High-Resolution Study of the Particle-Hole Multiplets in ^{208}Bi†

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Particle-hole multiplets in ^{208}Bi corresponding to the coupling of the $h_{9/2}$ proton with neutron holes in the $p_{1/2}$, $f_{5/2}$, $p_{3/2}$, $i_{13/2}$, $f_{7/2}$, and $h_{9/2}$ shells have been observed by the ^{209}Bi(p,d)-^{208}Bi reaction at 35 MeV with an over-all resolution of 5 keV in the deuteron spectra. The results generally show excellent agreement with the weak coupling model except for the $h_{9/2}$ hole states. However the observed $h_{9/2}$ multiplet states do contain a large fraction of the expected strength. There is also substantial agreement with earlier (d,t) work except for some spin assignments and in the location of the 2^- member of the $\pi h_{9/2}$, $\nu^{-1} i_{13/2}$ multiplet.

[NUCLEAR REACTIONS ^{209}Bi(p,d), $E=35$ MeV; measured levels, $\sigma(\theta)$, deduced S.]

I. INTRODUCTION

Recent discussions of the effective two-nucleon force obtained from the two-particle spectra of nuclei near closed shells[1] has again focussed attention on such nuclei. One important example near the doubly magic nucleus ^{208}Pb, is the nucleus ^{208}Bi with a proton outside the ^{208}Pb core and a neutron hole in the core. In the present experiment, we have studied ^{208}Bi by the reaction ^{209}Bi-$(p,d)^{208}$Bi using the high-resolution capability of the Michigan State University (MSU) cyclotron. In the simplest picture of this reaction, we expect to reach states which consist primarily of a proton in the $h_{9/2}$ orbit coupled to neutron holes in the $2p_{1/2}$, $1f_{5/2}$, $2p_{3/2}$, $0i_{13/2}$, $1f_{7/2}$, and $0h_{9/2}$ orbits.

A number of previous studies[2-4] have investigated the low-lying levels in ^{208}Bi. In particular the single-particle transfer reactions ^{209}Bi$(d,t)^{208}$Bi and ^{207}Pb$(^3$He$,d)^{208}$Bi have indicated the simple particle-hole multiplet structure of these states. This feature is also common to the theoretical descriptions of this nucleus,[5,6] at least for the low-lying multiplets.

The present experiment extends the previous work with the better resolution available with the MSU cyclotron facility and checks the spin-parity assignments from the (d,t) reaction. A further motivation for the experiment was the fact that the angular distributions for different angular momentum transfers in the (p,d) reaction at 35 MeV are quite unambiguous. This allows easy identification of the members of a multiplet and serves as an indication of any mixture of different l values in a particular transition.

Finally a careful comparison was made of the present ^{209}Bi$(p,d)^{208}$Bi reaction with a ^{208}Pb(p,d)-^{207}Pb experiment[7] carried out at the same energy with the same apparatus to check the strengths in the ^{208}Bi multiplets compared with the transition strength to the single-hole states in ^{207}Pb.

II. EXPERIMENTAL

The experiment was carried out using the 35-MeV proton beam from the Michigan State University isochronous cyclotron. For the high-resolution experiment the reaction products were analyzed in an Enge split-pole spectrograph and the deuterons were detected in NTA and NTB 25-μm nuclear emulsions. Thin Mylar absorbers were placed in front of the emulsions to eliminate tritons. The bismuth target used was 100 μg/cm^2 thick evaporated onto a 20-μg/cm^2 carbon backing.

Before making exposures the total resolution was optimized by passing first the elastically scattered protons and then the deuterons from the ground state of the ^{208}Pb$(p,d)^{207}$Pb reaction, into the "speculator" system[8] in the focal plane of the magnet. The basic method matches the dispersion of the beam transport system with the spectrograph dispersion to compensate for a coherent energy spread on the target. The on-line resolution meter allowed the final optimization of the dispersion of the beam on target and of the position of the plate holder and resulted in an improvement of more than a factor of 2 in resolution. We thus achieve a total resolution of less than 5 keV full width at half maximum (FWHM) for scattering angles from 6 to 50°. Two exposures were taken at each angle, one for the p and f multiplets and the other longer exposure to obtain adequate statistics on the $h_{9/2}$ and $i_{13/2}$ multiplets. In order to fully exploit the high resolution it was necessary to scan the nucle-

TABLE I. Optical parameters.

Parameters	V_r (MeV)	r_R (fm)	a_R (fm)	W_v (MeV)	W_{sf} (MeV)	r_I (fm)	a_I (fm)	V_{so} [a] (MeV)	r_{so} (fm)	a_{so} (fm)
Protons [b]	53.33	1.17	0.75	5.0	5.52	1.32	0.654	6.2	1.01	0.75
Deuterons [c]	115.6	1.17	0.78	2.28	16.49	1.29	0.651	3.1	1.01	0.75

[a] DWUCK72 uses values $4W_{sf}$ and $4V_{so}$.
[b] Becchetti-Greenlees, Ref. 10.
[c] Adiabatic model, Ref. 12.

ar emulsion in 100-μm steps and in some regions of close doublets to reduce the step size of the scan to only 50 μm.

