Giant $M1$ resonance in ^{207}Pb†

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The ^{207}Pb(γ,n) reaction has been studied with high-energy resolution and photon intensity to determine radiation widths, spins, and parities of resonances. The present data show an intense p-wave strength. A comparison between the measured and calculated integrated $M1$ strength suggests the existence of a giant $M1$ resonance in ^{207}Pb. The distribution of p-wave resonances suggests an envelope of $M1$ strength centered at $E_n \approx 700$ keV. No evidence was found for the photon doorway in ^{207}Pb(γ,n) proposed in earlier studies. This state had been interpreted as a common doorway occurring in both the photon and neutron channels.

[NUCLEAR REACTIONS ^{207}Pb(γ,n), $E=7.40$ and 8.28 MeV, measured $\sigma(E_n,\theta)$; deduced J, Γ_{γ_0}. Enriched target.]

I. INTRODUCTION

Rapid variation in the average strength of $M1$ transitions as a function of photon energy and atomic mass was first predicted by Mottelson.[1] The basic idea was that the strength is enhanced for states in regions of excitation containing strong two-quasiparticle excitations generated by spin-flip transitions between subshells of given shell-model orbitals split by spin-orbit coupling. The possibility of $\pi(h_{11/2})^{-1}(h_{9/2})$ and $\nu(i_{13/2})^{-1}(i_{11/2})$ excitations in ^{208}Pb makes that nucleus a promising one to study. Indeed, the Livermore group[2] found strong evidence for a giant $M1$ resonance at about 7.8 MeV in ^{208}Pb. They reported that the integrated strength of individual states in the proposed giant resonance was 50.8 eV (about 5 Weisskopf units and at least half of the maximum expected). However, subsequent measurements[3] at Argonne indicated that only 20 eV of this strength could be assigned with certainty because the possibility of s- and d-wave admixtures in the decay of 1^- states prevented definitive spin and parity assignments for the resonances at higher neutron energies. Unfortunately, recent reports notwithstanding,[4] no further information on the parities of these states can be obtained from studies of the total cross section of ^{207}Pb. In view of continuing interest in giant multipole resonances, a search for the same enhancement of $M1$ strength in ^{207}Pb(γ,n) appeared promising. Because $J^{\pi}_{\text{g.s.}}=0^+$ for ^{206}Pb, only one decay-channel spin and parity can occur for each resonance. No ambiguity arising from partial-wave admixtures can occur, and a more accurate study of $M1$ transitions should be possible.

A second reason for interest in the reaction ^{207}Pb(γ,n) is evidence for a common doorway state in ^{207}Pb with $J^{\pi}=\frac{1}{2}^+$ observed in both the ^{206}Pb$+n$ and the ^{207}Pb$+\gamma$ reactions.[5-7] Localization of strength in both reactions was reported, as well as a correlation between neutron and γ-ray widths. This case has been considered one of the best examples of a doorway common to both reaction channels. However, a recent examination[8] has indicated that the proposed explanation of this common doorway in terms of a 2p-1h excitation implies too high an energy and too large an integrated strength to be consistent with the data. Instead, the doorway state was described in terms of a $2g_{9/2}$ neutron coupled to a 4^+ vibrational state of the ^{206}Pb core. If this second interpretation is correct, a correlation between neutron and γ-ray widths is unexpected because the radiative transition is basically a single-particle transition not particularly influenced by the presence of such a collective doorway. In addition, studies[9] of capture in ^{206}Pb suggests that the resonance structure of ^{207}Pb is more complex than previously realized.

In view of the interest in these results, we have repeated the ^{207}Pb(γ,n) measurements with improved energy resolution and higher photon intensity. The results indicate the existence of a giant $M1$ resonance in ^{207}Pb. Several resonances reported in the earlier work were found to be multiplets which could be resolved in the present measurements. As a consequence new results were found for relative widths of several resonances, and angular distributions were measured in order to make spin assignments. The results of our correlation analysis are consistent with a correlation coefficient of zero, indicating no evidence for a common doorway in the ^{207}Pb$+\gamma$ reaction.

II. EXPERIMENTAL PROCEDURE

The data were obtained at the Argonne threshold photoneutron facility at the high-current linac. The

