Particle-Hole States in ^{208}Pb with the Configuration $(d_{5/2}, j^{-1})$*

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Neutron–neutron-hole configurations of states in ^{208}Pb were studied by proton scattering through the $d_{5/2}$ isobaric analog resonance in ^{209}Bi. Angular distributions for the scattered protons were taken from 60 to 173° for the states in ^{208}Pb which have excitation energies between 4.69 and 6.30 MeV. The on-resonance–to–off-resonance ratio for these states was at most 15:1. The resolution in all spectra was 18 keV or better. The data were analyzed to obtain total proton inelastic scattering cross sections. With this information and the proton single-particle widths extracted from elastic scattering data, total inelastic proton partial widths were calculated. Final-state spins were specified by fitting the observed angular distributions with an appropriate expression for the differential cross section and by comparing those results to information derived from other experiments.

I. INTRODUCTION

The low-lying neutron particle-hole configurations of ^{208}Pb have been studied by proton scattering through isobaric analog resonances in an effort to explore and parametrize the unique and simple structure of this doubly-closed-shell nucleus. Previous studies[1,2] have shown that the decay of isolated single-particle analog resonances in ^{209}Bi with spin J preferentially excite bands of states in the residual nucleus with the dominant configurations $(J,p_{1/2}^{-1})$, $(J,f_{5/2}^{-1})$, and $(J,p_{3/2}^{-1})$. Here we report the results of angular distributions taken from 60 to 173° with a maximum step size of 5° for 14 states in ^{208}Pb which have excitation energies between 4.69 and 6.30 MeV and which resonate in proton channels on the $d_{5/2}$ analog state in the compound nucleus ^{209}Bi. By assuming that direct contributions to these levels are negligible, we have extracted the total inelastic widths from the angle-integrated cross section backward from 90°. These results are then compared with the widths calculated by using previously determined shell-model wave functions for ^{208}Pb.[3] Similar data and analysis have been recently published for the $g_{9/2}$ ground-state analog resonance in ^{209}Bi.[4]

II. EXPERIMENT

The data were obtained in two separate experiments. First, studies were done with the three-stage FN Van de Graaff at the University of Washington. Later, further experimental work was performed at the University of Texas at Austin where an EN tandem Van de Graaff plus single-stage CN injector were used to obtain a proton beam of ~0.3 μA at a lab energy of 16.490 MeV. As determined by previous experiments,[1,2,5-7] this energy corresponds to the resonance energy of the $d_{5/2}$ isobaric analog state in ^{209}Bi. The intrinsic width (308 keV) of the resonance compensates for small uncertainties in energy calibrations of the accelerators. Both accelerators are calibrated using the $T=\frac{3}{2}$ resonance in ^{13}N at $E_p = 14.233$ MeV. The beam was energy-analyzed with a 90° magnet and switched into an 18-in. scattering chamber with a second 90° magnet. Collimation was accomplished as described in a previous paper.[8] The target used for the experiment was a 99% enriched ^{208}Pb self-supporting metallic film. The effective thickness of the ^{208}Pb was ~300 μg/cm^2. The charged-particle spectra were obtained with three 2-mm Si(Li) detectors which were positioned at 10° intervals and cooled to dry-ice temperatures. A PDP-7 computer was used on line as a 3072-channel analyzer with 1024 channels for each detector. The energy resolution for this configuration was less than 18 keV in all spectra. Typical spectra are given in Fig. 1.

Absolute differential cross sections were determined by comparing the inelastic scattering data with calculated differential cross sections for the elastic scattering of 5-MeV protons at a lab angle of 90°, where it was assumed that the only contribution to the cross section was from Coulomb scattering (1408 mb/sr).