The excitation energies were extracted by using the previously determined energy calibration of the magnet and fixing the ground-state energy. This is considered accurate to ± 0.7 keV per MeV of excitation energy.

The comparison between ^{208}Bi and ^{207}Pb data was made using a single-wire position-sensitive proportional counter in the focal plane of the Enge spectrograph to obtain better statistics on the areas of the peaks. A monitor counter at 90° checked the charge collection in all cases and permitted a comparison which depended only on the difference in the elastic scattering from ^{208}Pb and ^{209}Bi.

III. DISTORTED-WAVE CALCULATIONS

Distorted-wave calculations were carried out for the various angular momentum transfers observed namely $l = 0, 1, 3, 5, 6$ using the code DWUCK.[9] Proton optical parameters were taken from papers by Becchetti and Greenlees[10] and Smith *et al.*[11] Two sets of deuteron parameters were tried, one from the paper of Smith *et al.* and the other an adiabatic approximation suggested by Johnson and Soper.[12] The adiabatic deuteron parameters gave generally better fits to the data and were used in the analysis described below. A list of these proton and deuteron parameters is given in Table I. A comparison of one member of each multiplet with the appropriate distorted-wave Born-approximation (DWBA) calculation is shown in Fig. 1. The fits to the f and p hole multiplet states are excellent. For the higher l's the fit is not quite as good especially at forward angles.

IV. RESULTS AND DISCUSSION

A spectrum taken at a laboratory angle of 22° is shown in Fig. 2. A clear multiplet structure in ^{208}Bi is evident. Very few extraneous states are observed which do not fit into the simple picture of an $h_{9/2}$ particle coupled to a neutron hole even

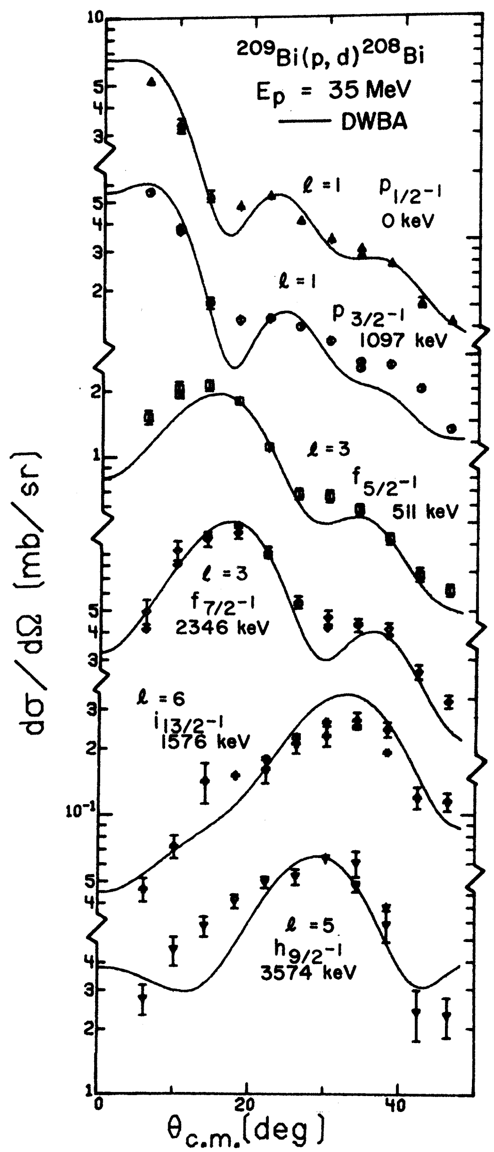

FIG. 1. Comparison of experimental angular distributions for a member of each multiplet with DWBA calculations. Each ^{208}Bi state is labeled by its excitation energy, the l transfer, and the configuration of the neutron hole for that multiplet.

as high in excitation as the $h_{9/2}$-$h_{9/2}^{-1}$ multiplet.

Excitation energies of states in ^{208}Bi observed in the present experiment are given in Table II together with results from other experiments. In the table, only states which show up in at least four separate runs are listed. The errors listed in the table are a combination of random errors in assigning the peak centroids and the uncertainty in the calibration of the spectrograph. Below an excitation energy of 3 MeV, the agreement with the (d,t) results[3] is generally very good. Below 1 MeV, the agreement with the γ-ray measurements[4] is also quite good. One exception is the separation of the 2^+ and 4^+ states at 927 and 961 keV where the (p,d) measurement imply a separation of 33.9 keV but the γ-ray results gave a difference of 43.7 keV, well outside the errors of both measurements.

Above 3 MeV the agreement with the (d,t) results is not so close although it does appear that the same states are seen in both experiments. Some states with $l=3$ angular distributions are also seen around 4.5 MeV of excitation where a fragment of the $f_{7/2}$ hole state strength in ^{207}Pb is observed. These states presumably arise from coupling of the $h_{9/2}$ proton to this $f_{7/2}$ neutron-hole component.

