, are E1 excitations. The only resonance in this energy region which could have a large $\Gamma_{\gamma 0}$ and a 1^+ assignment occurs near 600 keV. Indeed, this result was contrary to the Livermore findings. In order to complete the investigation of the alleged giant M1 resonance region of ^{208}Pb , the polarization method was applied to the low energy region where the 180- and 314-keV resonances were believed to be M1 excitations. The results are shown in fig. 7.

Fig. 7. The photoneutron polarization results obtained by using a natural Mg analyzer.

The photoneutron polarizations for the 180-, 254- and 314-keV resonances exhibit the angular dependence characteristic of E1 excitations.

It has long been believed that the 254-keV resonance is 1^- . Unfortunately, direct assignment of this resonance from neutron total cross section work was hindered by the presence of a large amount of s-d-wave mixing in the neutron channel. The s-d-wave admixtures are responsible for the large amount of photoneutron polarization at 135° which was observed¹⁵ at 180 keV and 254 keV. This finding has been confirmed by studies¹⁶ of neutron total cross sections. Consequently, of the alleged 1^+ -resonances with large $\Gamma_{\gamma 0}$ only the 610-keV resonance remains as a candidate for an M1 assignment in the energy region 180 to 1000 keV. The region near 600 keV was investigated in much greater detail and will be discussed later.

3.2 HIGH-RESOLUTION PHOTONEUTRON ANGULAR DISTRIBUTION STUDIES IN ^{208}Pb

In addition to the photoneutron polarization measurements, we observed the $^{208}\text{Pb}(\gamma, n_0)^{207}\text{Pb}$ reaction with extremely high resolution using the unique 35-ps wide electron-pulse mode available at the Argonne high-current linac and the newly-installed 25-m neutron flight paths. The resolution of the time-of-flight spectrometer ranged between 0.18 keV at $E_n = 180$ keV and 1.5 keV at 1000 keV. The objectives of this high-resolution study were (i) to resolve fine structure, particularly in the vicinity of the 610-keV resonance, (ii) provide values of ground-state radiation widths which are calibrated to the well-known $D(\gamma, n)H$ cross section, and (iii) deduce accurate angular distribution ratios. These new data are shown in fig. 8. The energy region near 600 keV, illustrated in the inset figures, is of particular interest since the photoneutron polarization results have indicated the presence of a candidate for an M1 excitation. The first observation from this data is that only two resonances with significant ground-state radiation widths exist in this region. These resonances are located at 600 and 610 keV. Another important finding is that the ground-state radiation widths for these two resonances are approximately half of the previously believed¹¹ values. The new radiation widths are compared with previous photoneutron experiments^{10,17} in table 1 for a few selected resonances. Only the latest results from Argonne are given in the table. The present results appear to be in agreement with the Livermore and Toronto experiments except near 600 keV where the Toronto measurement is ~50% larger. The angular distribution ratios for the three independent photoneutron experiments are in good agreement. Below 300 keV the ground-state radiation widths were determined in a separate experiment which employed ^6Li -loaded glass detectors. The widths were found to be approximately 65% of the values deduced from neutron capture studies¹⁸ at Oak Ridge. The widths for 1^+ resonances near 125 keV are given in table 2. The tendency to overestimate the ground-state radiation widths in neutron capture experiments is also prevalent above 300 keV.

Table 1

Comparison of present work with other measurements for selected resonances

E_n (keV)	Argonne		Toronto		Livermore	
	R	$\Gamma_{\gamma 0}$ (eV)	R	$\Gamma_{\gamma 0}$ (eV)	R	$\Gamma_{\gamma 0}$ (eV)
313.7	1.15	6.4	1.10±0.07	7.0	1.12±0.16	6.7
600	1.46	5.0	1.60±0.17	21.2	1.81±0.25	12.8
610	1.57	8.9				
647	1.20	6.9	1.24±0.22	6.7	1.26±0.18	5.5

Table 2

Comparison of present work with that of Oak Ridge for 1^+ resonances near 125 keV.

E_n (keV)	Argonne $\Gamma_{\gamma 0}$ (eV)	ORNL $\Gamma_{\gamma 0}$ (eV)
88.8	1.30	2.01
113.3	1.13	1.55
125.8	1.37	2.59
128.1	0.76	0.95
153.1	0.46	0.66
Total	5.02	7.76

Fig. 8. Very-high resolution photoneutron angular-distribution observation for ^{208}Pb .