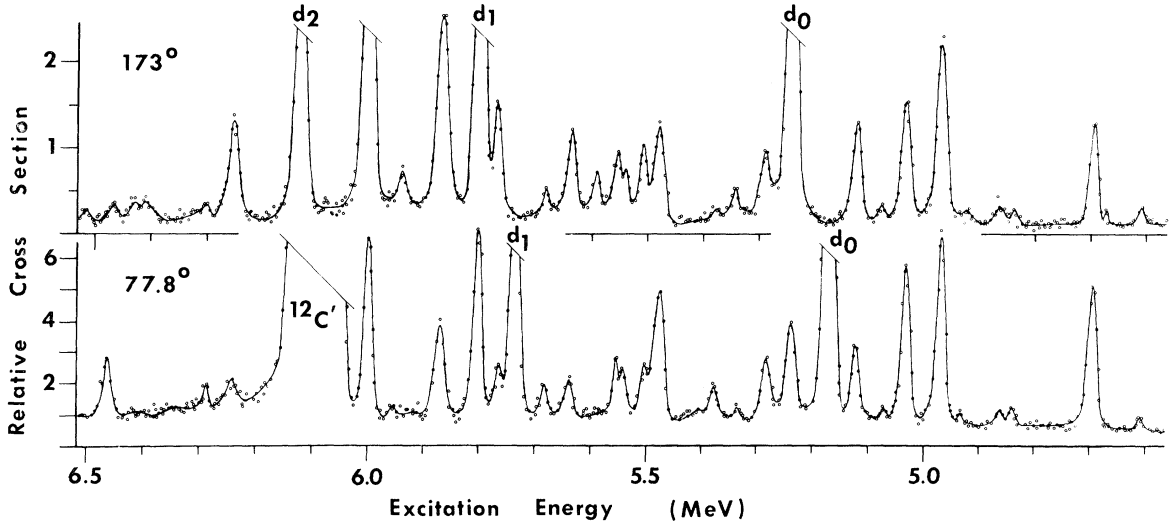

FIG. 1. Spectra of the reaction ^{208}Pb$(p,p')^{208}$Pb* for $E_p^{\text{lab}} = 16.490$ MeV at $\theta_{\text{lab}} = 173$ and 77.8°. Resolution is less than 18 keV full width at half maximum in both spectra.

III. ANALYSIS

The proton decay of an isolated isobaric analog resonance of spin J occurs through all channels spins j, the values of which are restricted to the values of the valence neutrons as allowed by the Pauli principle. These spins, when coupled to the particle spin J, form final neutron–neutron-hole configurations of spin I.[1,2,7] In order to relate the experimental results to those predicted from theoretical wave functions, one has to consider an S matrix of the form[9–11]

$$U_{cc'} = U^D_{cc'} - \frac{i(\gamma_c^J e^{i\phi_c}\gamma_{c'}^J e^{i\phi_{c'}})}{(E - E_0) + i\Gamma/2}, \tag{3.1}$$

where Γ is the total resonance width, E_0 is the resonance energy, and γ_c^J and ϕ_c are, respectively, the reduced width and the phase shift for channel c. If the contribution from the direct process $U^D_{cc'}$ is neglected, we can write the cross section in terms of even-ordered Legendre polynomials so that

$$(d\sigma/d\Omega)_{cc'} = \sum_L A_L P_L\,, \tag{3.2}$$

where for a spin-zero target the maximum value of L is restricted to the smaller value of $(2j_c - 1)$ or $(2j_{c'} - 1)$, where j_c is the spin in the entrance channel and $j_{c'}$ is the maximum spin in the exit channel. Equating the angle-integrated cross section applying the S-matrix formalism to the cross section as given by the above expansion, we get the following expression

$$\Gamma_{p'} = A_0 \frac{8k_{p_0}{}^2}{(2J+1)\Gamma_{p_0}}\left[(E - E_0)^2 + \Gamma^2/4\right], \tag{3.3}$$

where $\Gamma_{p_0} = |\gamma_{p_0}|^2$ is the elastic scattering partial width, and where the total proton inelastic width $\Gamma_{p'}$ for a given state I is taken to mean the sum over the partial widths for each value of j, i.e., $\Gamma_{p'} = \sum_j \Gamma^{p'}_{IjJ}$.

By establishing the proper theoretical expressions for the quantity $\Gamma^{p'}_{IjJ}$, we can make a simple and direct comparison of the measured and calculated values $\Gamma_{p'}$. This is accomplished by using the following expression involving the reduced widths and the nuclear matrix elements

$$\gamma_{IjJ} = \gamma_j^{\text{sp}} \langle (j \otimes \psi_I^A)_J | \psi_J^{A+1}\rangle\,, \tag{3.4}$$

where ψ^A and ψ^{A+1} represent the antisymmetrized wave functions for $|I\rangle$ in the residual nucleus and for $|J\rangle$ in the parent analog nucleus, respectively. The residual state can be written in terms of proton–proton-hole, $\pi(j^{-1}, J)$, and neutron–neutron-hole, $\nu(j^{-1}, J)$, configurations

$$\psi_I = \sum_{\alpha j J}\left[a^J_{Ij\alpha}\nu(j^{-1}, J)_I + b^J_{Ij\alpha}\pi(j^{-1}, J)_I\right], \tag{3.5}$$

therefore[12]

$$\gamma_{IjJ} = \gamma_j^{\text{sp}}\left(\frac{2I+1}{2J+1}\right)^{1/2}(a^J_{Ij\alpha})\,. \tag{3.6}$$

γ_j^{sp} represents the reduced width for the decay of a single-particle analog resonance of spin J. If we evaluate the reduced widths at the proper channel energy, we can reasonably use the values of γ_j^{sp} that have been determined for the decay of the 0^+ analog resonance in ^{208}Bi. This is accomplished[13] by using the ratio

$$\Gamma_j^{\text{sp}}(E_{p'}) = \frac{P_j(E_{p'}, R)}{P_j(E^0_{p'}, R)}\,\Gamma_j^{\text{sp}}(E^0_{p'})\,, \tag{3.7}$$

where the radius $R = 1.4A^{1/3}$ in units of F. The quantities $\Gamma_j^{sp}(E_{p'}^0)$ have been determined previously.[14, 15] For this analysis, they were extracted from a recent measurement of the quantity $(\Gamma_j^{sp}\Gamma_{g_{9/2}})/\Gamma^2$, which is reported to be accurate to within 10%.[15] The subsequent values for the single-particle widths and the corresponding resonant energies that were used in this calculation are

$$\begin{aligned}
\Gamma_{p_{1/2}}^{sp}\ (E_{p'}^0 = 11.49\ \text{MeV}) &= 28.6\ \text{keV}\ ,\\
\Gamma_{f_{5/2}}^{sp}\ (E_{p'}^0 = 10.92\ \text{MeV}) &= 4.2\ \text{keV}\ ,\\
\Gamma_{p_{3/2}}^{sp}\ (E_{p'}^0 = 10.59\ \text{MeV}) &= 15.8\ \text{keV}\ ,\\
\Gamma_{f_{7/2}}^{sp}\ (E_{p'}^0 = 9.15\ \text{MeV}) &= 0.6\ \text{keV}\ .
\end{aligned} \tag{3.8}$$

