Giant $M1$ Resonance in Pb

R. M. Laszewski, P. Rullhusen,[a] S. D. Hoblit, and S. F. LeBrun
Department of Physics and Nuclear Physics Laboratory, University of Illinois at Urbana-Champaign, Champaign, Illinois 61820
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Highly polarized tagged photon were used to measure the distribution of $M1$ transition strength in ^{206}Pb at excitations between 6.7 and 8.1 MeV. The observed $B(\uparrow M1)$ of about $19\mu_0^2$ can account for most of the isovector $M1$ strength that is expected in the Pb nucleus. This result in ^{206}Pb is compared with the current experimental situation in ^{208}Pb. The discrepancy between predicted and observed $M1$ strengths in ^{208}Pb can probably be attributed to local fragmentation of the strength into states that are too weak to have yet all been identified.

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It has been long expected that one of the best examples of the giant magnetic-dipole resonance phenomenon should be found in the case of Pb.[1-8] This has made it all the more disconcerting that extensive experimental efforts in ^{208}Pb have shown a total $M1$ transition strength that is only a small fraction of what is predicted by even the most sophisticated theoretical treatments of the problem.[9-13] A possible resolution of this quandry is suggested by the experimental results themselves. Many approaches have been used in the search for $M1$ strength in ^{208}Pb, including resonance fluorescence with polarized photons,[9,13,14] backward-angle inelastic electron scattering,[15,16] photoneutron polarization,[11,17] and neutron scattering and transmission measurements.[10] Of these, the neutron method is by far the most sensitive to the parities of even weak individual transitions; and although it can only be used reliably over a relatively narrow window of excitation above 7.4 MeV, this method has been responsible for the identification of levels with about 80% of the known $M1$ strength in ^{208}Pb.[11,12] It is probably significant that even the strongest $M1$ transitions found in this window are either at or below the lower detection limits of the other techniques that have been employed. Additional $M1$ strength that is spread among comparably weak resonances at energies outside of this limited excitation range very likely would not have been seen.

The average elastic scattering cross section measured with tagged photons is sensitive to all of the dipole transition strength located in a particular excitation-energy interval, ΔE.[18,19] While the energy resolution that can be obtained with tagged photons is modest, the measured strength corresponding to unresolved weak transitions is quite independent of either the number of resonances included in the interval of excitation, or their respective individual magnitudes. In addition, the coincidence requirement means that there is no background subtraction problem to complicate or confuse the interpretation of experimental results. For these reasons, polarized tagged photons may ultimately provide the best determination of $M1$ transition strength in the heavier nuclei.

In this paper we report the first measurement of the distribution of magnetic dipole transition strength in ^{206}Pb using highly polarized elastically scattered tagged photons. The ^{206}Pb nucleus was selected for this initial study because its neutron emission threshold, at 8.1 MeV, is significantly higher in excitation than that found, at 7.4 MeV, in ^{208}Pb. Above threshold, elastic photon scattering is greatly inhibited by competition from the open neutron channel. We have found a total $M1$ strength of about $19\mu_0^2$ spread over an interval of 1 MeV centered at an excitation of 7.5 MeV. This amount of strength can account for essentially all of the $M1$ isovector strength that is expected in Pb.

The present measurement was made possible by the recent development of a technique which allows the linear polarization of an off-axis tagged photon beam to be greatly enhanced by means of a kinematic selection of the postbremsstrahlung electrons that are used for tagging.[20] In the current experiment, the ^{206}Pb scattering target and a large NaI photon detector at 90° could be moved remotely between the positive (s) and negative (o) beam-polarization orientations. The detector could also be moved to 0° in either orientation to directly measure the photon flux incident on the target and the detector response. As a consequence, all geometric and detector efficiency factors cancel in the experimental asymmetry ratios. The incident cw electron-beam energy was 12.9 MeV, and photons were tagged in the range $6.7 \leq E_\gamma \leq 8.1$ MeV, with a residual-electron azimuthal acceptance $3.0° \leq \Delta \leq 4.5°$, following the convention of Ref. 20. The isotopic composition of the ^{206}Pb target was such that over this energy range the only contamination was at most a 3% contribution from ^{208}Pb at excitations below 7.4 MeV.

