good isospin the results for ^{40}Ca agree on the average with the results of Dieperink *et al.*[6] For the lowest 3^- state our result is closer to the experimental value. In the calculation of ^{48}Ca we used two different sets of single-particle energies[7,8]; our result for the lowest 3^- ground-state transition is in both cases comparable with the outcome of Jaffrin and Ripka.[8] For ^{208}Pb we obtain for this transition approximately the same values as in Refs. 9–11.

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$^{208}Pb(\gamma, n)^{207}Pb$ and the Giant $M1$ Resonance*

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Photoneutron resonances and their angular distributions have been studied in a high-resolution measurement of the $^{208}Pb(\gamma, n)^{207}Pb$ reaction near threshold. The angular distributions observed for lower-energy photoneutron resonances tend to confirm the conclusions of earlier experiments which suggest the existence of a giant $M1$ resonance in ^{208}Pb.

Recently, Bowman *et al.*[1] at Livermore reported a surprising concentration of $M1$ strength in the $^{208}Pb(\gamma, n)^{207}Pb$ reaction within 1 MeV of threshold. The observed $M1$ strength of 51 eV, more than five Weisskopf units, is at least 50% of the total $M1$ strength available in shell-model calculations. In their interpretation, this strength was associated with spin-flip transitions in the $i_{13/2}$ neutron shell and $h_{11/2}$ proton shell; if polarization effects are included in the calculation, all the available $M1$ strength is exhausted by the Livermore data. In their experiment, the total $M1$ strength was obtained by summing the yields for all resonances identified by their angular distributions as p-wave decays from 1^+ states. An alternative explanation of the angular distributions of these resonances is a substantial d-wave photoneutron component mixed with the s-wave yield from $E1$ resonances ($J^\pi = 1^-$). In view of the interest in the Livermore result, we have repeated the experiment at the Argonne threshold photoneutron facility, with improved energy resolution and higher photon intensity. The angular distributions for the strong resonances at higher energies appear more nearly isotropic than indicated in the Livermore data, and the previous 1^+ parity assignments are questionable. However, at lower energies our data tend to support the conclusions of Bowman *et al.* that the spectrum of ^{208}Pb displays an $M1$ giant resonance.

The threshold photoneutron technique has been described in detail elsewhere.[2,3] Briefly, an electron beam from the Argonne high-intensity linac struck a 40-mil-thick Ag converter on the front of a 5-cm-thick Al stopping block. The resulting bremsstrahlung irradiated a 49.3-g sample of ^{208}Pb, $\frac{1}{8}$ in. thick, enriched to 99.1%. Photoneutrons were detected with a proton-recoil detector at laboratory angles of 90 and 135° to the electron beam, and their energies were determined by time of flight over a 9-m path. The electron endpoint energy was 8.4 MeV, 1.02 MeV above the photoneutron threshold. The photoneutron time-of-flight spectra are shown in Fig. 1.

With the usual approximation that $\Gamma_n \approx \Gamma$, the yield Y in a photoneutron resonance directly measures $\Gamma_{\gamma 0}$. To calculate angular distributions and widths, the yield of each resonance was normalized to the 254-keV resonance, a 1^- state with isotropic yield.[1] The 254-keV resonance was normalized in turn to the 41-keV resonance, a well-established[4] 1^- level with $\Gamma_{\gamma 0} = 4.2$ eV, by use of data taken in a short run with a ^{6}Li glass detector. The resulting resonance parameters, including those from data taken by the Livermore group, are listed in Table I. To aid the comparison, the Livermore data have been corrected for their use of $\Gamma_{\gamma 0}$ (41 keV) = 4.8 eV as a standard. Also tabulated are the results of Allen and Macklin[5] at ORNL for neutron capture in ^{207}Pb. We have not included the ORNL parity assignments since they are based on the Livermore data. We estimate our widths to be accurate to within 20%, except for levels above 900 keV, where the error rises to 50%. The reason for this large error is that the yields of these levels are small because of the low photon intensity near the tip of the bremsstrahlung spectrum.

The critical measurement in this experiment is the angular-distribution ratio $R = Y(90°)/Y(135°)$. From the tables of Carr and Baglin,[6] these ratios are $R = 0.67$ for $E2$ absorption to 2^+ states followed by p-wave neutron emission; $R = 1.0$ (isotropy) for $E1$ absorption to 1^- states followed by s-wave emission; and $R = 0.67$–2.0 for $M1$ absorption to 1^+ states followed by p-wave emission. The $M1$ ratio has a range of values because it depends on the relative amplitudes of the two channel spins involved.