In order to compare the strength of states in the different multiplets and to check the spin assignments, assuming a $(2J+1)$ dependence of the cross section for the members of a multiplet, the following procedure was adopted.

Using DWBA calculations a Q-value correction was first made to each member of a multiplet and to the corresponding hole state in ^{207}Pb, to take account of the different cross sections expected due simply to the different excitation energies in the final nuclei. Then the ratio

$$R=\frac{\sigma_J(\theta)[^{208}\mathrm{Bi}]\,\Sigma\, 2J+1}{\sigma_j(\theta)[^{207}\mathrm{Pb}]\,(2J+1)} \tag{1}$$

was calculated for each state, assuming a particular spin J of the state in ^{208}Bi. The sum extends over all the possible J states in the multiplet. The symbol j refers to the appropriate hole state in ^{207}Pb which couples to the $h_{9/2}$ proton to produce the particular multiplet. The cross section for the (p,d) reaction to the corresponding hole state in ^{207}Pb is used in Eq. (1) to avoid incorrect J assignments in the event that not all the strength is found in the ^{208}Bi multiplet. The summed strength for the ground-state multiplet was independently shown to be within 5% of the strength of the ^{207}Pb ground-state transition (see Sec. V). Thus, in a weak coupling picture, if $\sigma_J(\theta)[^{208}\mathrm{Bi}]$ is proportional to $(2J+1)$ and if the J's are correctly assigned then R will equal approximately 1 for all states in the multiplet. For an unresolved doublet R should be about 2.0 if the J's are correct. The values of R calculated at each angle were averaged after weighting with the statistical error to obtain an average $\bar{R}$ for each state. These values, together with the best J^π values are presented in Table III. The errors quoted with the $\bar{R}$ values in Table III

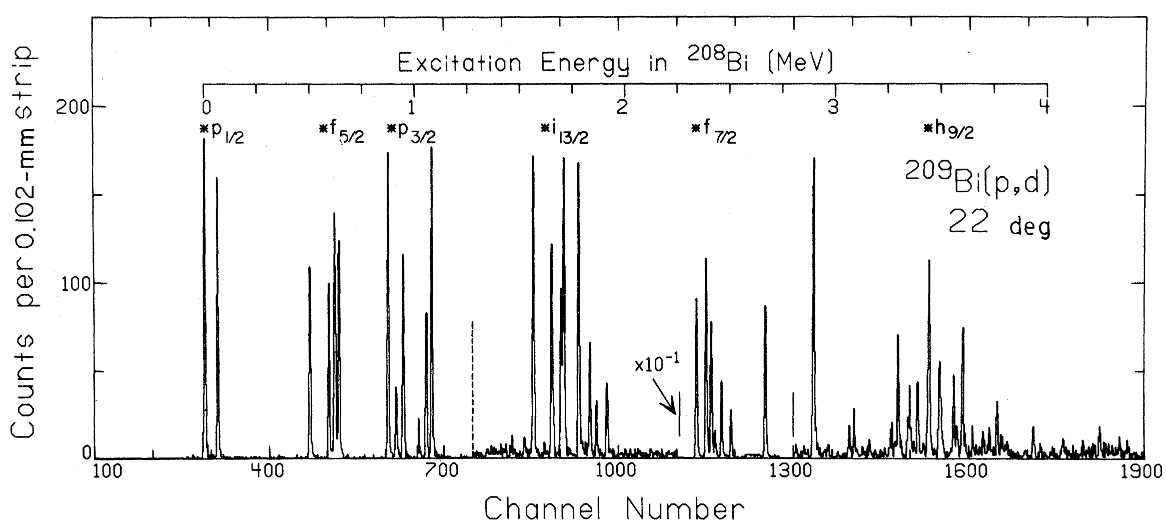

FIG. 2. A deuteron spectrum at $\sigma_{\rm lab}=22°$ from the reaction ^{209}Bi(p,d) at $E_p=35$ MeV. This is a composite spectrum from successive runs. The portion from channels 0 to 750 was obtained with a total charge collected of 500 μC and a 1° by 1° entrance aperture in the spectrometer. The remaining channels were taken for a collected charge of 2500 μC and a 2° by 2° entrance aperture to obtain better statistics on the weaker states. The * marks the positions of the excitation energies of the neutron-hole states observed in the ^{208}Pb$(p,d)^{207}$Pb reaction.

are the standard errors in the mean obtained from the deviations at different angles.

It should be pointed out that making spin assignments based on spectroscopic strength does not depend on a weak coupling argument. If (1) the states in ^{208}Bi can be described as particle-hole states outside a ^{208}Pb closed core and (2) the full pick-up strength for the given l_j value is observed then the pick-up strength must be distributed to states with the various possible J finals with strength proportional to $2J+1$. See Ref. 7 for a full discussion.