The experimentally determined polarized-photon elastic scattering asymmetry, η_0^s, is shown in Fig. 1. The expected asymmetries corresponding to pure $E1$ and pure $M1$ scattering are indicated by the solid curves. These curves were derived from a detailed calculation of the photon polarization,[20] which was normalized to measured asymmetries for the strong isolated 1^+ transitions in ^{24}Mg and ^{28}Si, as well as to the

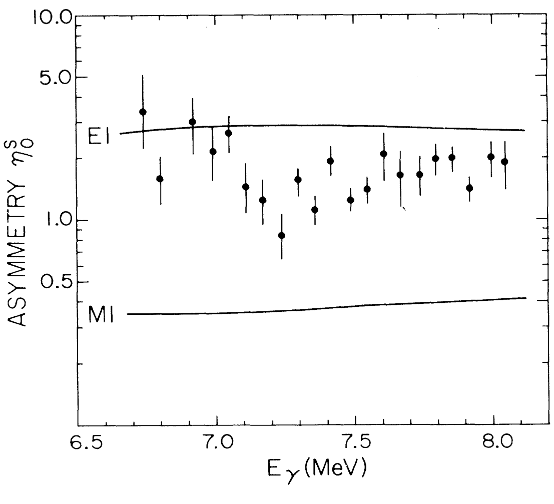

FIG. 1. The observed polarized photon elastic scattering asymmetry at 90° in ^{206}Pb. The curves correspond to the expected asymmetries for pure $E1$ and pure $M1$ scattering.

four largest asymmetries in the present ^{206}Pb data. These latter could be assumed to reflect predominantly $E1$ scattering. All of the calibration points were found to be quite consistent with a single normalization factor, $P_{\rm obs} = AP_{\rm calc}$. The observed photon beam polarizations were 90% of the corresponding calculated values, the actual factor being $A = 0.90 \pm 0.08$. Over the energy range $6.7 \leq E_\gamma \leq 8.1$ MeV, the polarizations in the two target orientations were nearly constant, with mean values $\bar{P}^s = +0.44$ and $\bar{P}^o = -0.48$. Normally, the maximum polarization that can be obtained with off-axis tagged bremsstrahlung is only about $P \sim 0.2$. This enhancement of the degree of polarization by more than a factor of 2 increases the sensitivity with which experimental asymmetries can be determined by an order of magnitude.

The fraction of the dipole cross section in each tagging interval that is due to $M1$ transition strength can be obtained from the observed asymmetries[20]:

$$m = \tfrac{1}{2}[1 + (1 - \eta_0^s)/(P^s - P^o \eta_0^s)].$$

This quantity is plotted in the upper part of Fig. 2. In the lower portion of the figure, m is combined with previously measured ^{206}Pb average elastic cross-section data[18] to give the actual $M1$ scattering cross-section distribution. The error bars reflect all statistical uncertainties in the ^{206}Pb dipole cross sections, the observed asymmetries, and the photon beam polarization normalization. Over the excitation interval $6.7 \leq E_\gamma \leq 8.1$ MeV, the total $M1$ strength is $\sum g\Gamma_0^2(M1)/\Gamma = 4.7.7^{+5.3}_{-4.3}$ eV.

The magnetic-dipole reduced transition probability, $B(\uparrow M1)$, can be derived from this strength if it is assumed that the ground-state partial widths follow a Porter-Thomas distribution, and if the average ratio,

