Distribution of $M1$ Transitions in ^{208}Pb

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The distribution of $M1$ strength in ^{208}Pb has been measured between 5.8 and 7.4 MeV with highly polarized tagged photons. $\sum\Gamma_0^2(M1)/\Gamma = 14.6^{+1.5}_{-1.3}$ eV corresponding to $\sum B(M1\uparrow) = (10.7^{+1.1}_{-0.9})\mu_N^2$ was found, and can fully account for the much discussed "missing" $M1$ in ^{208}Pb. When the present result is combined with known 1^+ transitions above neutron threshold, an $M1$ giant resonance emerges at 7.3 MeV, 1 MeV wide, with $\sum B(M1\uparrow) \approx 15.6\mu_N^2$. Smaller 1^+ resonances are also seen at both 5.85 and 6.24 MeV. The total $M1$ strength below 6.4 MeV amounts to $\sum B(M1) = (1.9^{+0.7}_{-0.4})\mu_N^2$.

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The question of the distribution of magnetic dipole ground-state transition strength in ^{208}Pb has been the subject of intensive experimental and theoretical study for many years.[1-3] A large part of this reason for the continuing interest in this problem has been the fact that the predictions of sophisticated theoretical models, which have been successful in describing the magnetic properties of other nuclei, have remained substantially at variance with the experimental observations of $M1$ transition strength in ^{208}Pb. The relatively small amount of $M1$ strength found below 8 MeV in ^{208}Pb has tended to be particularly troublesome because spin-flip excitations of both of the closed-shell configurations $\pi(h_{11/2})$ and $\nu(i_{13/2})$ can occur, and would suggest that this nucleus should exhibit the best possible example of an $M1$ giant resonance.

The discovery of a strong localized $M1$ resonance in the neighboring nucleus ^{206}Pb (Ref. 4) leads to the suggestion that there might in fact be more $M1$ strength near 7.5 MeV in ^{208}Pb than had been suspected.[3,4] This could be the case if the $M1$ were sufficiently fragmented to make the strengths of individual transitions fall below the respective detection limits of the experimental probes that had been employed. Most of the known $M1$ strength in ^{208}Pb is found to be distributed among a large number of weak transitions located in a band of excitations just above the 7.4-MeV neutron-emission threshold.[5-7] Significantly, the detection limits that are characteristic of the neutron work responsible for the identification of these $M1$ transitions are far better than corresponding limits on the other techniques that had been used to search for $M1$ strength below threshold.[3]

In order to address the question of the "missing" $M1$ in ^{208}Pb, we have measured the distribution of magnetic dipole transition strength at excitations between 5.8 and 7.4 MeV using highly polarized tagged photons. The present technique avoids many of the difficulties that are inherent in other methods.[3] In particular, the tagged-photon elastic-scattering cross section is sensitive to the sum of the dipole transition strength in each tagging interval ΔE, and does not depend on the actual number of resonances among which the strength is shared.[8,9] The tagging-coincidence requirement ensures that there is no background subtraction problem to complicate the interpretation of the data, and the measured polarization asymmetry serves to separate $M1$ from the dominant $E1$ transition strength.[10] This technique is ideally suited to the search for substantially fragmented magnetic dipole strength.

The off-axis linear polarization of the tagged-photon beam was enhanced by means of residual-electron selection in the manner previously described.[10] The scattering target was 99.7% enriched ^{208}Pb. The incident cw electron-beam energy was 11.2 MeV, and photons were tagged in the range $5.8 < E_\gamma < 7.6$ MeV. Unpolarized photon-scattering cross sections were obtained by our simply moving the target-detector system to an on-axis orientation and eliminating the residual-electron selection constraint. Because elastic photon scattering below threshold in ^{208}Pb is dominated by a number of very strong $E1$ transitions,[8,9,11,12] it was decided to place an enriched (99.7%) 4.19-gm/cm^2 ^{208}Pb absorber into the photon beam. This nuclear-resonant absorber[9,13] served to preferentially reduce the scattering due to the very strong $E1$ lines and effectively enhance any asymmetry due to much weaker $M1$ transitions.

The measured polarized-photon elastic-scattering asymmetries, η_0^δ, are shown in the top part of Fig. 1. The asymmetries that would be expected for pure $E1$ and pure $M1$ scattering are indicated by the curves. These curves come from a calculation of the photon polarization in first Born approximation with screening, averaged over the scattering target and the residual-electron acceptance.[10] Experimentally measured asymmetries for known $M1$ and $E1$ transitions were used to determine a normalization factor of 1.03 ± 0.06 for the theoretical polarization.[14] It is clear from the asymmetry plot alone that there is significant $M1$ strength near 7 MeV in ^{208}Pb.