While the DWBA calculations are generally in good agreement with the shapes of the angular distributions and could be used to extract relative spectroscopic factors, a preferable technique in this case is to use the empirical ^{208}Pb$(p,d)^{207}$Pb cross sections, since the theoretical spectroscopic factors[5,6] assume a closed ^{208}Pb core. Such a comparison of ^{209}Bi(p,d) with ^{208}Pb(p,d) better reflects this assumption. These spectroscopic factors are also listed in Table III together with

TABLE II. Excitation energies of states in ^{208}Bi.

$E_x \pm \Delta E_x$ (keV) ^{209}Bi(p,d) (Present)	E_x (keV) (d,t) and $(^3$He$,d)$ [a]	E_x (keV) ^{208}Pb$(p,n\gamma)$ [b]	$E_x \pm \Delta E_x$ (keV) ^{209}Bi(p,d) (Present)	E_x (keV) (d,t) and $(^3$He$,d)$ [a]	E_x (keV) ^{208}Pb$(p,n\gamma)$ [b]
0.0	0.0	0.0	2727.0 ± 2.3	2716	
63.4 ± 0.7	65	63.4		2888	
511.4 ± 0.8	512	510.5	2891.6 ± 2.3	2890	
603.0 ± 0.8	603	601.3		2915	
631.8 ± 0.8	631	628.4		2945	
(doublet)		632.4	3057 ± 3		
652.3 ± 0.8	652	650.0	3079 ± 3	3070	
888.6 ± 0.8	890	890.4	3122 ± 3		
927.3 ± 0.9	930	923.9	3149 ± 3	3173	
	939	934.5	3220 ± 3		
961.2 ± 0.9	963	967.6	3248 ± 3	3260	
1035.6 ± 1.5	1038	1032.0		3270	
1071.2 ± 1.5	1075	1068.3	3281 ± 3	3288	
1097.4 ± 1.5	1099		3326 ± 3	3323	
	1467		3335 ± 3		
1533.5 ± 1.5	1534		3355 ± 3		
	1565		3371 ± 3	3365	
1575.6 ± 1.5	1574		3396 ± 3	3393	
	1606		3421 ± 3	3410	
1628.8 ± 1.5	1630			3412	
1664.1 ± 1.6	1662		3473 ± 3	3459	
	1673			3460	
1708.2 ± 1.6	1699			3525	
1720.6 ± 1.6	1719		3533 ± 3	3535	
	1734		3550 ± 3		
1791.5 ± 1.5	1791		3574 ± 3	3565	
	1806		3620 ± 3	3612	
1843.9 ± 1.5	1842		3671 ± 3	3652	
1875.7 ± 1.5	1878		3697 ± 3	3683	
	1885		3732 ± 3	3716	
1924.7 ± 1.6	1927		3751 ± 3		
	2132		3776 ± 3		
2345.9 ± 2.2	2345		3896 ± 3		
2391.2 ± 2.2	2389		4025 ± 4		
2414.9 ± 2.2	2413		4194 ± 4		
2434.2 ± 2.3	2431		4555 ± 4		
2463.5 ± 2.2	2462		4568 ± 4		
2507.7 ± 2.2	2506		4599 ± 4		
2667.5 ± 2.2	2665		4629 ± 4		
	2688				

[a] Reference 3.

[b] Reference 4.

the predictions of Kuo[6] and of the simple weak-coupling model.

$\pi h_{9/2} - \nu^{-1} p_{1/2}$ Multiplet

Both members of this 63-keV doublet show quite a pure $l = 1$ shape and agree well with the angular distribution for the ground-state transition in ^{208}Pb(p, d) (see Fig. 3). The spectroscopic factors are in very good agreement with the assumption of pure simple configurations for these states. The 10% smaller spectroscopic factor for the 4^+ state, predicted by Kuo, is not apparent in these data.

$\pi h_{9/2} - \nu^{-1} f_{5/2}$ Multiplet

The 600- to 660-keV region of the ^{208}Bi spectrum, scanned in 50-μm steps, is shown in Fig. 4. While the state at 632 keV is not clearly resolved, the peak is definitely broadened compared to the single states nearby. On running the data through a peak stripping program, SAMPO, the separation of the two peaks was found to be about 4.5 keV with the state at lower excitation energy having about 50% more counts that the higher-energy state. This implies that the lower-excitation-energy state has $J^\pi = 5^+$. Because of the uncertainties in stripping the peaks, the summed cross section was used to extract the combined spectroscopic factor. The angular distributions for all six states together with the appropriate ^{208}Pb(p, d) angular distribution are shown in Fig. 5, and again the agreement is very good. The spectroscopic factors from Table III are also in good agreement with both theoretical predictions. There is an indication that the spectroscopic factors for Bi are slightly higher than expected which would imply more $f_{7/2}$ pickup strength on ^{209}Bi than on ^{208}Pb. However, greater accuracy would be needed to confirm this point.

TABLE III. Spin-parity assignments and spectroscopic factors.