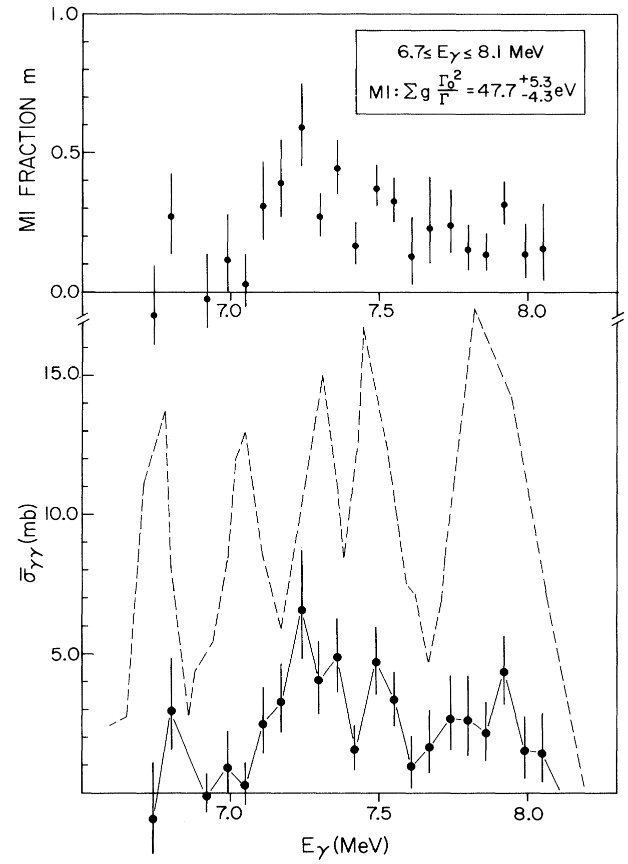

FIG. 2. The fraction of the elastic dipole cross section which is due to $M1$ transition strength is shown above. This fraction is combined with ^{206}Pb average elastic cross-section data from Ref. 18 (indicated by the dashed curve), to give the actual $M1$ cross-section distribution.

$\langle\Gamma\rangle/\bar{D}$, can be estimated for this range of excitations in ^{206}Pb.[18,21] With $\langle\Gamma\rangle$ taken from an analysis of total radiative widths,[22] and the average spacing of 1^+ levels, $\bar{D}$, obtained from an experimental estimate for 1^- levels[19] with the usual statistical assumption of the equiprobability of the two parities[23] and an appropriate nuclear temperature,[23] the indication is that between 7 and 8 MeV in ^{206}Pb, $\langle\Gamma\rangle/\bar{D} \sim 5\times10^{-5}$. The total reduced transition probability corresponding to the measured $M1$ strength is then $B(\uparrow M1) = (19 \pm 2)\mu_0^2$. It should be emphasized that the derived $B(\uparrow M1)$ is not very strongly dependent on the assumed values for the average parameters $\langle\Gamma\rangle$ and $\bar{D}$.[21] In the present case, a 30% change in the quantity $\langle\Gamma\rangle/\bar{D}$ would produce only a 10% change in $B(\uparrow M1)$.

The distribution of $\bar{B}(\uparrow M1) = \sum_{\Delta E} B(\uparrow M1)$ in ^{206}Pb is shown in the upper half of Fig. 3. The predictions of two recent calculations of the magnetic dipole resonance in ^{208}Pb were found to be in rather good quantitative agreement with this experimental distribu-