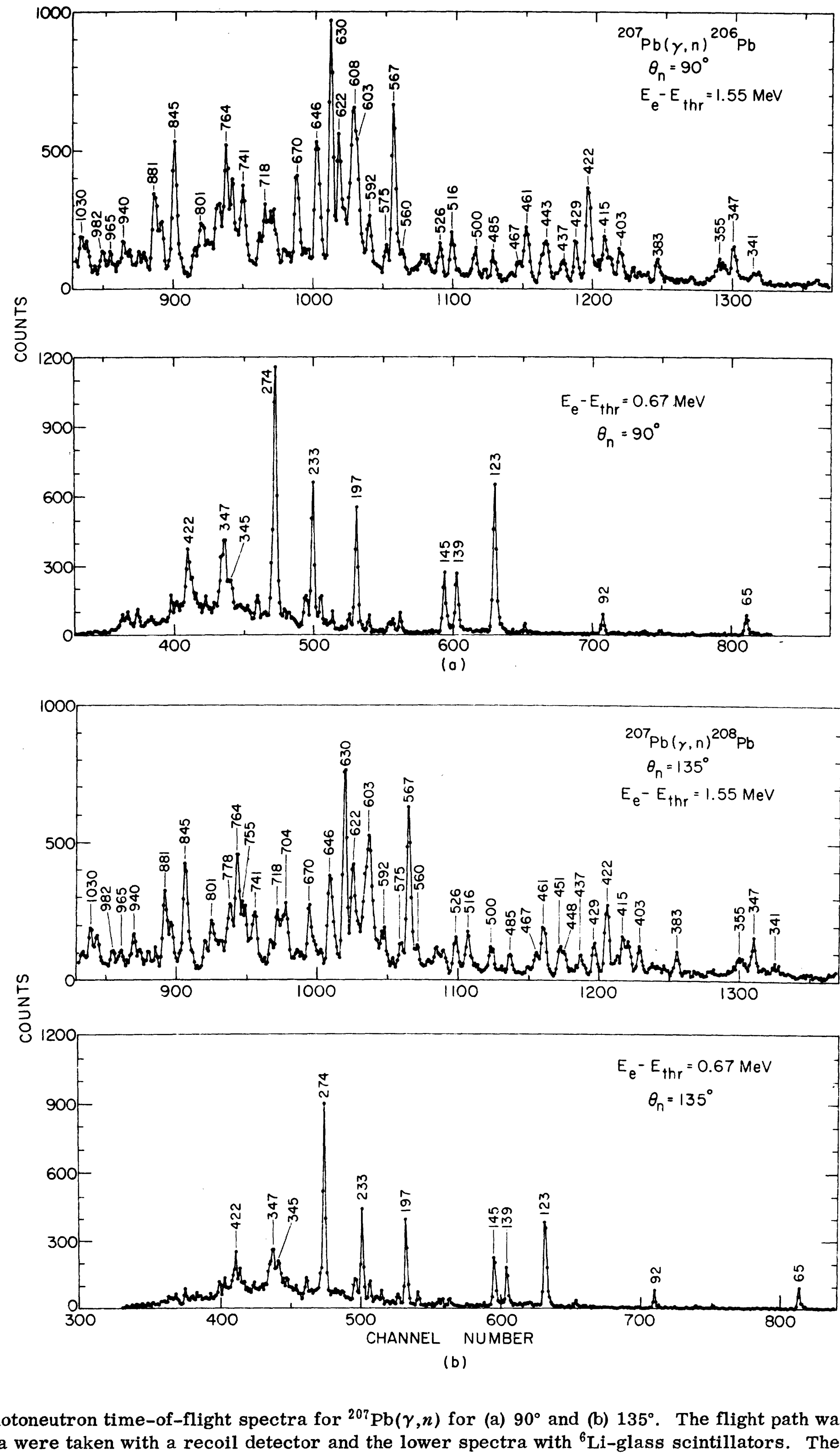

FIG. 1. Photoneutron time-of-flight spectra for ^{207}Pb(γ,*n*) for (a) 90° and (b) 135°. The flight path was 9 m. The upper spectra were taken with a recoil detector and the lower spectra with ^{6}Li-glass scintillators. The peaks are labeled with the neutron lab energies in keV measured in the present (γ,*n*) experiment. The resonance at E_n = 500 keV was shown to result from the decay to the first excited state in ^{206}Pb.

TABLE I. Calculated ratios of the cross sections at 90 and 135° for the expected spin sequences. I and J are the spins of the ground state and excited state, respectively, in ^{207}Pb.

Spin sequence $I \to J \to 0^+$	Neutron decay	Multipolarity	$R \equiv \frac{(d\sigma/d\Omega)_{90°}}{(d\sigma/d\Omega)_{135°}}$
$\frac{1}{2}^- \to \frac{1}{2}^+ \to 0^+$	s wave	$E1$	1.0
$\frac{1}{2}^- \to \frac{1}{2}^- \to 0^+$	p wave	$M1$	1.0
$\frac{1}{2}^- \to \frac{3}{2}^- \to 0^+$	p wave	$M1$	1.43
		$M1+E2$	$0.67 \le R \le 1.43$
		$E2$	0.67
$\frac{1}{2}^- \to \frac{3}{2}^+ \to 0^+$	d wave	$E1$	1.43

experimental technique has been described in detail elsewhere.[10] A 1.02-mm-thick Ag converter on the front of a 5-cm-thick Al stopping block was struck by the electron beam. The resulting bremsstrahlung irradiated a 1-mm-thick target of ^{207}Pb, enriched to 92.8%. The end-point energy of the beam was adjusted so that the nuclear states of interest excited by photon absorption could decay only by neutron emission via a transition to the ground state of ^{206}Pb or by radiative decay to lower states in the target.