Neutron-hole configurations [a]	l	E_x (keV)	J^π	$\bar{R}$(Bi)/(Pb)	S (rel to Pb)	S_{theo} (weak coupling)	S_{theo} (Kuo) [b]
$p_{1/2}$	1	0.0	5^+	0.95 ± 0.02	1.05	1.10	1.08
		63.4	4^+	0.95 ± 0.03	0.87	0.90	0.82
$f_{5/2}$	2	511.4	6^+	1.02 ± 0.02	1.33	1.30	1.27
		603.0	4^+	1.04 ± 0.03	0.93	0.90	0.77
		631.8 [c]	$5^+, 3^+$	2.10 ± 0.03	1.89	1.80	1.74
		652.3	7^+	1.01 ± 0.03	1.52	1.50	1.50
		927.3	2^+	0.95 ± 0.03	0.48	0.50	0.47
$p_{3/2}$	1	888.6	5^+	0.92 ± 0.02	1.02	1.10	1.09
		961.2	4^+	0.81 ± 0.03	0.73	0.90	0.75
		1071.2	3^+	0.85 ± 0.02	0.60	0.70	0.64
		1097.4	6^+	0.91 ± 0.03	1.19	1.30	1.24
$i_{13/2}$	6	1575.6	10^-	1.07 ± 0.03	2.24	2.10	2.09
		1664.1	8^-	1.20 ± 0.02	2.05	1.70	1.69
		1708.2	5^- [d]	1.11 ± 0.04	1.22	1.10	1.05
		1720.6 [c]	$6^-, 7^-$	1.83 ± 0.07	2.56	2.80	2.72
		1791.5	9^-	1.03 ± 0.04	1.95	1.90	1.86
		1843.9	4^- [d]	1.03 ± 0.06	0.92	0.90	0.87
		1924.7	3^-	1.00 ± 0.05	0.70	0.70	0.68
		2434.2	11^-	1.09 ± 0.05	2.50	2.30	2.30
		2900.6	(2^-)	0.46 ± 0.10	0.23	0.50	0.47
$f_{7/2}$	3	2345.9	7^+	0.99 ± 0.02	1.49	1.50	1.50
		2391.2 [c]	$4^+, 5^+$	1.88 ± 0.04	1.89	0.90 + 0.80	1.92
		2414.9	6^+	0.99 ± 0.02	1.29	1.30	1.24
		2463.5	3^+	1.03 ± 0.04	0.72	0.70	0.67
		2507.7	2^+	0.92 ± 0.04	0.46	0.50	0.45
		2667.5	8^+	0.90 ± 0.02	1.54	1.70	1.59
		2891.6	1^+	1.16 ± 0.07 [e]	0.35	0.30	0.28

[a] Since all states consist of a proton in the $0h_{9/2}$ orbit coupled to various neutron holes, the configurations $[\pi h_{9/2}, \nu^{-1}j]$ are simply designated by the j of the neutron hole.

[b] Reference 6.

[c] Probably doublets. $\bar{R}$ should equal 2.0 for a doublet.

[d] This corresponds to reversing the J^π of Ref. 3.

[e] This includes the state at 2900.6 keV since at most angles the two states could not be separated.

$\pi h_{9/2} - \nu^{-1} p_{3/2}$ Multiplet

Angular distributions for the four states in this multiplet are shown in Fig. 6 together with ^{208}Pb(p,d) angular distribution to the $\frac{3}{2}^-$ state in ^{207}Pb. The fits are quite good implying a nearly pure $l=1$ transfer although the points at 18° are consistently high.

The spectroscopic factors for the 5^+ and 6^+ states are in good agreement with both of the theoretical predictions suggesting pure weak-coupling wave functions. However, the 3^+ and especially the 4^+ state at 961 keV have smaller spectroscopic factors than predicted by the weak-coupling model. If the cross section for the 4^+ state at 1036 keV (which is about 10% of the cross section for the 4^+ at 961 keV) is included, the total strength to 4^+ states increases from 0.73 to 0.81 which is closer to the value of 0.90 expected from the weak-coupling picture. The value of 0.73 agrees very well with the Kuo prediction of 0.75. The 4^+ state at 1036 keV is predominately a $\pi f_{7/2}\nu^{-1}p_{1/2}$ configurations since it was observed strongly in the ^{207}Pb(^{3}He, d)^{208}Bi reaction.[3] The other member of the doublet with the same configuration is a 3^+ state observed at 939 keV in the (^{3}He, d) reaction. There is a small indication of this state observed in some of the spectra in the present experiment but it is not clearly resolved from the 2^+ state at 927 keV. The spectroscopic factor of 0.60 agrees very well with Kuo's prediction of 0.64 for the 1071-keV 3^+ state.