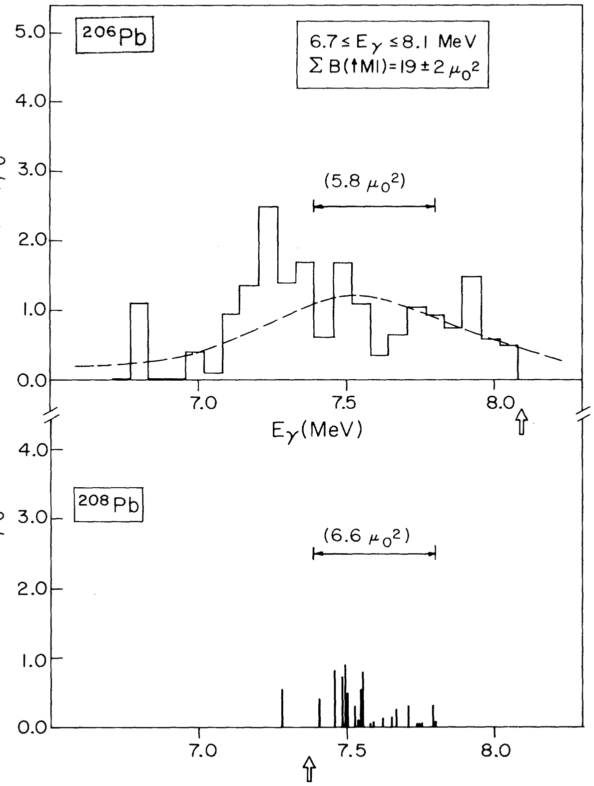

FIG. 3. The distribution of $\bar{B}(\uparrow M1)$ in ^{206}Pb from the present work is contrasted with the currently known isovector $M1$ strength in ^{208}Pb (Refs. 9–11). The arrows correspond to respective neutron emission thresholds. A calculation of the magnetic dipole resonance in ^{208}Pb from Ref. 8 is indicated by the dashed curve.

tion.[7,8] Both calculations find an isovector strength of about $19\mu_0^2$ near 7.5 MeV, and a much weaker isoscalar contribution at a somewhat lower energy. The isoscalar component appears to have been observed experimentally at 5.85 MeV.[13] The total predicted $M1$ strength is only about half that expected from the naive independent-particle model, with most of the reduction attributable to ground-state correlations and the effects of 2p-2h and 1Δ-1h couplings. The more recent calculation,[8] which includes these effects explicitly, find the 7.5-MeV isovector strength to be spread over an interval of on the order of 1 MeV. This corresponds very well with what we have now observed experimentally in ^{206}Pb (Fig. 3). It is interesting to note that the calculation also predicts the presence of a very small amount of $M1$ strength in a rather uniform tail which extends upward to much higher energies. Such a distribution of strength could be sufficient to account for the photoneutron polarization interference effects that have been observed with poor resolution up to 10 MeV in ^{208}Pb.[11,17]

The known $M1$ isovector strength[9–11] in ^{208}Pb is shown in the lower half of Fig. 3, and can be compared with the strength found in ^{206}Pb at corresponding excitations. In particular, the $6.6\mu_0^2$ that has been identified in ^{208}Pb between 7.4 and 7.8 MeV does not differ significantly from the $(5.8 \pm 1)\mu_0^2$ that we have observed in ^{206}Pb over the same energy interval. If the distribution of $M1$ strength is in fact similar in the two Pb isotopes, one would expect that there is perhaps $\sum\Gamma_0^2(M1)/\Gamma \sim 7$ eV as yet unidentified between 6.7 MeV and neutron threshold in ^{208}Pb. This amount of strength is less than 25% of the total dipole strength that is known to be below the resolution limit of nuclear resonance fluorescence measurements in this energy range.[18,19] Similarly, one might expect to find $\sum\Gamma_0^2(M1)/\Gamma \sim 4.5$ eV above threshold in ^{208}Pb between 7.8 and 8.1 MeV. A strength of 4.5 eV would correspond to less than 40% of the strength that remains unassigned in this region because it is below the sensitivity limit of the photoneutron polarization technique.[11]

In summary, we have measured the distribution of magnetic dipole transition strength in ^{206}Pb at excitations between 6.7 and 8.1 MeV using highly polarized tagged photons. We have found a total $M1$ strength of $\sum g\Gamma_0^2/\Gamma = 47.7^{+5.3}_{-4.3}$ eV corresponding to a reduce transition probability $B(\uparrow M1)$ of about $19\mu_0^2$. This strength can account for all of the $M1$ isovector strength that has been predicted near 7.5 MeV in Pb. An implication of the present work is that there is probably no "missing" $M1$ strength in ^{209}Pb, but rather that the discrepancy between current theory and experiment can be attributed to local fragmentation of the strength into states in the vicinity of 7.5 MeV that are individually too weak to have yet all been identified.

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(a)On leave from: II. Physikalisches Institut, Bunsenstrasse 7-9, D-3400 Gottingen, West Germany.

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