Observations were made at 90 and 135° to the electron beam with 9-m flight paths. The over-all time-of-flight resolution was typically 0.4 ns/m. The duration of each run was approximately 16 h. Data taken for ^{207}Pb(γ,n) at 90° are shown in Fig. 1. Observations covering the low-energy region (lower two sections of Fig. 1) were taken with a ^{6}Li-glass neutron detector, while those covering the higher-energy region (upper two sections of Fig. 1) were made with a proton-recoil detector. Energies of neutrons from the total capture cross sections of ^{206}Pb agree very well with the energies of the present observed resonance energies upon correcting the latter for recoil effects. Shifts of more than 2 keV in the values of the neutron energies reported here lead to serious inconsistencies between those values and the energies reported for strong resonances in ^{206}Pb(n, tot). The energies and resonance parameters are listed in Table II.

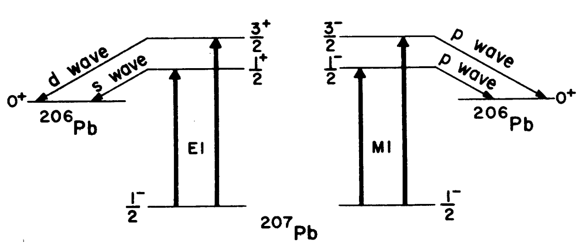

FIG. 2. Excitation and decay scheme for the reaction ^{207}Pb(γ,n). The excitation is assumed to result from dipole photon absorption, and decay is assumed to be by neutron emission to the ground state of ^{206}Pb.

In the thin-target approximation, the yield in the neutron channel for a given level is

$$Y(\lambda\!\!\!^{-}) = 2\pi^2 \lambda\!\!\!^{-2} g \Gamma_{\gamma_0} \Gamma_n / \Gamma ,$$

where $g = \frac{1}{2}(2J+1)/(2I+1)$ is the statistical factor. I and J are the spins of the target and excited state, respectively, $\lambda\!\!\!^{-}$ is the reduced photon wavelength, Γ_{γ_0} is the radiative width for direct decay to the ground state of the target, and Γ_n and Γ are the neutron and total resonance widths, respectively. The individual resonance yields were analyzed by means of a peak fitting computer program to determine the values of $g\Gamma_{\gamma_0}\Gamma_n/\Gamma$. Using tabulated optical-model transmission coefficients[11] for $l \le 1$, we have estimated $\langle \Gamma_n \rangle / \langle \Gamma \rangle > 0.99$ for the region of interest. On this basis, the values of Γ_{γ_0} can be derived from the measured yield. The experimental values of Γ_{γ_0} were normalized to a value of $\Gamma_{\gamma_0} = 4.04 \pm 0.08$ eV for the 275-keV resonance. This value was obtained by comparing the relative yields of the 275- and 254-keV photoneutrons from a natural lead target and by assuming a value $\Gamma_{\gamma_0} = 16.4$ eV for the 254-keV resonance which occurs in the ^{208}Pb(γ, n) reaction.[3]

The spins of states excited in the (γ, n) reaction were determined from the angular distributions of the photoneutrons by comparing the measured and calculated values of the ratio $R = (d\sigma/d\Omega)_{90°}/(d\sigma/d\Omega)_{135°}$. (See Fig. 2.) The experimental values of R were obtained by normalizing the photoneu-

TABLE II. Energies and parameters for s-wave resonances in the ^{206}Pb(n,γ) and ^{207}Pb(γ,n) reactions. The $E_n(n,\gamma)$ in column 4 were calculated from the measured $E_n(\gamma,n)$.

^{206}Pb(n,γ)				^{207}Pb(γ,n)		
E_n [a] (±0.2%) (keV)	E_n [b] (keV)	Γ_n^0 (eV)	$E_n(n,\gamma)$ Calc. (keV)	$E_n(\gamma,n)$ Obs. (keV)	R (90°/135°)	$\frac{\Gamma_{\gamma_0}\Gamma_n}{\Gamma}$ (eV)
	66.0	0.97	66	65.	0.91 ± 0.10	1.8
	206.0	2.64	204	202	0.94 ± 0.11	0.5
	218.5	1.82	219.1	216.4	0.95 ± 0.13	0.4
	255.5	2.97	255	252	0.83 ± 0.13	0.17
(346)	346.0	13.60	345	341	1.04 ± 0.16	1.6
352.6	353.5	6.73	351	347	1.06 ± 0.18	5.6
378.5	381.3	4.70	...	...	...	...
395.2	394.8	7.64	...	...	...	...
(418)	420.0	7.72	420	415	1.06 ± 0.14	2.5
493.0	493.3	12.53	(495)	(490)		(0.4)
549.0	548.7	7.29	(548)	(541)		(0.7)
(617)	618.5	5.09				
(658)	661.5	0.92	...	...	...	...
	681.2	1.21		...	...	...
	725.0	2.35	726	718	1.10 ± 0.17	5.9
			N = 10	Total		19.6

[a] Reference 9.
[b] Reference 5.