$\pi h_{9/2}\nu^{-1} i_{13/2}$ Multiplet

The region of the 6^-, 7^- doublet at 1721 keV was also scanned in 50-μm steps but in this case, unlike the doublet at 632 keV, no broadening was observed. This implies that the two states are less than 3 keV apart. One extra state of comparable strength appears at 1876 keV but it has an $l=1$ rather than an $l=6$ angular distribution and therefore has a small spectroscopic factor (≈ 0.02). The angular distributions for these states are shown in Fig. 7 together with the angular distribution for the ^{208}Pb(p,d) reaction to the $i_{13/2}$ hole state in ^{207}Pb. While the statistical accuracy is

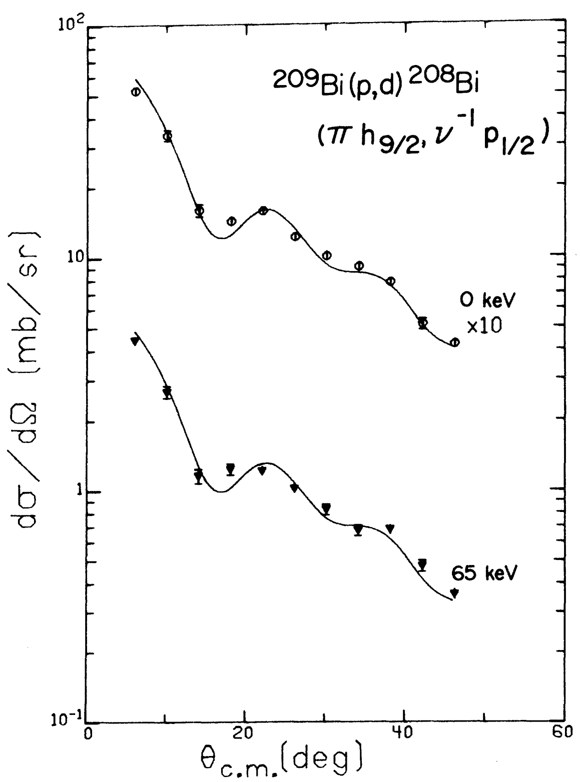

FIG. 3. Angular distributions for the $\pi h_{9/2}, \nu^{-1}p_{1/2}$ multiplet. The solid lines are the angular distribution for the $\nu^{-1}p_{1/2}$ state in ^{207}Pb from the ^{208}Pb(p, d)^{207}Pb reaction.

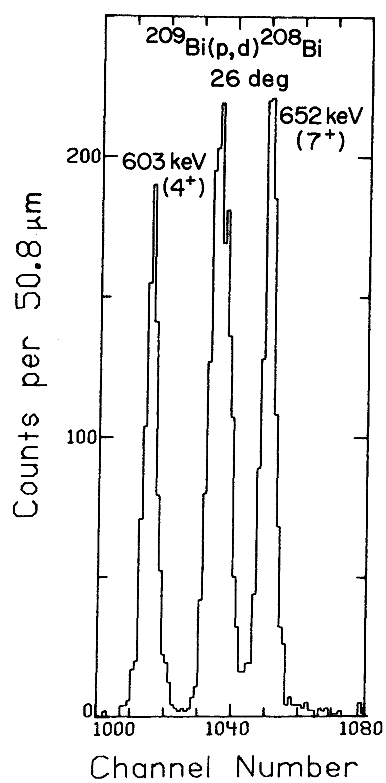

FIG. 4. Deuteron spectrum scanned in 50-μm steps from ^{209}Bi(p, d)^{208}Bi near 600 keV of excitation in ^{208}Bi, showing the broadening of the peak near 630 keV. Unfolding of this peak suggested two states were present about 4.5 keV apart.

less for this weak multiplet the shape of the angular distributions match that for the ^{208}Pb(p, d) quite well.

The spectroscopic factors shown in Table III are in good agreement with the theoretical predictions, although there is again the tendency for the values to be 10% or more high especially for the states with larger spin. Unfortunately the errors are also larger so that no definite conclusions can be drawn. In order to obtain consistent $\overline{R}$ values for the 5^- and 4^- states it was necessary to reverse the spins suggested by Alford, Schiffer, and Schwartz[3] since with their J values, the $\overline{R}$ values were 1.38 and 0.82, respectively. In addition no state was observed at 2716 keV, the position where the 2^- member of this multiplet was reported in the (d, t) experiment.[3] In searching for the missing 2^- state, the 1^+ state at 2892 keV was observed to have a small shoulder at some angles. This state was therefore scanned in 50-μm steps and a weak peak was observed on the high-excitation-energy side at a number of angles (Fig. 8). While it was difficult to obtain an accurate angular distribution for this weak state, it appeared to peak around 38° which is consistent with an $l = 6$ angular distribution as expected for a 2^- level. The $\overline{R}$ extracted for the few angles where the state could be stripped fairly cleanly were significantly smaller than unity suggesting either that the 2^- strength may be fractionated or that some doubt still exists as to its identification.

$\pi h_{9/2} \nu^{-1} f_{7/2}$ Multiplet

Angular distributions for the eight members of this multiplet are shown in Fig. 9 together with corresponding ^{208}Pb(p, d) angular distributions. The similarity of these angular distributions is quite close and the spectroscopic factors obtained are shown in Table III. The region of the 4^+, 5^+ doublet was scanned in 50-μm steps but no broadening of the line was observed implying that the two states must be closer than 3 keV.

