ture dependence of the strengths of the thresholds), seem to indicate that this interpretation, if restricted to direct processes (Ref. 30), is not likely to hold here. Further discussion of this point will be published in a more extended paper (Capizzi and Frova, Ref. 22).

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# $M1$ Giant Resonance in $^{208}$Pb From Threshold Photoneutron Measurements*

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From threshold photoneutron cross-section and angular-distribution measurements on $^{208}$Pb, seven $1^+$ states have been detected, which have a total $M1$ strength of 51 eV. This $M1$ strength, centered at an excitation energy of 7.9 MeV and spread over a range of 700 keV, constitutes at least half and perhaps all of the total $M1$ strength obtained from shell-model calculations.

In the measurements reported here, an exceptionally large concentration of ground-state $M1$ radiation strength (more than five Weisskopf units) has been detected in $^{208}$Pb, centered at an excitation energy of 7.9 MeV. This strength is spread over seven resonances in the energy range from 7.40 to 8.25 MeV. Two of these resonances individually have widths in excess of one Weisskopf unit.

The $M1$ strength was detected in photoneutron cross-section measurements on $^{208}$Pb by the threshold photoneutron technique, which has been described elsewhere.[1,2] This method, which makes use of electron bremsstrahlung, is applied near threshold where neutron time-of-flight techniques allow the measurement of $(\gamma, n)$ cross sections with very high resolution.

The 135° (lab) differential photoneutron cross section is shown in Fig. 1, plotted as a function of both the detected neutron energy and the excitation energy in the compound system. The low-energy data (upper plot) were taken with an enriched sample of $^{208}$Pb (with isotopic ratios $^{208}\mathrm{Pb}:{}^{207}\mathrm{Pb}:{}^{206}\mathrm{Pb} = 99.75:0.05:0.20$), using a neutron detector which operates by detecting a multiplicity of $\gamma$ rays and neutrons from a fission event.[3,4] The high-energy data (lower plot) were taken with natural lead, using a proton-recoil neutron detector.[5] Both measurements were carried out with an end-point energy of 9.8 MeV. Additional measurements were performed at lower energies with each detector in order to identify both excited-state photoneutron transitions (designated by arrows in the upper plot) and, with the help of previous measurements on separated $^{207}$Pb samples, resonances associated with contaminant isotopes (designated by arrows in the lower plot). The prominent peaks at 547, 620, 660, and 860 keV were shown definitely to be resonances in $^{208}$Pb associated with ground-state transitions. No prominent peaks were observed between 860 and 1200 keV. The measured area $A$ under a resonance is proportional to the ground-state radiation width $\Gamma_{\gamma 0}$ (since $\Gamma_{\gamma 0} \ll \Gamma_n \cong \Gamma$ here). Table I contains the laboratory neutron energy $E_l$ (column 1) and a quantity proportional to $A$ (column 2) for each prominent resonance in the Fig. 1.

The spins of most of these resonances were determined by comparing the data of Fig. 1 with that of similar measurements carried out at 90°, with the natural lead sample, for each neutron detector. The measurements which used the multiplicity detector covered the range from 10 to 1000 keV; those with the proton-recoil detector, from 130 to 1200 keV. The 90 and 135° data from the multiplicity-detector runs were normalized at the 40.8-keV resonance, a well-established $1^-$ state,[6] which de-excites with $l=0$ neutrons and whose angular distribu-