Employing a more explicit approach, the data were reanalyzed with the following expression for the differential cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_{cc'} = \frac{1}{4k^2}\frac{1}{(2i+1)^{1/2}(2I+1)^{1/2}}\sum_{l'j'}\sum_{\bar{l}'\bar{j}'}\sum_{L}(-l)^{i-i'+I-I'}(2J+1)\overline{Z}(lj\bar{l}\bar{j}\,|\,iL)\overline{Z}(l'j'\bar{l}'\bar{j}'|i'L)$$
$$\times W(jJ\bar{j}J\,|IL)W(j'J\bar{j}'J\,|I'L)(U_{cc'}U_{\bar{c}\bar{c}'}{}^*)P_L^0(\cos\theta_r')\ , \tag{3.9}$$

where $I(i,l)j$, $I'(i',l')j'$ characterize the quantum numbers and coupling scheme in the entrance and exit channels, respectively; where $U_{cc'}$ is given by Eq. (3.1); and where the barred and unbarred quantum numbers independently take on the same set of values. Only the $p_{1/2}$, $f_{5/2}$, and $p_{3/2}$ hole states were assumed to contribute in any significant manner to the final-state configurations. Again we assumed that the contribution from the direct processes could be neglected. We then fit Eq. (3.9) to the data by varying the partial widths Γ_{IjJ}. Coulomb phase shifts were used in the calculation, since the energy of the outgoing proton was considered to be sufficiently below the Coulomb barrier for this approximation to be valid. The use of relation (3.9) is equivalent to restricting the ratio A_L/A_0 of the expansion coefficients in Eq. (3.2). In some cases, one can eliminate certain values of the final-state spin in the process of fitting Eq. (3.9) to the data. The quantities $\Gamma_{p'}$ can be computed from these results and compared with the corresponding values obtained from Eq. (3.3).

IV. RESULTS

The angular distributions for the 14 states in ^{208}Pb between 4.69 and 6.30 MeV in excitation which resonate at the $d_{5/2}$ analog resonance are shown in Fig. 2. The excitation energies used to identify these states were taken from a previous publication.[1] Those results indicate a maximum on-resonance–to–off-resonance ratio of approximately 15 to 1 for the energy levels in this range of excitation.

The angle-integrated cross sections for these states were determined by least squares fitting an even-ordered Legendre polynomial series up to the sixth degree to the data. In order to minimize the effects due to interference between the resonance and direct scattering amplitudes, only the data backward of 90° were used in the analysis. The expansion coefficients and their errors (due only to statistics) are given in Table I along with the quantities $\Gamma_{p'}$ as calculated from Eq. (3.3).

Vector-addition restrictions imposed by the Racah coefficients in Eq. (3.9) prohibit any A_6 term under the assumptions we have made. The fact that these values are nontrivial in some cases indicates the presence of direct contributions to the cross section.

The total inelastic proton widths $\Gamma_{p'}$ versus excitation energy are plotted in Fig. 3. In the process of analyzing similar results at the $g_{9/2}$ resonance,[4] the wave functions of True and Pinkston were used to calculate the quantities $\Gamma_{p'}$. This enabled at least a first-order comparison of states with known spin and parity to the states that were observed. This approach was also attempted in

TABLE I. Coefficients of Legendre-polynomial fits to angular-distribution data from ^{208}Pb(p,p') at $E_p = 16.490$ MeV, as determined by Eq. (3.2). The total proton inelastic widths were derived from these data according to Eq. (3.3).

E_x (MeV)	A_0 (μb/sr)	A_2 (μb/sr)	A_4 (μb/sr)	A_6 (μb/sr)	$\Gamma_{p'}$ (keV)
4.692	154 ± 12	−133 ± 7	74 ± 2.0	−33 ± 1.0	8.7
4.835 4.857	37 ± 6.0	−20 ± 1.6	6 ± 0.3	−21 ± 1.8	2.1
4.967	223 ± 15	−140 ± 5	90 ± 3.0	−40 ± 1.0	12.6
5.030	191 ± 14	−101 ± 4	0.9 ± 0.3	−7 ± 0.3	10.8
5.121	119 ± 11	−69 ± 3.3	19 ± 0.7	6 ± 0.5	6.7
5.284	91 ± 10	−63 ± 3.5	22 ± 1.1	18 ± 1.1	5.1
5.338	30 ± 5.4	−18 ± 1.7	13 ± 1.2	17 ± 1.8	1.7
5.373	64 ± 7.9	−38 ± 2.8	−19 ± 1.5	16 ± 0.8	3.6
5.474 5.505	314 ± 17	−204 ± 6	13 ± 0.1	36 ± 1.0	17.7
5.536 5.554	151 ± 12	−41 ± 2.0	−8 ± 0.4	−12 ± 0.6	8.5
5.646	103 ± 10	4 ± .2	−12 ± 0.6	−9 ± 0.5	5.8
5.869	225 ± 15	−39 ± 1.3	−6 ± 0.3	−16 ± 0.5	12.7
6.000	327 ± 16	61 ± 1.7	51 ± 0.4	−20 ± 0.6	18.4
6.255	42 ± 6.4	34 ± 1.2	14 ± 1.3	−0.9 ± 0.1	2.4