The spectroscopic factors are all in good agreement with the theoretical predictions except for the 1^+ state at 2892 keV where the value of $\overline{R} = 1.16$ implies too large a cross section. As mentioned above after scanning in finer steps, this state was

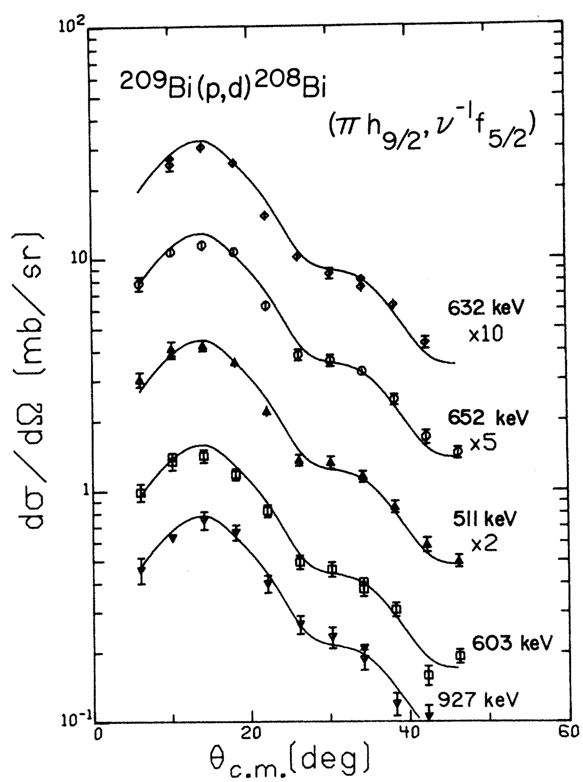

FIG. 5. Angular distributions for the $\pi h_{9/2}, \nu^{-1} f_{5/2}$ multiplet. The solid lines are the angular distribution for the $\nu^{-1} f_{5/2}$ state in ^{207}Pb from the ^{208}Pb$(p, d)^{207}$Pb reaction.

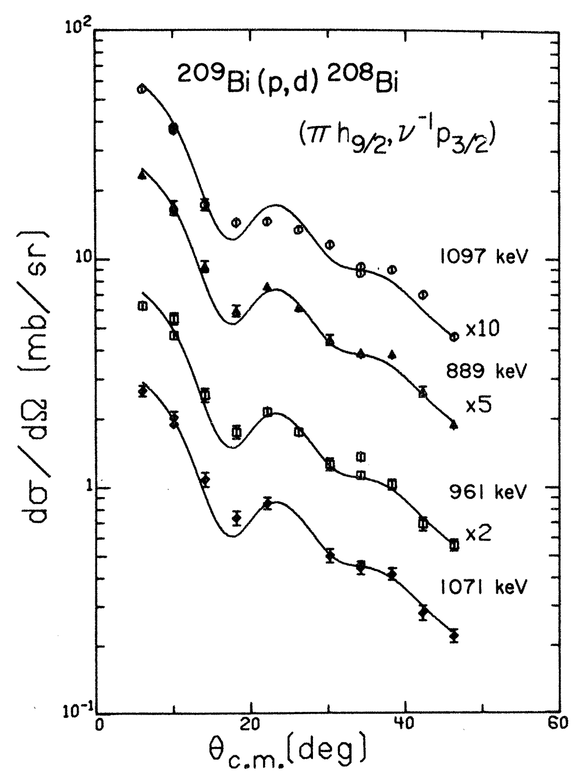

FIG. 6. Angular distributions for the $\pi h_{9/2}, \nu^{-1} p_{3/2}$ multiplet. The solid lines are the angular distribution for the $\nu^{-1} p_{3/2}$ state in ^{207}Pb from the ^{208}Pb$(p, d)^{207}$Pb reaction.

shown to be a close doublet with the higher-excitation-energy member being a candidate for the missing 2^- for the $i_{13/2}$ multiplet. Subtracting this state from the 1^+ strength would reduce the value of $\bar{R}$ to around 1.06, consistent with the other members of this multiplet.

$\pi h_{9/2}\nu^{-1}h_{9/2}$ Multiplet

This multiplet is quite weak and there is an increasing level density in this region so that there is an increased probability of overlapping states. Nevertheless, eight states with a predominantly $l = 5$ angular distribution appear in this region so that the multiplet still seems to maintain its identity. The angular distributions for these states are shown in Fig. 10 together with the

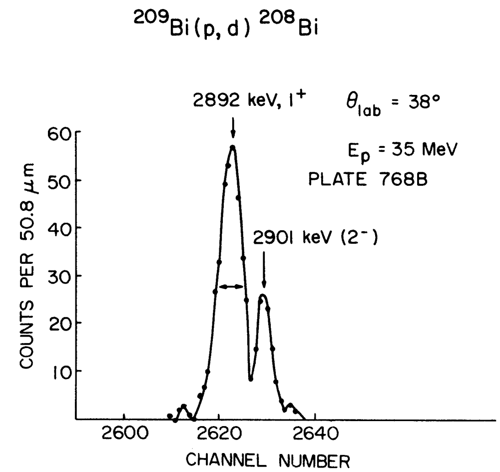

FIG. 8. Deuteron spectrum scanned in 50-μm steps from the ^{209}Bi(p, d)^{208}Bi reaction. The probable 2^- state is seen resolved from the 1^+ state at 2892 keV.