The photoneutron polarization results can be described with a simple two-level R-matrix analysis in which the 600-keV resonance is assumed to be E1 and the 610-keV level, M1. However, Horen et al.¹⁹ demonstrated that the J^π assignment by the polarization method may not be unique if there are small "hidden" non-E1 resonances in the energy region of interest. The 610-keV resonance was assigned 1^- in ref. 19 on the basis of the angular distribution for the $^{207}\text{Pb}(n,n)^{207}\text{Pb}$ reaction and by coordinating the energy scale with that of the (γ,n) or (n,γ) work. This method is somewhat indirect. It is difficult, if not impossible, to verify the uniqueness of a multi-level R-matrix analysis when the level density is high. Furthermore, the assignment of ref. 19 also hinged on the determination of the absolute energy scales to less than a half-keV. Although, that work presented a strong argument for an E1 excitation at 610 keV, it fell short of removing all skepticism.

The present high-resolution measurements show unambiguously and directly that the 600- and 610-keV resonances must have the same spin and parity, and consequently, must be E1 excitations. The observed cross section at 90° near 600 keV is shown in fig. 9.

Fig. 9. Cross section for the $^{208}\text{Pb}(\gamma, n)^{207}\text{Pb}$ reaction at 90° and in the vicinity of the $E_n=600$ - and 610-keV resonances. The solid curve represents the analysis when the two resonances are E1 excitations, while the dashed curve is the result when the 610-keV level is assumed to be M1.

The enhanced cross section between the two large levels is due to constructive level-level interference. The solid curve in the figure is a fit to the high resolution data assuming that the 600-keV levels are E1 in nature. This interference effect vanishes if the 610-keV resonance is assumed to be M1. (See the dashed curve in fig. 9). In order to predict the observed angular distribution ratio an E2 resonance²⁰ with $\Gamma_{\gamma 0} = 0.4$ eV was placed at 610.8 keV. Since the 610.8-keV resonance is not directly observed in the (γ, n) data, the parameters for this resonance, including $\Gamma_{\gamma 0}$, are unknown. It also appears that more than three levels are required to interpret the polarization data at 90° in this energy region. Consequently, no attempt was made to explain the polarization at 90° . However, the polarization at 135° is dominated by the two large E1 levels, and the calculated polarization at this angle agrees very well with the observations. (See fig. 10). It now appears that no strong M1 excitation occurs below 8.4 MeV in ^{208}Pb . As yet, no evidence for a strong M1 excitation above 8.4 MeV has been reported.

Fig. 10. Photoneutron polarization for the $^{208}\text{Pb}(\gamma, \bar{n}_0)^{207}\text{Pb}$ reaction at 135° . The curve is the prediction based upon the R-matrix analysis of the high-resolution (γ, n) cross sections. The analysis assumes that the two major levels in this region are E1 excitations. The arrows point to the locations of the levels in this analysis.

3.3 EVIDENCE FOR M1 EXCITATIONS IN ^{208}Pb ABOVE 8.4 MeV

We speculated that if a collective M1 resonance exists in ^{208}Pb , it must lie outside this energy interval— $E_{\text{exc}} = 7.4$ to 8.4 MeV. Consequently, we adapted²¹ the threshold photoneutron polarimeter to be useful at higher energies in order to study the region from 8.4 MeV to 10 MeV. It is now becoming evident²² from elastic scattering of polarized bremsstrahlung at Urbana that there is very little M1

strength below 7.4 MeV. Above 8.4 MeV in ^{208}Pb individual resonances can no longer be resolved. In this energy range we looked only for E1-M1 interference patterns i.e. a nonzero polarization of photoneutrons emerging from the target at a reaction angle of 90° . The results of this experiment are shown in fig. 11.

Fig. 11. Photoneutron polarization results above 8.4 MeV in ^{208}Pb . The lower panel illustrates the analyzing powers of the targets employed in this energy range. The central panel shows the final polarization results at $\theta=90^\circ$. The upper panel demonstrates the quality of the raw time-of-flight data. The symbol x represents the observed background level.

The raw time-of-flight spectra after the photoneutrons scattered from either ^{16}O or natural C are shown in the top panel. Three different electron end-point energies were used in order to eliminate effects of non ground-state photoneutron transitions. The lower panel illustrates the analyzing powers of the scatterers used in this measurement. The final deduced polarization are shown in the central panel. Indeed, there are many regions which show a nonzero polarization. The lines in this figure indicate the regions of significant photoneutron polarizations. This is a definite indication of non E1 strength. Of course, since the level structure is not fully resolved and since the photoneutron polarization was observed at

only one angle. One cannot distinguish whether the polarization is due to E1-M1 or E1-E2 interference. Most importantly, these data illustrate the potentially most fruitful locations for future searches for M1 excitations in ^{208}Pb . If we assume that the polarization is due to E1-M1 interference, then a lower estimate for the M1 strength between 8.4 and 9.5 MeV is 15% of the sum rule. The collection of small 1^+ states at 7.63 MeV comprises approximately, 10 % of the sum rule.