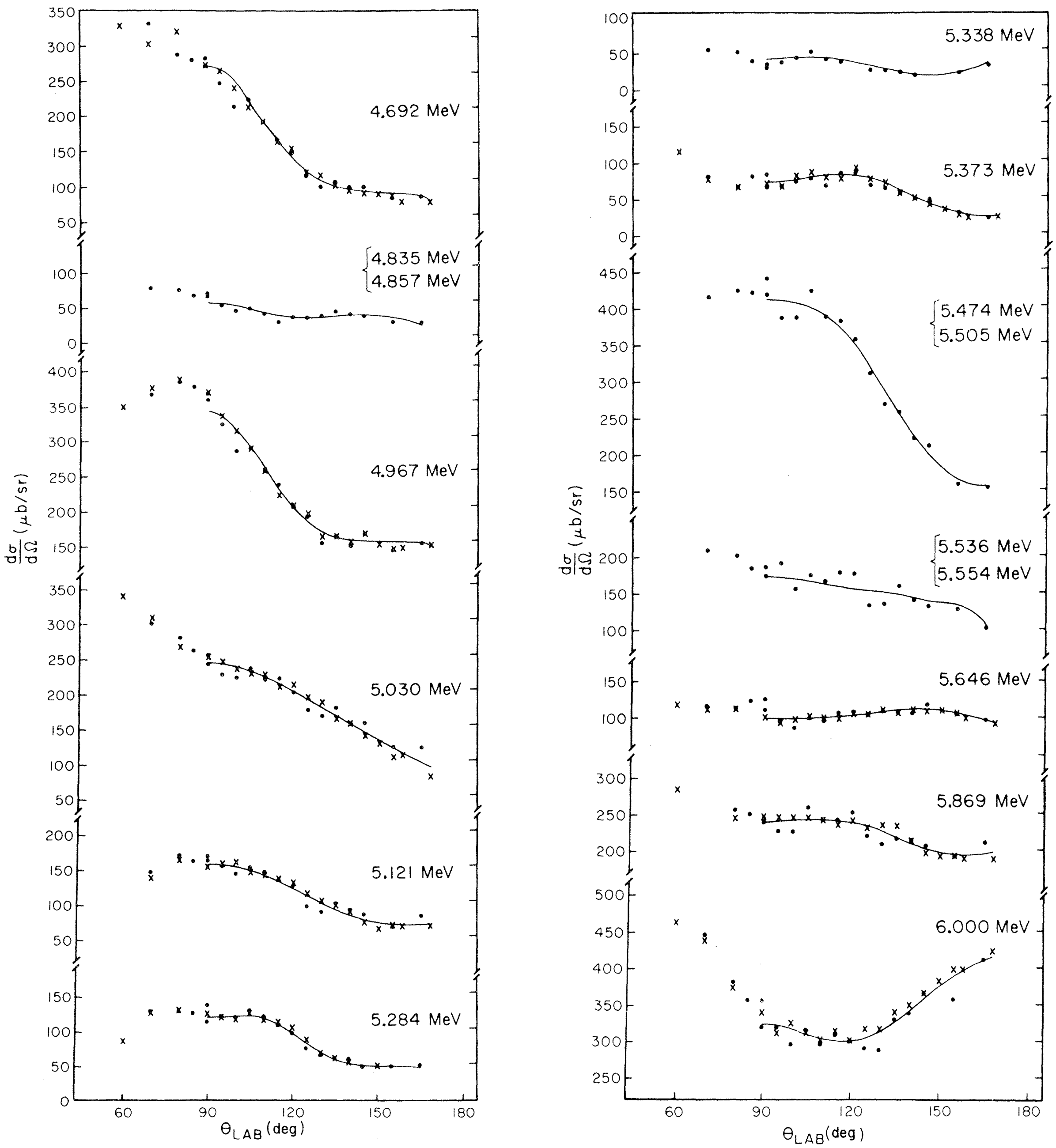

FIG. 2. Angular distributions for states observed in the reaction ^{208}Pb$(p,p')^{208}$Pb* for $E_p^{\mathrm{lab}} = 16.490$ MeV. Excitation energies were taken from Ref. 1. x's represent data taken at the University of Washington. Dots represent data from the University of Texas at Austin. Solid curves represent even-ordered-Legendre-polynomial fits to the data. Coefficients obtained from the fitting procedure are listed in Table I.

this analysis, i.e., the total inelastic proton widths were calculated from those wave functions having a reasonably large $d_{5/2}$ particle amplitude. These results are plotted in Fig. 4. The excitation energies of these states are consistently higher and show only minor correlations in magnitude to the measured widths.