TABLE III. Energies and resonance parameters for states below 718 keV with $J^{\pi}=\frac{1}{2}^{-}$ and $\frac{3}{2}^{-}$. The $E_n(n,\gamma)$ in column 2 were calculated from the measured $E_n(\gamma,n)$.

^{207}Pb(γ,n) $E_n(\gamma,n)$ Obs. (keV)	^{206}Pb(n,γ) $E_n(n,\gamma)$ Calc. (keV)	E_n [a] (±0.2%) (keV)	^{207}Pb(γ,n) R (90°/135°)	$g\frac{\Gamma_{\gamma_0}\Gamma_n}{\Gamma}$ (eV)
16.2	16.5		0.87 ± 0.12	0.22
24.8	25.2		1.09 ± 0.30	0.15
92	92		0.84 ± 0.14	0.8
114	115		1.18 ± 0.27	0.33
123	125		1.14 ± 0.07	5.4
139	141		1.23 ± 0.10	2.1
145	147		0.91 ± 0.08	2.5
168	170		1.31 ± 0.25	0.31
172	174		0.89 ± 0.16	0.3
197	199		0.99 ± 0.06	4.0
215	218		0.89 ± 0.09	0.3
226	229		1.12 ± 0.10	0.4
240	243		0.98 ± 0.08	0.7
256	259		1.20 ± 0.15	0.4
263	266	267.1	1.28 ± 0.20	0.5
274	277	277.6	1.09 ± 0.10	4.0
278	281		1.28 ± 0.30	0.7
297	301		1.23 ± 0.11	1.5
311	315	315.7	1.22 ± 0.14	0.6
333	337		1.22 ± 0.12	0.9
344	348	350.0	1.05 ± 0.24	1.0
351	355		1.09 ± 0.10	1.5
367	371		1.09 ± 0.21	0.8
383	387		1.11 ± 0.16	1.4
403	408	(408)	1.00 ± 0.12	1.5
409	413		0.91 ± 0.26	0.8
412	417	418	1.17 ± 0.10	2.6
422	426	429	1.25 ± 0.08	5.8
429	434	436	1.13 ± 0.12	2.1
437	442	440	1.14 ± 0.18	1.5
451	456		1.12 ± 0.14	1.2
516	522		0.97 ± 0.11	2.1
526	532	528	0.97 ± 0.12	1.7
544	550		0.86 ± 0.19	0.5
560	566		1.04 ± 0.13	1.3
567	573	576	0.96 ± 0.05	7.7
575	581		1.15 ± 0.17	1.3
600	607		0.93 ± 0.09	2.1
616	623	619	1.20 ± 0.09	2.5
622	629	631	1.25 ± 0.07	5.9
630	637		1.10 ± 0.05	10.7
642	649		1.13 ± 0.14	1.4
686	693		1.28 ± 0.15	0.8
698	706		0.97 ± 0.10	2.8
704	712		1.28 ± 0.12	2.2
N = 45		Total		89.5

[a] Reference 9.

tron spectra to the ratio of the total charge collected during the 90 and 135° runs. This normalization was checked by requiring that known s-wave resonances have $R=1.0$. A second check was to compare R for the 275-keV resonance with the value (normalized to the isotropic 254-keV resonance in ^{208}Pb) in a run with a PbO target. The possible values of R are shown in Table I. Where possible, the $E1$ excitations were located by identifying isotropic resonances which correspond

TABLE IV. Neutron resonance energies and parameters for states in ^{207}Pb with $J^{\pi}=\frac{3}{2}^{\pm}$. The $E_n(n,\gamma)$ in column 2 were calculated from the measured $E_n(\gamma,n)$.