The observed asymmetry in each tagging interval gives

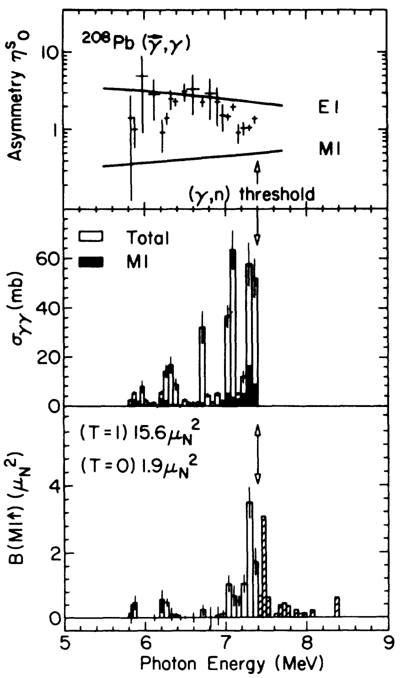

FIG. 1. Top: The observed polarized-photon elastic-scattering asymmetry at 90° in ^{208}Pb. The curves correspond to expected asymmetries for pure $E1$ and pure $M1$ scattering. Horizontal lines on the data points indicate the widths of respective tagging intervals. Center: Total photo-elastic-scattering cross section below threshold in ^{208}Pb. The $M1$ contribution is indicated by the solid histogram. Bottom: The distribution of $B(M1\uparrow)$ in ^{208}Pb. The open histogram shows the results of the present work. The shaded histogram indicates the previously known $M1$ strength above threshold in ^{208}Pb (Ref. 7). Histogram widths correspond to respective tagging intervals.

the fraction of the total elastic scattering that is due to $M1$ transition strength.[10] This fraction is combined with the unpolarized elastic-scattering measurement to give the $M1$ photon cross section which is shown in the central part of Fig. 1 (solid histogram). For comparison, the total dipole cross section is also shown (open histogram). This latter includes the appropriate nuclear resonant-absorption corrections for all of the strong $E1$ transitions that were observed in the nuclear-resonance-fluorescence work of Ref. 9. The plot of the cross section shows that there is indeed a large amount of $M1$ strength extending below threshold, with the overall distribution of dipole strength clearly dominated by the well-known $E1$ resonances. The total magnetic-dipole-transition strength in the interval between 6.7 and 7.4 MeV is $\sum\Gamma_0^2(M1)/\Gamma=12.9^{+1.4}_{-1.2}$ eV. The corresponding electric-dipole strength is $\sum\Gamma_0^2(E1)/\Gamma=65.7^{+6.3}_{-6.2}$ eV, or 84% of the total $(M1+E1)$. Between 5.8 and 6.7 MeV, $\sum\Gamma_0^2(M1)/\Gamma=1.7^{+0.6}_{-0.4}$ eV and $\sum\Gamma_0^2(E1)/\Gamma=11.1^{+1.5}_{-1.4}$ eV.

The measured $M1$ elastic-scattering cross section can be most directly compared with theoretical predictions if it is expressed in terms of the reduced transition probability $B(M1\uparrow)$. There is a simple relation between these two quantities if it is assumed that $\Gamma_0/\Gamma\approx 1$ (Ref. 15); and in the case of ^{208}Pb it appears that this assumption is quite reasonable.[9] To the extent that Γ_0/Γ deviates from 1, the $B(M1\uparrow)$ values given here will be lower limits.[16]

Our results are presented at the bottom of Fig. 1 (open histogram). All of the statistical uncertainties associated with the asymmetry measurement, the elastic-scattering measurement, and the polarization normalization are reflected in the error bars. We find that between 6.7 and 7.4 MeV, $\sum B(M1\uparrow)=(8.8^{+1.0}_{-0.8})\mu_N^2$ and that below 6.7 MeV down to 5.8 MeV, $\sum B(M1\uparrow)=(1.9^{+0.7}_{-0.4})\mu_N^2$. Also shown (shaded histogram) are the results of previous neutron-scattering and -capture measurements on individual $M1$ resonances above threshold.[5-7] We have summed these data over 50-keV bins to facilitate comparison with the present experiment. The neutron work has observed $\sum B(M1\uparrow)\approx 6.8\mu_N^2$ from threshold to about 8.4 MeV.[7] Looking at the figure, we can see that there is in fact a compact giant $M1$ resonance in ^{208}Pb centered at about 7.3 MeV, having a full width of about 1 MeV. The total strength of this resonance is $\sum B(M1\uparrow)=15.6\mu_N^2$, more than half of which lies below threshold and is reported here for the first time. Similar amounts of $M1$ strength have been observed in the photofission of actinide nuclei.[17] The presence of a previously observed[18] weak 1^+ level at 7.28 MeV $[B(M1\uparrow)\approx 0.5\mu_N^2]$ is consistent within the present measured distribution of $M1$ strength.