The fits obtained with the use of Eq. (3.9) provided a more reliable means of specifying final-state spins. Correlating these results with the results obtained from other experiments[1,2,16–27] which populate the same final states in ^{208}Pb (shown in Table II), we have been able to specify the spins of various levels or at least restrict the number of possible

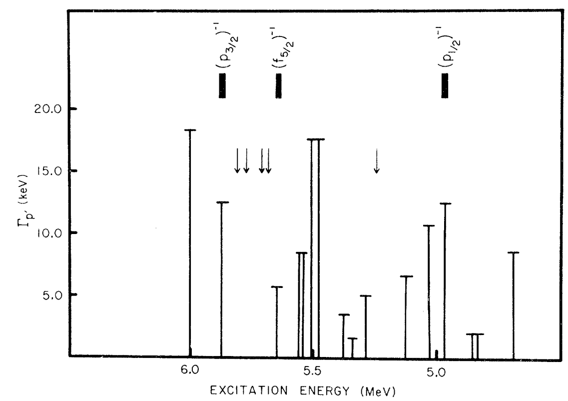

FIG. 3. Total inelastic proton widths extracted from angular-distribution data enumerated in Table I. The bars at the top of the figure represent the positions of the unperturbed particle-hole strengths for the outgoing partial waves being considered. Arrows represent the positions of states that have been observed in spectrograph studies but were obscured by deuterons in our charged-particle spectra. The magnitude of the proton widths for the doublets are shown as double lines. Their size represents the sum of the widths for the states involved.

assignments for any one particular state. No attempt was made to analyze the doublets at 4.835-4.857 MeV, 5.474-5.505 MeV, and 5.536-5.554 MeV. However, other experiments have indicated that the state at 4.602 MeV and the doublet at 4.835-4.857 MeV contain the majority of the $j_{15/2}$ particle strength. The cross sections for these states and the state at 5.338 MeV were considered too small and the statistics too low to get any meaningful information for these levels. The following sections will be devoted to the remaining 10 states.

4.692-MeV state. Inelastic proton scattering and (d,p) stripping reactions have definitely established the $d_{5/2}$ particle nature of this state. Even though it is basically collective in nature, its position with respect to the $p_{1/2}$ hole strength in this

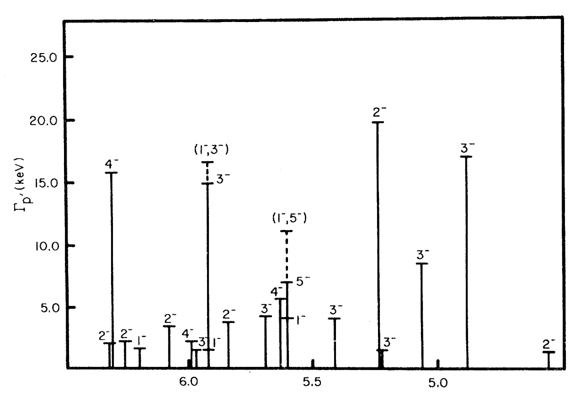

FIG. 4. Total inelastic proton widths calculated from the wave functions of True and Pinkston for states in ^{208}Pb with dominant $d_{5/2}$ particle configurations.

experiment and the $p_{3/2}$ hole strength in a similar experiment[4] performed on the $g_{9/2}$ resonance restricts its final-state spin to 3^- when a simple particle-core coupling picture is assumed. The inelastic scattering data of Wharton *et al.*[2] also indicates a substantial cross section at the $i_{11/2}$ resonance near the $f_{5/2}$ hole strength. This is again consistent with a 3^- assignment. The fit we achieve with Eq. (3.9) is optimum using a 3^- spin and the following values for the inelastic widths: $|\Gamma_{p_{1/2}}| = 2.0$ keV, $|\Gamma_{f_{5/2}}| = 5.0$ keV, and $|\Gamma_{p_{3/2}}| = 1.5$ keV. Recently, this level has been assigned 3^- by Earle *et al.*[16] in a $(d,p\gamma)$ experiment.

4.967-, 5.030-, 5.121-MeV states. The predominant $d_{5/2}$ particle nature of these states is obvious from the tabulated data. An acceptable fit was achieved using a spin assignment of 3^- and the inelastic widths $|\Gamma_{f_{5/2}}| = 9.7$ keV and $|\Gamma_{p_{3/2}}| = 1.5$ keV in the process of fitting the 4.967-MeV level. This same spin and the widths $|\Gamma_{p_{1/2}}| = 3.5$ keV and $|\Gamma_{f_{5/2}}| = 2.5$ keV provided the most acceptable fit for the level at 5.121 MeV. Because of the quadratic character of the appearance of the inelastic widths in Eq. (3.9), these values cannot be considered unique. However, they provided the most reasonable results for the inelastic widths $\Gamma^{p'}_{ljJ}$ that were considered.