^{207}Pb(γ,n) $E_n(\gamma,n)$ Obs. (keV)	^{206}Pb(n,γ) $E_n(n,\gamma)$ Calc. (keV)	E_n (±0.2%) (keV)	^{207}Pb(γ,n) R (90°/135°)	$g\frac{\Gamma_{\gamma_0}\Gamma_n}{\Gamma}$ (eV)
82.8	83.9		1.30 ± 0.35	0.11
175	177		1.37 ± 0.29	0.28
233	235		1.36 ± 0.09	1.4
260	263		1.31 ± 0.19	0.8
267	271		(2.03)	0.8
289	293	291.2	1.38 ± 0.18	0.7
305	309	305.6	1.43 ± 0.22	0.5
338	342		1.49 ± 0.11	0.8
355	359	358.8	1.39 ± 0.18	1.4
395	400	402.2	1.30 ± 0.24	1.0
448	453	455	1.53 ± 0.17	2.1
461	466	469	1.30 ± 0.13	3.2
467	472	474	1.48 ± 0.26	1.1
485	490	493	1.48 ± 0.26	1.1
540	546	549	1.36 ± 0.19	1.1
586	593		(2.21)	0.9
592	599		1.53 ± 0.11	2.6
603	610	612	1.65 ± 0.10	6.5
646	654		1.36 ± 0.07	5.9
657	664		1.68 ± 0.20	1.0
663	670		1.37 ± 0.29	0.9
670	677		1.54 ± 0.11	3.9
679	687		1.65 ± 0.36	0.8
711	719		1.39 ± 0.13	2.2
726	734		1.44 ± 0.14	0.5
741	749		1.40 ± 0.11	3.3
755	763		1.40 ± 0.09	4.0
790	798		1.55 ± 0.19	1.2
899	909		1.40 ± 0.20	1.1
912	922		1.45 ± 0.21	1.1
928	938		1.40 ± 0.19	1.4
965	976		1.30 ± 0.17	1.7
982	993		1.46 ± 0.17	1.8
1047	1059		1.50 ± 0.24	2.1
1107	1119		1.71 ± 0.23	2.0
1122	1134		1.58 ± 0.16	3.5
1194	1207		1.38 ± 0.16	3.2
1260	1274		1.65 ± 0.18	4.6
1293	1307		1.36 ± 0.24	1.9
1343	1358		1.30 ± 0.21	3.0
N = 40		Total		77.3

to s-wave resonances determined in ^{206}Pb total cross-section measurements.[5] Depending on the admixture of $E2$ excitations, R can vary from 0.67 to 1.43 for $\frac{3}{2}^-$ resonances. Therefore, for resonances with $R \approx 1.0$, states with $J^\pi = \frac{1}{2}^-$ and $\frac{3}{2}^-$ could not be distinguished. However, for a large fraction of the resonances, the measured values from the present study are $1 < R < 1.43$. This implies $E2$ admixtures less than 5% for these resonances. Because $R < 1.43$, most of the resonances are not d wave and are assumed to be p wave arising from $M1$ and $M1+E2$ excitations. Therefore, the lower limit on the value of the $M1$ strength could be estimated on the basis of the present data.

III. RESULTS

The s-wave resonances in the (γ, n) spectrum were located from the measured[5] total neutron cross sections of ^{206}Pb. The excellent agreement in energies is shown in Table II. Resonances were found which correspond to 10 of the 15 known s waves. In Table III, the parameters are listed for non-s-wave resonances with $E_n < 717$ and with $R < 1.43$ (and therefore identified as p-wave resonances arising from $M1+E2$ excitations). The data on resonances with $R = 1.43$ ($J = \frac{3}{2}$) are listed in Table IV for the whole energy range studied presently. Table V contains the data on resonances with $R < 1.43$ ($J^\pi = \frac{1}{2}^\pm$ and $\frac{3}{2}^-$) in the region $E_n > 717$, over which no neutron cross-section data is available for identification of s-wave resonances.

An important feature of the present measurements is the intense p-wave strength (as seen in Table VI). 45 resonances were identified as due to $M1$ and $M1+E2$ transitions to states with $J^\pi = \frac{1}{2}^-$ and $\frac{3}{2}^-$. The measured integrated strength is $\sum g\Gamma_{\gamma_0} = 89.5$ eV. A minimum value of the $M1+E2$ strength can be calculated from this value by assuming that all the $\frac{3}{2}^-$ resonances are contained in this group and that the number of states with spin J is proportional to $(2J+1)$. Then the average value of g is $\frac{5}{6}$. The minimum $M1+E2$ integrated strength is therefore $\sum \Gamma_{\gamma_0} = 108$ eV. In addition, for the 12 resonances with $E_n > 717$ keV (Table V), 17 eV of strength is due to spin sequences with $1.0 < R < 1.43$ and therefore must be due to $M1+E2$ transitions to $\frac{3}{2}^-$ states. The lower limit of $M1+E2$ integrated strength can then be placed at 125 eV. An exact value cannot be obtained without further information about the parities of spin-$\frac{3}{2}$ resonances. If $\rho(J) \propto 2J+1$ is assumed, the number of s-wave resonances in the region $E_n < 717$ keV would imply that most of the 40 resonances with $J = \frac{3}{2}$ (whose strength is $\sum g\Gamma_{\gamma_0} = 77.3$ eV) are $J^\pi = \frac{3}{2}^-$ and that the total $M1$ strength is ~200 eV.

Another point of interest is the extent to which the observed distribution of radiative strength among s-wave resonances can be interpreted as evidence for a common doorway state. Sharp concentrations of strength in a small energy interval represent clear departures from the usual statistical picture and imply the existence of doorway states if the spins and parities correspond to simple excited-state configurations of the target. A common doorway would be described by the isolated doorway in the neutron channel plus admixtures of doorways which allow for γ decay. The presence of a common doorway state will manifest itself in corresponding anomalous concentrations of strength in two reaction channels. In the case of ^{207}Pb, such evidence has been reported in the total cross-section data of Farrell *et al.*[5] and in the (γ, n) results of Baglan, Bowman, and Berman.[7] The present high-precision study should provide a definitive test for the proposed doorway state.