4. SEARCH FOR COLLECTIVE PROTON SPIN-FLIP TRANSITIONS IN THE MASS-120 REGION

In the mass-120 region the GMDR would primarily be due to $g_{9/2}^{-1} \rightarrow g_{7/2}^{-1}$ proton spin-flip transitions. Photoneutron experiments²³ at Harwell indicated that a broad (~ 400 keV) resonance structure occurs at an excitation energy of approximately 7.8 MeV in both ^{119}Sn and ^{117}Sn . Moreover, Axel et al²⁴ observed evidence for intermediate structure in the even-A Sn isotopes in this excitation region with the photon elastic scattering method. These findings might lead one to speculate that the resonance structures are giant M1 resonances. However, the collective spin-flip model of Bohr and Mottelson⁸ would place the GMDR at a somewhat higher energy, approximately 10 MeV, in the mass-120 region. Nevertheless, it would be interesting to study these broad peaks in greater detail. First, the cross section was observed for ^{119}Sn at both 90° and 135° in order to verify the existence of the prominent peaks. Indeed, a relatively broad resonance structure centered at ~ 7.6 MeV was observed in ^{119}Sn . (See the lower panel of fig. 12). This group of resonances was found to be significantly smaller in cross section than the Harwell data. This discrepancy could be due to difficulties at Harwell in using natural Sn targets as already discussed in ref. 25.

If we assume, for the moment, that this peak is the giant M1 resonance, then the ground state radiation width can be deduced to be ~ 19 eV. This almost exactly exhausts the M1 sum rule. Thus, the broad resonance cannot be eliminated as an M1 excitation on the basis of radiative strength. Rather, we have chosen to observe the photoneutron polarization in the $^{119}\text{Sn}(\gamma, n)^{118}\text{Sn}$ reaction in the vicinity of the broad resonance and at a reaction angle of 90° . In a manner analogous with the case of ^{208}Pb , a nonvanishing polarization at 90° would be the signature for E1-M1 or E1-E2 interference. The observed polarization is shown in the upper panel of fig. 12.

Fig. 12. Present observations of the cross section at 90° for the $^{119}\text{Sn}(\gamma, n)^{118}\text{Sn}$ reaction. The upper panel shows the photoneutron polarization for this reaction. The two curves represent the polarizations expected if the resonance structure is assumed to be the GMDR.

The polarization is consistent with zero in the resonance region. The gap near $E_n = 1.0$ MeV is a consequence of the analyzing power of ^{160}Gd traversing through zero.

Although no polarization was observed, it is informative to estimate the amount of polarization one would expect to observe if the resonance structure were M1 in nature. In order to perform this estimate we assume: (i) the broad peak near 7.6 MeV is a collective M1 resonance, (ii) the background cross section underlying the resonance is E1 in nature, and (iii) the nonresonant phase shifts can be represented approximately by hard-sphere phase shifts. The expression for the differential polarization at 90° becomes:

$$\frac{dp}{d\Omega} = \frac{3}{32} \lambda_Y^2 \left\{ \left[1.33 a_{p1/2}(E1) - 0.67 a_{p3/2}(E1) \right] a_{s1/2}(M1) \sin\Delta_{sp} - \left[0.67 a_{p1/2}(E1) + 2.67 a_{p3/2}(E1) \right] a_{d3/2}(M1) \sin\Delta_{dp} \right\}$$

The observed angular distribution ratios for the E1 background and the tentative M1 resonance provide limits for the ratios of the amplitudes. For the E1 background, $R = 1.26$ and for the resonance, $R = 1.6$. Thus, $a_{p1/2}/a_{p3/2} = -0.15$ or 6 and $a_{s1/2}/a_{d3/2} \ll 1$. Then for $a_{p1/2}/a_{p3/2} = -0.15$ the absolute polarization can be shown to be

$$|P_1| = 1.5 \left[\frac{d\sigma}{d\Omega} (E1) \frac{d\sigma}{d\Omega} (M1) \right]^{1/2} \left[d\sigma/d\Omega \right]^{-1} \sin \Delta_{dp}$$

and for $a_{p1/2}/a_{p3/2} = 6$:

$$|P_2| = 0.63 |P_1|$$

where $\frac{d\sigma}{d\Omega} (E1)$ and $\frac{d\sigma}{d\Omega} (M1)$ are the differential cross sections

for the E1 background and M1 resonance, respectively. These two cases are represented by the curves in fig. 11. Within the framework of this estimate and the observed polarization only $\sim 25\%$ of the ground-state radiative strength in this resonance could be M1, or $\Gamma_{\gamma 0}(M1) \sim 5$ eV. This is four times smaller than the M1 sum rule for $g_{9/2}^{-1} \rightarrow g_{7/2}$ proton spin-flip transitions. We conclude from this study that the broad resonance structure in ^{119}Sn is photoexcited predominately by E1 radiation. Future studies of the mass-120 region should include the excitation region between 9 and 10 MeV in accord with the prediction of the simple collective model.