Using this method to distinguish between the possible spin assignments for the 5.030-MeV level proved to be ineffective. J^π values of 2^- and 3^- both produced differential cross sections that were consistent with the data. However, other experimenters[16] have assigned this state 3^- which is compatible with our results.

5.284-MeV state. This state receives its predominant particle strength from the $s_{1/2}$ resonance, although some $d_{5/2}$ contributions seem to be present. (d,p) experiments characterize this state as the only strong $s_{1/2}$ particle state. The basic relationship between the (d,p) spectroscopic factor and the differential cross section for that particular reaction implies that the higher spin state from a specific particle-hole coupling should possess the larger cross section. Since no large fractionation is apparent, the spin of this state should be 1^-. This is verified by the $(p,p'\gamma)$ experiment of Cramer *et al.*[22] and the $(d,p\gamma)$ work previously mentioned.

In our analysis, we were unable to fit the angular distribution for this level using a 1^- spin assignment. Instead, a reasonable fit was achieved with a spin of 3^- ($|\Gamma_{p_{1/2}}| = 1.5$ keV, $|\Gamma_{f_{5/2}}| = 3.0$ keV). This indicates the possible presence of an unresolved doublet, which would not have been observed in the ungated $(p,p'\gamma)$ experiment. However, the presence of a $p_{1/2}$ decay width in our analysis and the absence of an appropriate γ ray from the $(d,p\gamma)$

TABLE II. Experimental results for excited states in ^{208}Pb between 4.6 and 6.3 MeV in excitation (widths in keV).

(p,p') Ref. 1		(p,p') Ref. 2			$(d,p\gamma)$ Ref. 16[a]		(d,p) Ref. 17		(d,p) Ref. 18			
E_x	J^π	E_x	$\theta_{p'}$ (deg)	$\lvert n\rangle - \frac{d\sigma}{d\Omega}_{max}$ (μb/sr)	E_x	J^π	E_x	Relative yield (60°)	E_x	$\lvert n\rangle$	$(2I+1)S_{dp}$	$\Gamma_{p_{1/2}}$[b]
4.602		4.602	158	$j_{15/2}-39$			4.61	7				
4.692	(3^-)	4.692	158	$g_{9/2}-118$, $i_{11/2}-83$, $d_{5/2}-92$	4.6982	3^-	4.70	21	4.70	$d_{5/2}$	1.5	7.2
4.835		4.835 }		$j_{15/2}$	4.839		4.83	6	4.83 }	$j_{15/2}$	20.9	35.8
4.857		4.857 }					4.86	8	4.86 }			
4.928		4.928	90	$i_{11/2}-95$			4.94	7				
					4.953							
4.967	(2^-)	4.967	90	$d_{5/2}-399$, $s_{1/2}$	4.974	$2^-,3^-$	4.98	53	4.98	$d_{5/2}$	3.6	17.2
5.030		5.030	90	$d_{5/2}-306$	5.0380	3^-	5.03	40	5.03	$d_{5/2}$	2.6	12.4
5.071		5.071	90	$i_{11/2}-148$			5.08	10				
5.121		5.121	90	$d_{5/2}-181$	5.127	$2^-,3^-$	5.12	26	5.12	$d_{5/2}$	1.4	6.7
							5.16	10				
5.205							5.20	9				
5.238					5.2446	3^-	5.24	32	5.24	$d_{5/2}$	1.3	6.2
					5.281	(0^-)						
5.284	(1^-)	5.284	90	$d_{5/2}-149$, $s_{1/2}-464$	5.288	1^-	5.28	88	5.28	$s_{1/2}$	3.6	51.5
5.338							5.34	16				
5.373							5.37	14				
							5.41	10				
5.474												
5.505	(0^-)				5.506	1^-						
5.536												
5.554					5.564							
					5.599		5.58	13				
5.646												
5.679												
5.703												
5.769					5.778		5.77	9	5.77 }	$d_{3/2}$	0.46	3.3
5.804		5.804	90	$d_{5/2}-449$, $s_{1/2}$, $d_{3/2}-109$			5.80	9	5.80 }			
									5.85	$g_{7/2}$	3.1	11.1
5.869		5.869	90	$d_{5/2}-276$, $s_{1/2}-119$, $g_{7/2}-336$	5.873	$2^-,1^-$						
5.914		5.914	100	$s_{1/2}-95$, $d_{3/2}-240$	5.923	$2^-,1^-$	5.89	27	5.89	$d_{3/2}$	1.8	12.9
5.936		5.936	158	$d_{3/2}-238$	5.943	1^-	5.93	61	5.93	$d_{3/2}$	1.4	10.0
5.958		5.958	100	$g_{7/2}-641$	5.968	$4^-,3^-$	5.96	38	5.96	$g_{7/2}$	6.9	24.7
6.000		6.000	90	$d_{5/2}-374$, $s_{1/2}$, $g_{7/2}-352$			6.00	12	6.00	$g_{7/2}$	1.7	6.1
							6.05	10	6.05 }	$d_{3/2}$	0.67	4.8
6.078		6.078	158	$s_{1/2}-40$, $d_{3/2}-115$	6.083	$2^-,1^-$	6.07	14	6.07 }			
6.232		6.232 }	158	$d_{5/2}-70$, $s_{1/2}$, $g_{7/2}-123$	6.257	$2^-,1^-$						
6.255		6.255 }										

[a]See also R. Ballini, N. Cindro, J. Delaunay, J. P. Fouan, O. Nathan, J. P. Passerieux, Phys. Letters, 26B, 215 (1968).