The results of an analysis of the correlation between the ground-state radiation widths Γ_{γ_0} and the

TABLE V. Neutron resonance energies and parameters for states in ^{207}Pb with $J^\pi = \frac{1}{2}^\pm$ and $\frac{3}{2}^-$ and with $E_n > 717$ keV. The $E_n(n,\gamma)$ were calculated from the measured $E_n(\gamma,n)$.

$E_n(\gamma,n)$ Obs. (keV)	$E_n(n,\gamma)$ Calc. (keV)	R(90°/135°)	$g\frac{\Gamma_{\gamma_0}\Gamma_n}{\Gamma}$ (eV)
764	772	1.05 ± 0.05	6.8
778	787	1.13 ± 0.07	4.2
801	810	1.19 ± 0.09	2.8
845	854	1.14 ± 0.12	8.0
869	879	1.21 ± 0.06	3.0
881	891	1.04 ± 0.10	4.5
940	951	1.09 ± 0.10	2.7
1015	1027	0.88 ± 0.09	2.8
1030	1041	0.95 ± 0.09	3.8
1069	1080	1.26 ± 0.08	7.2
1095	1107	0.75 ± 0.07	3.9
1165	1177	1.16 ± 0.13	2.6
$N = 12$	Total		52.3

TABLE VI. Integrated strengths of excitations to states with spin and parity J^π. N is the number of states observed. The first three entries are for $E_n \le 717$ keV.

J^π	Multipolarity	N	$\sum g\frac{\Gamma_{\gamma_0}\Gamma_n}{\Gamma}$ (eV)
$\frac{1}{2}^+$	$E1$	10	9.8
$\frac{1}{2}^-, \frac{3}{2}^-$	$M1, M1+E2$	45	89.5
$\frac{3}{2}^\pm$	$E1, M1$	40	77.3
$E_n > 717$ keV $\frac{1}{2}^\pm, \frac{3}{2}^\pm$	$E1, M1, M1+E2$	8	35.1
$E_n > 717$ keV $\frac{3}{2}^-$	$M1+E2$	4	17.2

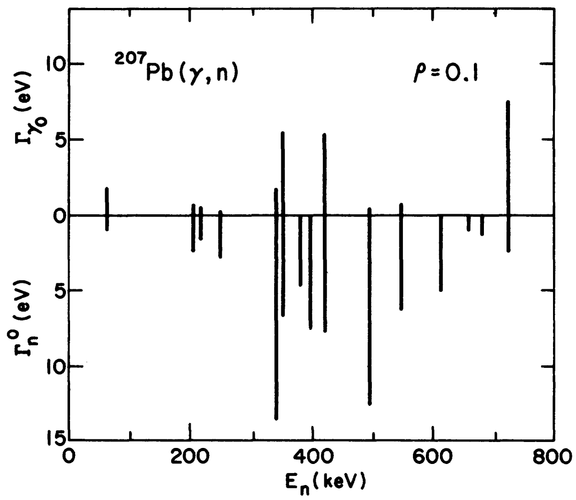

FIG. 3. Reduced neutron widths and ground-state radiation widths for resonances in the ^{207}Pb compound nucleus with $J^\pi = \frac{1}{2}^+$.

neutron widths reported by Farrell *et al.* are shown in Fig. 3. No strong evidence for a correlation can be seen, and this result is confirmed by the value of the correlation coefficient

$$\rho = \frac{\sum_i (\Gamma_{\gamma_{0i}} - \langle\Gamma_{\gamma_0}\rangle)(\Gamma^0_{ni} - \langle\Gamma^0_n\rangle)}{\left[\sum_i (\Gamma_{\gamma_{0i}} - \langle\Gamma_{\gamma_0}\rangle)^2 \sum_j (\Gamma^0_{nj} - \langle\Gamma^0_n\rangle)^2\right]^{1/2}} = 0.1\,,$$

which is obtained for the 15 $\frac{1}{2}^+$ resonances observed in the neutron reaction (see Table II). The probability of obtaining the result $\rho > 0.1$ from 15 paired observations is ≈ 0.30 when $\rho_{\rm true} = 0$. Our results should therefore be interpreted as consistent with a correlation of zero.