However, as mentioned by the Livermore group,

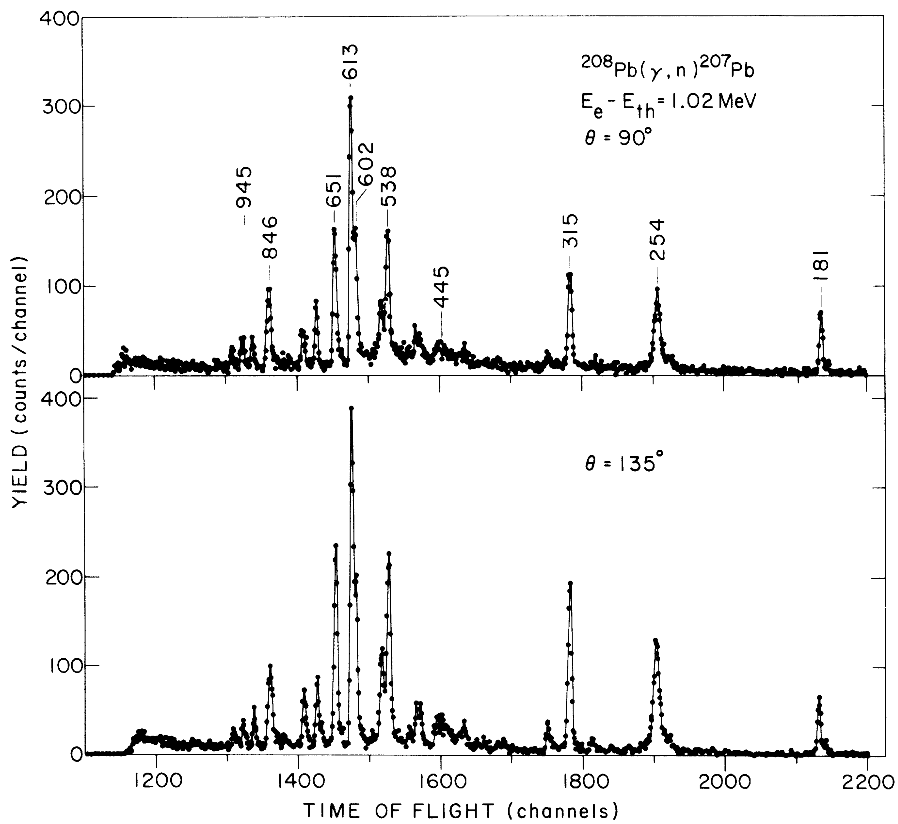

FIG. 1. Threshold photoneutron spectrum measured at 90 and 135°. The neutron yield from the ^{208}Pb(γ, n) reaction is plotted as a function of the neutron time of flight, and the peaks are labeled with the neutron energy E_n in keV.

TABLE I. $^{208}Pb(\gamma, n)^{207}Pb$ resonance parameters. Underlined resonances are discussed in the text.

	Argonne National Laboratory [a]			Lawrence Radiation Laboratory [b]			Oak Ridge National Laboratory [c]	
E_n (keV)	R (90°/135°)	J^π	$\Gamma_{\gamma 0}$ (eV)	R (90°/135°)	J^π	$\Gamma_{\gamma 0}$ (eV)	J^π	$\Gamma_{\gamma 0}$ (eV)
996	1.55 ± 0.29	1	5.8					
951	1.34 ± 0.36	1	3.5					
945	2.04 ± 0.52	1	2.9					
907	1.25 ± 0.20	1	6.5					
846	1.38 ± 0.12	1	10.1	1.46 ± 0.20	1^+	6.8		
737	0.99 ± 0.12	1	3.5					
699	1.17 ± 0.12	1	4.4					
651	1.11 ± 0.08	1	11.8	1.37 ± 0.20	1^+	5.5	2^+	7.3
613	1.23 ± 0.08	1	19.7	1.81 ± 0.25	1^+	12.8	1	7.2
602	1.25 ± 0.09	1	8.0				1	8.5
551	0.80 ± 0.08		3.3					
538	0.99 ± 0.07	1	12.4	0.94 ± 0.13	1^-, 1^+	7.2	1	11.1
491	1.01 ± 0.16	1	2.0					
484	0.86 ± 0.15		1.6				1	8.5
457	1.02 ± 0.16	1	2.2					
445	0.68 ± 0.13	2^+, 1^+	1.5					
422 [d]	*ES*							
334	0.60 ± 0.17	2^+, 1^+	0.7				1	2.3
315	0.94 ± 0.07	1	10.2	1.13 ± 0.16	1^+	6.7	1	8.5
297	0.90 ± 0.25		0.9				1	0.7
254	1.00 ± 0.07	1^-	16.4	1.00	1^-	15.3		28.3
181	1.67 ± 0.16	1^+	9.9	1.45 ± 0.20	1^+	11.0		13.6

[a] Present work.
[b] Reference 1.
[c] Reference 5.
[d] Decay to first excited state of ^{207}Pb.

the presence of a d-wave admixture in the s-wave yield from 1^- states may increase the value of R for $E1$ transitions. In fact, R is an extremely sensitive function of the intensity ratio δ^2, where δ^2 is defined as the ratio of the magnitudes squared of the matrix elements for d- and s-wave decay.