[b]Evaluated from the relation: $\Gamma_{I\,p_{1/2}\,j} = \left(\frac{2I+1}{2J+1}\right)\Gamma_{p_{1/2}}^{sp} S_{dp}$

[c]These levels that have been identified as two-particle–two-hole excitations were not differentiated from particle-hole states which are seen at approximately the same excitation energy in this survey.

TABLE II *(Continued)*

(d,p) Ref. 19				(t,p) Ref. 20[c]			(p,t) Ref. 21		$(p,p'\gamma)$ Ref. 22		(α,α') and (α,α)[d]		(ee') and $(ee'\gamma)$[e]		Results of this study[f]		
E_x	$\lvert n\rangle$	$(2I+1)S_{dp}$	$\Gamma_{p_{1/2}}$[b]	E_x	$\sum \frac{d\sigma}{d\Omega}$	J^π	E_x	J^π	E_x	J^π	E_x	J^π	E_x	Multipolarity	E_x	$\Gamma_{p'}$	J^π
				4.62	5±1						4.59						
4.704	$d_{5/2}$	2.04	9.7	4.71	17±2						4.75		4.75		4.692	8.7	3^-
											4.83				4.835 }	2.1	
				4.87	45±3	0^+	4.878	0^+							4.857 }		
4.979	$d_{5/2}$	3.51	16.7	4.98	42±3										4.967	12.6	3^-
5.039	$d_{5/2}$	3.28	15.6												5.030	10.8	$2^-, 3^-$
									5.08	(1^-)							
5.123	$d_{5/2}$	1.76	8.4												5.121	6.7	3^-
5.250	$d_{5/2}$	1.86	8.9	5.25	15±2		5.259	$0^+, 3^-$					5.24				
5.294	$s_{1/2}$	4.66	66.6	5.30	47±3				5.27	1^-					5.284	5.1	1^-
															5.338	1.7	
															5.373	3.6	(2^-)
5.392	$d_{5/2}$	0.31	1.5														
				5.49	7±1								5.50		5.474 }	17.7	
5.518	$s_{1/2}$	0.51	2.2	5.52	36±3				5.50	1^-					5.499 }		
															5.536 }	8.5	
5.559				5.56	72±4		5.575	2^+							5.554 }		
5.604											5.6	(3^-)					
				5.65	22±2				5.63	(1^-2^-)					5.637	5.8	
				5.70	7±3												
5.789																	
5.826				5.82	40±3		5.828	2^+					5.8	{$E5$ $E3$			
5.858																	
5.882	$d_{3/2}$	0.57	4.1												5.869	12.7	2^-
5.933	$d_{3/2}$	3.85	27.5	5.88	7±2								5.9				
5.952	$d_{3/2}$	2.18	15.6	5.93	69±4				5.94	1^-							
5.972	$g_{7/2}$	18.31	65.5	5.96	24±2												
6.018				5.99	19±3										6.000	18.4	4^-
				6.04													
6.096	$d_{3/2}$	1.37	9.8	6.07													
				6.11	15±3												
				6.20													
									6.27	(1^-2^-)					6.255	2.4	1^-

[d] (α,α') states at 4.59, 4.83 taken from Ref. 23. (α,α) states at 4.75, 5.6 taken from Ref. 24.

[e] (ee') states at 4.75, 5.24, 5.50, 5.9 taken from Ref. 25. $(ee'\gamma)$ state at 5.8 and $E5$ assignment taken from Ref. 26, $E3$ assignment for the state at 5.8 MeV taken from Ref. 27.

[f] The excitation energies were in agreement with Ref. 1 except for states at 5.499 and 5.637 MeV.

study seem to be incompatible. Considering these conflicting results, we feel that no specific spin assignment can be made.

5.373–5.656-MeV states. Because of their small cross sections, little information is available to supplement our results with reference to these levels. Data that have been accumulated[1] show the 5.373-MeV state to be collective. The observed angular distribution for this level can be adequately described by several final-state spins. The J^π assignment 2^-, shown in Table II, was based on subtle differences between the calculated cross sections and the experimental data, so that this conclusion can only be considered tentative.

The larger cross section for the 5.646-MeV level makes its analysis somewhat easier. In this instance, adequate agreement was achieved with a final-state spin of 2^- and with $|\Gamma_{p_{1/2}}| = 2.7$ keV, $|\Gamma_{f_{5/2}}| = 2.3$ keV, and $|\Gamma_{p_{3/2}}| = 0.3$ keV. Contrary to Cramer *et al.*,[22] we believe it is more reasonable to associate their level at 5.63 MeV with this state.