This conclusion is in clear disagreement with the earlier results of Baglan, Bowman, and Berman,[7] who reported a strong correlation between Γ_n^0 and Γ_{γ_0} for 10 $\frac{1}{2}^+$ resonances below 600 keV. If our correlation analysis is restricted to the same energy region they studied, we obtain the result $\rho = 0.2$ in contrast to their result, $\rho = 0.44$. (The probability of obtaining the result $\rho > 0.2$ from 10 paired observations is ≈ 0.30 when $\rho_{\rm true} = 0$.) A clue to the origin of this discrepancy can be found by comparing the individual widths and integrated strengths for the s-wave resonances measured in the two experiments. The values of Γ_{γ_0} in Table II are very much less than those reported by the Livermore group. The integrated strength, 19.6 eV, is less than half that reported by Baglan, 48.6 eV. This discrepancy cannot be attributed to an error in absolute normalization of one of the experiments. The integrated strength of all ground-state resonances measured in the two experiments in the corresponding energy region were compared to check this point. From the data of Ref. 6, $\sum g\Gamma_{\gamma_0}\Gamma_n/\Gamma = 103$ eV while we find for the same energy region $\sum g\Gamma_{\gamma_0}\Gamma_n/\Gamma = 119$ eV. Thus the normalizations in the two experiments are reasonably consistent. We feel that the suggestion of Allen *et al.*[9] offers a more likely explanation; namely that a major portion of the radiative strength attributed in Ref. 7 to s-wave resonances in reality results from the intense background of much narrower resonances with $l \geq 1$.

IV. DISCUSSION

In order to compare the experimental limit of $M1$ strength with the expected value, we have calculated the strength relative to that in ^{208}Pb. A weak-coupling model in which ^{207}Pb is approximated by a $p_{1/2}$ neutron hole coupled to a ^{208}Pb core can be used to predict the total $M1$ strength. A detailed calculation shows that $\sum\Gamma_{M1}(^{207}\text{Pb}) = 2\sum\Gamma_{M1}(^{208}\text{Pb})$ in this approximation. The factor of 2 can be viewed as arising because twice as many excited states can be populated in ^{207}Pb(γ, n) as in ^{208}Pb(γ, n). The total $M1$ strength for the ^{208}Pb core can in turn be estimated by assuming spin-flip transitions generating states with configurations $\pi(h_{9/2})(h_{11/2})^{-1}$ or $\nu(i_{11/2})(i_{13/2})^{-1}$. Using the relationship between the width and the reduced matrix element,[12] we obtain

$$\sum_{I_f, a_f} \Gamma_{M1} = 0.01158 E_\gamma{}^3 \sum_{I_f, a_f} \Lambda(M1),$$

where

$$\sum_{I_f, a_f} \Lambda(M1) = \sum_\mu |M^1_\mu \psi(^{208}\text{Pb})|^2 .$$

Here I_f and a_f are the spins of the final particle states, μ is the projection 1, 0, or −1 of the final $J = 1$ state, and M^1_μ is the magnetic dipole operator. Expanding this expression in terms of annihilation and creation operators and using the Wigner-Eckhart theorem, one obtains

$$|M^1_\mu \psi(^{208}\text{Pb})|^2 = \tfrac{10}{3} B_{sp} + \tfrac{12}{3} B_{sn},$$

where B_{sp} and B_{sn} are the reduced transition probabilities for protons and neutrons, respectively. After evaluating the B_{sp} and B_{sn}, we find that the integrated strength for ^{208}Pb is

$$\sum\Gamma_{M1} = (52\text{ eV})_\pi + (43\text{ eV})_\nu = 95\text{ eV}.$$

Therefore, the $M1$ strength predicted for ^{207}Pb in the weak-coupling approximation is ~200 eV. This present consideration agrees well with detailed calculations[13] in ^{208}Pb, using a Hamada-Johnston potential, which predicts an $M1$ giant resonance at 7.52 MeV. The calculated width is ~79 eV; however, if the effects of core polarization in the ground state of ^{208}Pb should be important, according to Ref. 13 this value could be reduced to ~61 eV.

From the present results, the measured lower limit (Table VII) is found to be 125 eV, over half of the estimated value. The parities of several states are undetermined and much of the strength ($\sum\Gamma_{\gamma_0}=77.3$ eV) for those may in fact be due to $M1$ transitions. We conclude that the major part of the estimated $M1$ strength is found in the region $E_n<1358$ keV.

It remains to be shown whether or not the $M1$ strength in ^{207}Pb is concentrated in the region studied ($E_n<1358$ keV). Unfortunately, further experimental data on the parities of many resonances reported here are needed in order to make definitive conclusions. Nevertheless, it is instructive to look at the distribution of strengths for (γ, n) resonances. Figure 4 shows a histogram of $g\Gamma_{\gamma_0}$ as a function of E_n for $M1$ and $M1+E2$ transitions tabulated in Table III and the $M1, M1+E2$, and $E1$ transitions tabulated in Table V. The contamination of $E1$ resonances is possible in the latter group because s-wave resonances have not been studied in ^{206}Pb(γ, n) above 718 keV and the parity cannot be determined in the present experiment when the angular distribution is isotropic. The effect of subtracting any $E1$ contaminations in the region $E_n>718$ keV would be to accentuate the concentration shown in Fig. 4. Additional contributions due to transitions to $\frac{3}{2}^{\pm}$ states (Table IV) will modify the histogram; however, the results shown in Fig. 4 are suggestive of an envelope of $M1$ strength centered at $E_n\approx700$ keV.