5. CONCLUSIONS

The evidence for a collective M1 resonance is best established in heavy nuclei for the mass-140 region. Here, the inelastic electron scattering and photoneutron experiments are in agreement. The excitation energy and reduced transition probability of the GMDR in ^{140}Ce are in good agreement with the predictions of Bohr and Mottelson. The 610-keV resonance in ^{208}Pb , previously believed to be an M1 excitation, was shown directly to be an E1 excitation. No large M1 excitations have been found in ^{208}Pb . The collection of small M1 excitations near 7.63 MeV were found to represent only 10% of the M1 sum rule. The M1 strengths were found to be only 65% of the values determined from neutron capture work. The polarization data chart locations between 8.4 and 9.5 MeV where future studies might focus. The absence of a strong M1 excitation in ^{208}Pb opposes every theory. Finally no evidence was found for a GMDR in the $^{119}\text{Sn}(\gamma, n)^{118}\text{Sn}$ reaction. The photoneutron polarization method was applied to the study of the region of intermediate structure in the ^{119}Sn nucleus near $E_{\text{exc}} = 8$ MeV. This resonance structure was found to be predominately E1 in nature.

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REFERENCES

- ¹J. D. Vergados, Phys. Lett. 36B (1971) 12.
- ²P. Ring and J. Speth, Phys. Lett. 44B (1973) 477.
- ³T.-S. H. Lee and S. Pittel, Phys. Rev. C11 (1975) 607.
- ⁴J. S. Dehesa, J. Speth and A. Faessler, Phys. Rev. Lett. 38 (1977) 208.
- ⁵M. R. Anastasio and G. E. Brown, Nucl. Phys. A285 (1977) 516;
G. E. Brown, S.-O. Backman, E. Oset and W. Weise, Nucl. Phys. A286 (1977) 191.
- ⁶R. Pitthan and T. Walcher, Phys. Lett. 36B (1971) 563.
- ⁷R. J. Holt and H. E. Jackson, Phys. Rev. C 12 (1975) 56; R. M. Laszewski, R. J. Holt and H. E. Jackson, Phys. Rev. C 13 (1976) 2257.
- ⁸A. Bohr and B. Mottelson, Nuclear Structure (Addison-Wesley, Reading, Mass., 1975), Vol. II, p. 638.
- ⁹L. M. Bollinger, in Proceedings of the International Conference on Photonuclear Reactions and Applications, Asilomar, 1973, edited by B. L. Berman (Lawrence Livermore Laboratory, Univ. of California, 1973), p. 783.
- ¹⁰C. D. Bowman, R. J. Baglan, B. L. Berman and T. W. Phillips, Phys. Rev. Lett. 25, 1302 (1970).
- ¹¹R. E. Toohey and H. E. Jackson, Phys. Rev. C 6 (1972) 1440.
- ¹²R. J. Holt and H. E. Jackson, Phys. Rev. Lett. 36 (1976) 244; R. J. Holt, R. M. Laszewski and H. E. Jackson, Phys. Rev. C 15 (1977) 827.
- ¹³J. E. Monahan, R. J. Holt, and R. M. Laszewski, to be submitted for publication.
- ¹⁴R. J. Holt, J. R. Specht, H. E. Jackson and R. M. Laszewski, Nucl. Instrum. Methods 141 (1977) 125.
- ¹⁵R. J. Holt, R. M. Laszewski and H. E. Jackson, in Proceedings of the International Conference on the Interactions of Neutrons with Nuclei, Lowell, 1976, edited by E. Sheldon (Technical Information Center, D.O.E., 1976), p. 1278.
- ¹⁶D. J. Horen, J. A. Harvey and N. W. Hill, Phys. Lett. 67B (1977) 268.
- ¹⁷L. C. Haacke and K. G. McNeill, Can. J. Phys. 53 (1975) 1422.

- ¹⁸S. Raman, M. Mizumoto and R. L. Macklin, Phys. Rev. Lett. 39 (1977) 598; D. J. Horen, J. A. Harvey and N. W. Hill, Phys. Rev. Lett. 38 (1977) 1344.
- ¹⁹D. J. Horen, G. F. Auchampaugh and J. A. Harvey, Bull. Am. Phys. Soc. 23 (1978) 507.
- ²⁰S. Raman, private communication.
- ²¹R. M. Laszewski, R. J. Holt and H. E. Jackson, Phys. Rev. Lett. 38 (1977) 813.
- ²²R. M. Laszewski and A. M. Nathan, private communication.
- ²³E. J. Winhold, E. M. Bowey, D. B. Guyther and B. H. Patrick, Phys. Lett. 32B (1970) 607.
- ²⁴P. Axel, K. K. Min and D. C. Sutton, Phys. Rev. C 2 (1970) 689.
- ²⁵H. E. Jackson, *ibid* 9, p. 817.