5.869–6.000-MeV states. In (p,p') studies, these levels exhibit strong collective characteristics and (d,p) experiments indicate negligible $p_{1/2}$ hole contributions. Under this restriction, only spins of 2^- and 4^- yield results similar to the experimental data for the state at 5.869 MeV. Considering its moderately large $s_{1/2}$ particle strength and assuming a simple particle-hole coupling scheme, one is forced to classify the final-state spin as 2^-. A best fit to the data is achieved with this assignment when $|\Gamma_{f_{5/2}}| = 0.05$ keV and $|\Gamma_{p_{3/2}}| = 11.6$ keV.

Multiple fits can be obtained for the 6.000-MeV level. However, the J^π value of 4^- is the only assignment that shows a negligible $p_{1/2}$ inelastic width, while producing a fit that is comparable to the data. $|\Gamma_{p_{3/2}}| = 17.5$ keV was the only value that was used as the final fitting parameter. It also generates the most acceptable fit to the data.

6.255-MeV state. We were able to reproduce the angular distribution of this state using the spin assignment 1^- ($\Gamma_{f_{5/2}} = 2.0$ keV and $\Gamma_{p_{3/2}} = 0.4$ keV). Considering a particle-hole coupling scheme, one would not expect to see a 1^- level in a (d,p) reaction leading to these final states. However, having assumed this assignment, its presence in that experiment can only reflect admixtures of hole states other than $p_{1/2}$ in the ground-state configuration of ^{207}Pb. This does not seem unreasonable, since the cross section to this level in that reaction is rather small. Its angular distribution (determined in this study but not shown in Fig. 2) peaks at backward angles. This is the last state that exhibits a cross section large enough to allow for a reasonable analysis.

CONCLUSION

This particular experiment demonstrates a generally useful approach for determining final-state configurations of neutron–neutron-hole excitations. The method of analysis is straightforward, and when related to results from other experiments, it constitutes an effective tool for nuclear spectroscopy. Although this procedure is not completely unambiguous, spin assignments for particular levels, when not precisely determined, can be severely restricted. An alternate approach is also described for checking the derived quantities $\Gamma_{p'}$. Using these methods, we have been able to assign spins for seven states between 4.69- and 6.30-MeV excitation in ^{208}Pb. Limitations imposed by the detection system did not allow analysis of all the $d_{5/2}$ particle states that have been observed.

A comparison of the widths predicted by the calculated wave functions and the equivalent experimental quantities show minor correlations. An over-all shift in the excitation energy was observed between the two sets of results. However, equivalence between excitation energies and magnitudes of partial widths was not as obvious as were similar calculations performed in connection with the $g_{9/2}$ resonance. This forced us to rely heavily on the procedure of fitting the angular distribution in the process of assigning final-state spins.

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Search for Parity Violation in the Gamma Decay of ^{159}Tb Polarized by Dilution Refrigeration*

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A search for the parity-nonconserving contribution to the γ decay of ^{159}Tb has been made. A complete description of the experimental technique is presented. The angular distribution of the 363-keV line of ^{159}Tb was measured with a pair of Ge(Li) detectors. The ^{159}Gd parent atoms were located in the +453-kG hyperfine field of $GdFe_2$ held at 28 mK by a ^{3}He-^{4}He dilution refrigerator. The resulting 7% polarization of the ^{159}Gd led to a $P_1(\cos\Theta)$ term of $+(2.7\pm1.8)\times10^{-4}$ in the γ-ray angular distribution, where Θ is measured with respect to the nuclear polarization. Thus, for full Tb polarization, the asymmetry would be $+(4.5\pm3.0)\times10^{-3}\,P_1(\cos\Theta)$, peaked in the direction of Tb nuclear spin alignment. This sign of the $P_1(\cos\Theta)$ term is based on an assumed negative moment of the ^{159}Gd parent. We measure the magnitude of this moment to be $(0.22\pm0.05)\mu_N$.

A small parity-nonconserving interaction between nucleons results from the current-current theory of weak interactions proposed by Feynman and Gell-Mann.[1] Assuming the presence of such an interaction, the nuclear states are not eigenstates of parity, and small parity impurities can be expected. The impurity amplitude F is estimated to be on the order of 10^{-6} to 10^{-7}.[2,3]

There are several possibilities for experimental measurements of the existence and extent of the parity-nonconserving amplitude. One type of experiment is to look for the presence of decays forbidden by parity. Studies of the α decay from excited states of O^{16} have placed a 3×10^{-13} upper limit on F^2.[4] The other type of experiment is to look for correlations which would not be present if parity were conserved. These experiments study F itself. To date, these experiments have examined the circular polarization of γ rays from unpolarized sources,[5,6] or the angular distribution of γ rays with respect to the polarization of neutrons captured by the nuclei.[7] In both cases the effect was enhanced by choosing γ decays in which a parity-conserving decay mode was hindered with respect to a parity-nonconserving mode. Some of these experiments give strong evidence for weak interactions between nucleons.

We used a different method to study γ-decay parity nonconservation. Our experiment was to measure the correlation between the angular distribu-