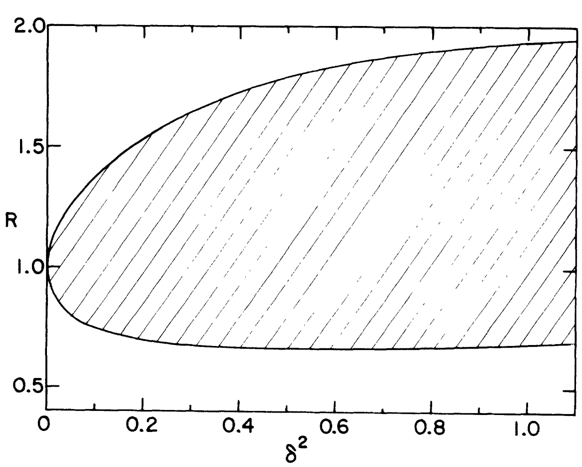

FIG. 2. Plot of the angular-distribution ratio $R = Y(90°)/Y(135°)$ as a function of the intensity ratio δ^2 of d-wave to s-wave decay from 1^- resonances.

The amplitude ratio δ is defined as the ratio of the magnitudes of the matrix elements. That is, $\delta = \pm\sqrt{\delta^2}$, where the ambiguity in sign physically results from the arbitrariness of the relative phase of the matrix elements within a factor of π. The angular distribution then is $W(\theta) = 1 + \delta^2 + [\sqrt{2}\delta \cos(\phi_0 - \phi_2) - \frac{1}{2}\delta^2]\, P_2(\cos\theta)$, where ϕ_l is the hard-sphere, or potential-scattering phase shift. R is plotted as a function of δ^2 in Fig. 2. The solid lines represent the extreme case of $\cos(\phi_0 - \phi_2) \approx 1$, valid only under 100-keV neutron energy; the upper curve corresponds to $\delta = +\sqrt{\delta^2}$, and the lower to $\delta = -\sqrt{\delta^2}$. For a given value of δ^2, R may lie anywhere between the curves, depending on the ϕ_l's. It is seen that a very small admixture of $\delta^2 = 0.05$ may give an angular-distribution ratio as great as $R = 1.25$. Since average values of δ^2 calculated from an optical-model potential vary from 0.10 to 0.25 over the energy range 400–1000 keV,[7] and considering that Porter-Thomas fluctuations may significantly increase δ^2 above its average value, an anisotropic angular distribution may be explained equally well by $s+d$-wave or by p-wave neutron decay. Consequently the parities of levels in this region, and therefore the assignment of $M1$ strength, cannot be determined from the photoneutron data.

It is seen from the table that our angular-distribution ratios, especially at higher energies, are significantly smaller than those measured at Livermore. Where our data favor one of several possible assignments of spin and parity, the listing in the table is in order of decreasing probability. That is, a resonance assigned 2^+, 1^+ is more likely 2^+. No entry is made for cases of extreme ambiguity.

The strong resonances around 600 keV are not well resolved in the Livermore data. They reported the very high value of $R = 1.8$ for the doublet at 602 and 613 keV. Our value of $R = 1.25$ for each member of this doublet overlaps the value of $R = 1.34 \pm 0.21$ reported by Mizumoto *et al.* at the Japanese Atomic Energy Research Institute.[8] Our value of $R = 1.11$ for the 651-keV resonance is inconsistent with the 2^+ assignment of Ref. 5. As mentioned above, the parity assignments for these resonances are ambiguous.

However, at lower photoneutron energies the ambiguity lessens. For the 181-keV resonance, the average d-wave penetrability $[\delta^2(\text{avg.}) = 0.02]$ is too small to account for the large anisotropy of $R = 1.67$. This resonance, therefore, must be p wave and assigned 1^+. For the 315-keV level, the Livermore group made a 1^+ assignment on the basis of transmission data[1]; it cannot be assigned from the photoneutron data. These two levels alone set a lower limit on the $M1$ strength of 20 eV, still a significant fraction of the expected total value.

Although an exact measurement of the total $M1$ strength will be possible only when the parity of each level can be unambiguously established, the threshold photoneutron data do indicate some concentration of $M1$ strength in this region. Consequently we feel that the presence of an $M1$ giant resonance in ^{208}Pb as reported by Bowman *et al.* is probable, but by no means certain.

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