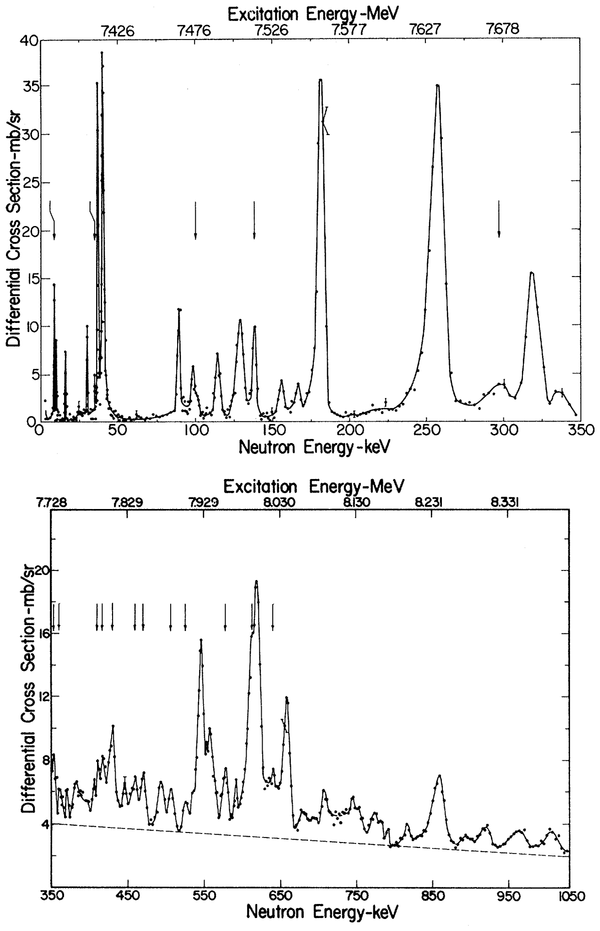

FIG. 1. The 135° differential photoneutron cross section for $^{208}$Pb as a function of both the energy of the detected neutron and the corresponding excitation energy of the nucleus. The data of the two plots were taken with different detectors, possessing different resolution and background characteristics. The arrows in the upper plot denote resonances associated with transitions to states other than the ground state of $^{207}$Pb. The data of the lower plot were taken with a natural lead sample — hence, the presence of contamination from resonances in $^{207}$Pb (arrows). The dashed line in the lower plot represents background in that measurement. The error flags in both plots indicate statistical uncertainties only.

tion therefore is isotropic. The 90 and 135° data from the recoil-detector runs were normalized at the 257-keV resonance; $J^\pi$ for this level was assigned to be $1^-$ from the multiplicity-detector data; this assignment was confirmed by neutron total cross-section measurements (see below). The resulting normalized area ratios for the two differential cross-section measurements $(d\sigma/d\Omega)_{90°}/(d\sigma/d\Omega)_{135°} \equiv R$ are given for each resonance in columns 3 and 4 of the table (except for the 90- and 129-keV resonances, which were obscured in the 90° spectrum by resonances in the $^{207}$Pb contaminant).

The theoretical values for the cross-section ratios were calculated in accordance with the usual prescription[7] for $1^-$, $2^+$ and $1^+$ states. The expected ratios are 1 for $E1$ ($s$-wave) transitions, 0.67 for $E2$ transitions, and the range from 0.67 to 2 for $M1$ transitions (depending upon the relative amplitudes for the two channel spins possible). Thus, in the absence of an abnormally large $d$-wave contribution (see below), any ratio $>1$ identifies an $M1$ transition. A ratio equal to 0.67 strongly favors an $E2$ transition, since all such transitions will have that ratio, while the ratio for an $M1$ transition can take on any value from 0.67 to 2. The same possible confusion arises between $E1$ and $M1$ transitions, although the same argument can be used that a ratio of 1 will strongly favor an $E1$ assignment. Assignments made in this way on the basis of the present measurements are given in column 5 of the table.

Additional information on the parity of several resonances is provided by high-resolution neutron total cross-section data on $^{207}$Pb from Duke University.[8] Most of the resonances reported here also were detected in that experiment. Those resonances showing interference minima in the neutron total cross section must correspond to $l=0$ transitions and hence have negative parity; symmetric resonances most likely have $l=1$ and hence positive parity, since higher-order multipole transitions will be very weakly induced by photons, and penetrability considerations militate against any appreciable $l>1$ contribution. Also, the peak cross sections of these neutron resonances can be used for parity assignments, since the theoretical maximum is limited by the statistical factor for neutrons. These parity assignments are given in column 6 of the Table I. The combined final spin and parity assignments are given in column 7 of the table.

Since correct spin assignments are crucial for the conclusions of this paper, it is worthwhile to consider each resonance. The only information on the spin of the 30.2-keV resonance is provided by the present multiplicity-detector data. Since it is a weak transition, the uncertainty of the $1^+$ assignment is somewhat greater than for most of the other resonances. The $2^+$ assignment for the 37.5-keV resonance is strongly supported by the detection in neutron-capture $\gamma$-ray spectra of a strong transition to the $3^-$ state of $^{208}$Pb in this energy region.[9] No spin

Table I. $^{208}$Pb resonance parameters.

| $E_\ell$ (keV) | $\frac{4\pi A}{2\pi^2 ƛ^2}$ (eV)[a,b] | $\frac{d\sigma}{d\Omega}\Big\vert_{90^\circ} / \frac{d\sigma}{d\Omega}\Big\vert_{135^\circ}$ Multiplicity | Recoil | $J^\pi$ Ang. Dist. | $\pi$ $\sigma_t^c$ | $J^\pi$ Final | $\Gamma_{\gamma 0}$ (eV) |
|---|---|---|---|---|---|---|---|
| 30.2 | 0.30 | 1.41 ± 0.20 | | $1^+$ | | $1^+$ | 0.23 |
| 37.5 | 1.8 | 0.64 ± 0.09 | | $2^+$ | | $2^+$ | 0.64 |
| 40.8 | 7.2 | 1 | | $1^-$ | | $1^-$ | 4.8 |
| 90.0 | 2.6 | | | | | | |
| 114 | 2.0 | 1.54 ± 0.22 | | $1^+$ | + | $1^+$ | 1.6 |
| 129 | 5.4 | | | | + | $1^+,2^+$ | (3.6,1.9) |
| 182 | 16.0 | 1.61 ± 0.23 | 1.45 ± 0.20 | $1^+$ | + | $1^+$ | 12.6 |
| 257 | 26.2 | 1.10 ± 0.15 | 1 | $1^-,1^+$ | - | $1^-$ | 17.5 |
| 318 | 11.0 | 1.10 ± 0.15 | 1.13 ± 0.16 | $1^-,1^+$ | + | $1^+$ | 7.7 |
| 547 | 12.3 | 1.14 ± 0.16 | 0.94 ± 0.13 | $1^-,1^+$ | | $1^-(1^+)$ | 8.2 |
| 620 | 17.2 | 1.80 ± 0.25 | 1.81 ± 0.25 | $1^+$ | | $1^+$ | 14.6 |
| 660 | 8.6 | 1.15 ± 0.16 | 1.37 ± 0.20 | $1^+$ | | $1^+$ | 6.3 |
| 860 | 10.0 | 1.51 ± 0.21 | 1.46 ± 0.20 | $1^+$ | | $1^+$ | 7.8 |