The results of the present experiment can account for the missing $M1$ strength in ^{208}Pb. In the independent-particle shell model, the two configurations $\pi[(h_{11/2})^{-1}, (h_{9/2})]$ and $\nu[(i_{13/2})^{-1}, (i_{11/2})]$ are mixed by the residual interaction to produce two 1^+ states.[19] One of these, in which the neutron and proton components oscillate out of phase, is nominally referred to as an "isovector" state and carries most of the excitation strength. The other is an "isoscalar" state which lies lower in energy and has little strength. A variety of nuclear dynamics effects including ground-state correlations, coupling to nucleon excitations, and coupling to more complicated nuclear configurations serve to modify this simple picture and reduce the $M1$ strength relative to the independent-particle shell model. Recent theoretical calculations[20-23] all tend to predict a total magnetic dipole strength in ^{208}Pb of about $20\mu_N^2$, with most of it expected at excitations near 7.5 MeV. The coupling to two-particle–two-hole configurations, which is responsible for the substantial local fragmentation of the $M1$, also distributes a small part of this strength upwards to higher excitations.[20] One calculation, which explicitly includes a very large two-particle–two-hole space, finds that below about 8.5 MeV in ^{208}Pb, $\sum B(M1\uparrow)=17.4\mu_N^2$.[21,24] This result is in excellent agreement with out new experimental total, $\sum B(M1\uparrow)\approx 17.5\mu_N^2$.

Our data also show two small $M1$ resonances at 5.85

MeV [$\sum\Gamma_0^2(M1)/\Gamma = 0.5^{+0.4}_{-0.2}$ eV] and at 6.24 MeV [$\sum\Gamma_0^2(M1)/\Gamma = 1.2^{+0.5}_{-0.3}$ eV]. The excitation energies and strengths of these resonances suggest that they may be a reflection of the isoscalar state, although it may also be that at least some of the strength in this region is due to a low-energy tail extending from the isovector $M1$ giant resonance at 7.3 MeV. The results of the present experiment are in basic accord with previous claims that have been made for a 1^+ state at 5.846 MeV.[12,25] The maximum $M1$ strength that we can attribute to a single state at this excitation is $\Gamma_0^2(M1)/\Gamma = 0.5^{+0.4}_{-0.2}$ eV, which is somewhat less than has been reported elsewhere[12,25]; but all of the results are consistent within the experimental uncertainties. We note that there are at least two effects which could have contributed to a possible overestimate of the nuclear-resonance-fluorescence strength reported in Ref. 12. The single-escape peak of a line at 6.363 MeV in ^{208}Pb falls at 5.852 MeV and cannot be cleanly resolved from the line at 5.846 MeV[9]; and ^{206}Pb, which was present in the partially enriched ^{208}Pb target of Ref. 12, also has a resonance at 5.846 MeV.[9] From the present work, the total $M1$ strength below 6.4 MeV amounts to $\sum B(M1\uparrow) = (1.9^{+0.7}_{-0.4})\mu_N^2$.

In summary, the distribution of magnetic dipole-transition strength in ^{208}Pb has been measured at excitations between 5.8 and 7.4 MeV with highly polarized tagged photons. A total $M1$ strength of $\sum\Gamma_0^2(M1)/\Gamma = 14.6^{+1.5}_{-1.3}$ eV corresponding to $\sum B(M1\uparrow) = (10.7^{+1.1}_{-0.9}) \times \mu_N^2$ was found, and can fully account for the much discussed "missing" $M1$ in ^{208}Pb. When the present results are combined with previously reported $M1$ above neutron threshold it becomes clear that there is in fact a locally fragmented $M1$ isovector giant resonance in ^{208}Pb centered at 7.3 MeV having a width of about 1.0 MeV and a strength of $15.6\mu_N^2$. There is also additional $M1$ strength below 6.4 MeV that amounts to about $1.9\mu_N^2$.

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