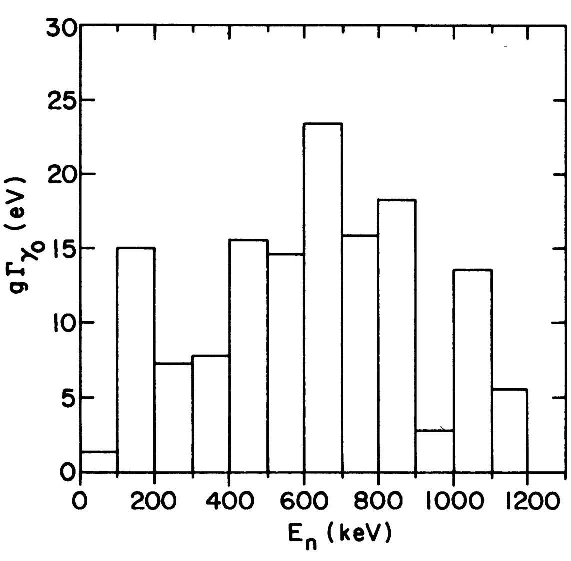

FIG. 4. Histogram of the values of $g\Gamma_{\gamma 0}$ for resonances from Tables III and V. In effect, this population includes $\frac{1}{2}^-$ and $\frac{3}{2}^-$ resonances over the full region and possible contamination of $\frac{1}{2}^+$ resonances in the region above 718 keV. This is true because s-wave resonances have not been studied in ^{206}Pb(γ,n) above this energy.

The reduced widths corresponding to $E1$ and $M1$ radiative transitions in ^{207}Pb were calculated from the expressions

$$\bar{k}_{E1}=\sum\Gamma_{\gamma_0}/E_\gamma{}^3A^{2/3}\Delta E$$

and

$$\bar{k}_{M1}=\sum\Gamma_{\gamma_0}/E_\gamma{}^3\Delta E,$$

where $\bar{k}$ is the average reduced width and ΔE is the energy interval in which resonances were found. Γ_{γ_0} is in eV; ΔE and E_γ are in MeV.

The results of this experiment give $\bar{k}_{E1}=2.2\times10^{-3}$. Axel[14] has estimated the $E1$ photon strength function on the basis of the behavior of the tail of the giant dipole resonance in the excitation region near the neutron binding energy. This leads to a reduced width of

$$\bar{k}_{E1}=(6.1\times10^{-9})E_\gamma{}^2A^2\,.$$

For ^{207}Pb, the estimate is $\bar{k}_{E1}=13.1\times10^{-3}$, larger than the measured value. Axel's relationship has been found to overestimate the reduced widths for heavy nuclei.

The value of $\bar{k}_{M1}$, calculated assuming a two-spin population, is shown in Table VII. The result is based on the total strength observed for all p-wave resonances in the region studied and the assumption that $\bar{k}_{M1}$ is the same for $J^\pi=\frac{1}{2}^-$ and $\frac{3}{2}^-$. The available data on reduced widths for $M1$ transitions have been summarized by Bollinger.[15] The essential conclusion is that the data on nuclei in the range $A=80$–250 are consistent with $\bar{k}_{M1}\approx20\times10^{-3}$. As shown in Table VII, $\bar{k}_{M1}$ is strongly enhanced

TABLE VII. Integrated strengths $\sum\Gamma_{\gamma 0}$ and reduced widths $\bar{k}$ for $M1$ transitions in ^{208}Pb and ^{207}Pb.

	$\sum\Gamma_{\gamma 0}(M1)$		$\bar{k}_{M1}$	
Isotope	Experiment	Calculated	Experiment	Estimate [a]
^{208}Pb	>51 eV [b]	100 eV	>0.12	0.02
^{207}Pb	>125 eV	200 eV	>0.25	0.02

[a] See Ref. 15.
[b] See Ref. 2.

over this value for both ^{207}Pb and ^{208}Pb.

In summary, for ^{207}Pb(γ, n) both the distribution of radiative strength among p-wave photoneutron resonances and the total strength summed over these levels indicate a localization of $M1$ transitions which can be attributed to a giant $M1$ resonance centered at an excitation energy of ~7.5 MeV. The present results agree well with detailed calculations[13] in ^{208}Pb which predict an $M1$ giant resonance at 7.52 MeV. From the present measurements, a lower limit on the integrated $M1$ strength is 125 eV, over half of the estimated value. Until definite parities can be determined for the uncertain assignments, an exact evaluation of the total $M1$ strength from the (γ, n) data is not possible. Further data on the resonances with energies greater than 725 keV are needed in order to identify s-wave resonances. The present study has also investigated the possibility of an $E1$ common doorway state in ^{207}Pb; however, no evidence was found for the proposed state.

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