[a] Errors in measurement of area are less than 10%. The integrations were carried out on the 135° data of Fig. 1.

[b] No states with values larger than 3 eV were observed between 860 and 1200 keV.

[c] Ref. 8.

information for the 90-keV resonance has been published. The large cross-section ratios for the 114- and 182-keV resonances together with their symmetric shapes in the neutron data firmly establish their $1^+$ assignment. The two possibilities for the 129-keV resonance are equally probable.

The asymmetric shape of the prominent 257-keV resonance in the neutron data (together with its observation here) establishes its $1^-$ assignment. The 318-keV level is symmetric in the neutron data, and also its peak height is several times the theoretical maximum neutron total cross section for an $l=0$ resonance; thus, it must have positive parity. The $1^-$ assignment for the 547-keV resonance is somewhat uncertain, but was selected because the cross-section ratio for $1^-$ states always is 1, while the ratio for $1^+$ states can vary (see above). The two independent angular-distribution measurements reported here provide very strong support for the $1^+$ assignments for the 620- and 860-keV resonances; that for the 660-keV resonance is a little weaker.

Knowing the ratio $R$, the photon wavelength $ƛ$, and the statistical factor $g=(2J+1)/2(2I+1)$ for each resonance, the values for $\Gamma_{\gamma 0}$ can be calculated from

$$\Gamma_{\gamma 0}=\tfrac{1}{3}(2+R)4\pi A/2\pi^2ƛ^2 g.$$

These values are given in the last column of the table.

The total $M1$ strength of the seven states definitely assigned to have $J^\pi=1^+$ is 50.8 eV. The total assigned strength for $E1$ transitions is 30.5 eV; for $E2$ transitions, 0.64 eV. These values are uncertain by ±20%, owing to uncertainty in the normalization to the 40.8-keV resonance. Further, about 16 small resonances (average $\Gamma_{\gamma 0}\sim 2$ eV) were detected below $E_l=850$ keV, but were not assigned. If it is assumed that the resonance parameters are equally divided among $1^+$, $1^-$, and $2^+$, then an additional 10 eV of $M1$ strength would become possible. Combining this 10-eV uncetainty with that resulting from the normalization, the integrated $M1$ strength measured in this experiment becomes $50.8^{+14}_{-10}$ eV.

According to the shell model, the $M1$ excitation strength in $^{208}$Pb arises from spin-flip transitions from the $i_{13/2}$ neutron shell and the $h_{11/2}$ proton shell. The single-particle (Weisskopf) widths[10] for these transitions are 8.0 and 11.5 eV, respectively. However, polarization effects caused by spin-dependent forces between the excited particle and the residual nucleus[11] should be taken into account; these effects typically reduce the effective magnetic moments by about a factor of 2,[12] and therefore the widths by a factor of 4. The present measured strength, therefore, is at least five times the average single-particle width.

Since the $i_{13/2}$ and $h_{11/2}$ orbits in $^{208}$Pb each contain more than one particle, the total $M1$ strength should be several times the single-particle value. This strength has been calculated by Weiss,[13] neglecting polarization effects, to be 100 eV, consisting of 43 eV for the $i_{13/2}$ neutrons and 57 eV for the $h_{11/2}$ protons. Thus, if polarization effects actually are not present, the present measured $M1$ strength would be only about half the total required, and additional strength should be present outside the energy range studied here [perhaps in the $(\gamma, \gamma)$ cross-section peaks found by Axel et al.[14] below the $(\gamma, n)$ threshold (7.4 MeV)]. Indeed, Gillet, Green, and Sanderson[15] calculate a splitting of the order of 1 MeV for the $M1$ strength in Pb$^{208}$. But if polarization effects in fact reduce the expected $M1$ strength by only a factor of 2, then the $1^+$ levels identified here exhaust the entire $M1$ strength for this nucleus.

Finally, it should be pointed out that 96% of the $M1$ strength detected here is associated with only five resonances, whose variation in size is approximately a factor of 2. This group of resonances represents, in a sense, a particle-hole doorway state for photons. However, the configurations for the $1^+$ states themselves, which might be thought to be more complex, are rather severely restricted. Since the measured values for $\Gamma_{\gamma 0}$ are at least half the Weisskopf estimate, the major portion ($\gtrsim 50\%$) of the wave functions of these states must be a linear combination of one-particle, one-hole configurations.

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