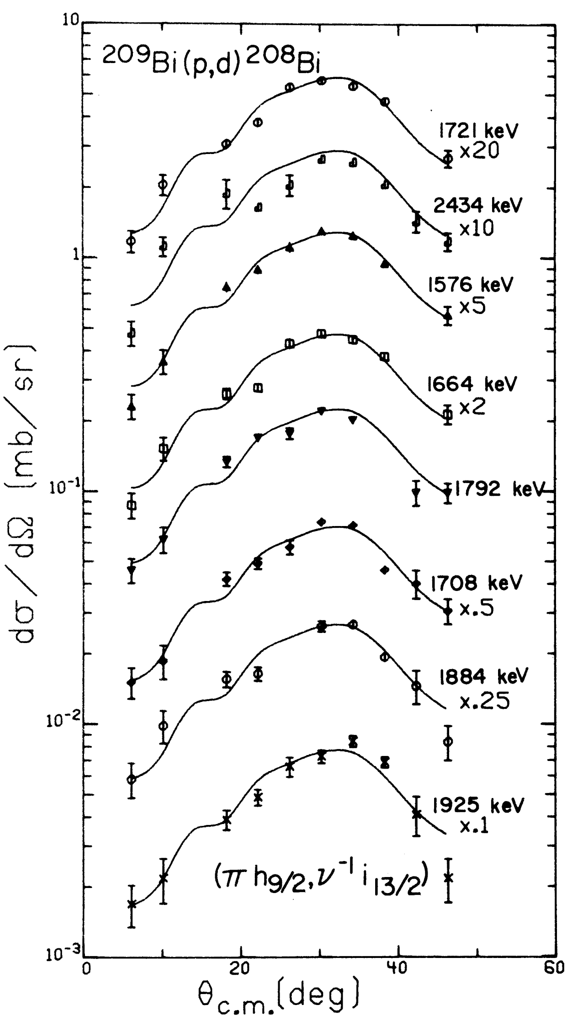

FIG. 7. Angular distributions for the $\pi h_{9/2}, \nu^{-1}i_{13/2}$ multiplet. The solid lines are the angular distribution for the $\nu^{-1}i_{13/2}$ state in ^{207}Pb from the ^{208}Pb(p, d)^{207}Pb reaction.

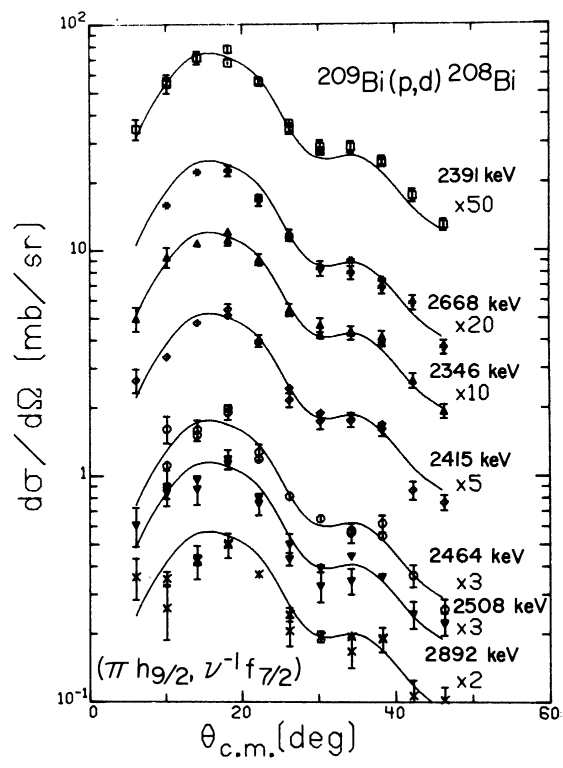

FIG. 9. Angular distributions for the $\pi h_{9/2}, \nu^{-1}f_{7/2}$ multiplet. The solid lines are the angular distribution for the $\nu^{-1}f_{7/2}$ state in ^{207}Pb from the ^{208}Pb(p, d)^{207}Pb reaction.

^{208}Pb(p,d) to the $h_{9/2}$ hole state in ^{207}Pb. For most states the comparison with the lead data is good. However, a few levels did appear to have some $l=3$ admixture, especially the 3281- and 3371-keV levels. The experimental cross sections were therefore analyzed with a least-squares search to extract the relative $l=3$, $l=5$ contributions using the known $l=3$ and $l=5$ shapes from ^{208}Pb(p,d). The results were then used to extract the $l=5$ spectroscopic factors shown in Table IV.

Although, by assuming that a number of single peaks are really close doublets, it is possible to obtain a number of $\bar{R}$ values close to one (or two for a doublet) and therefore to assign probable spins, we did not believe the technique was unambiguous enough to make reliable assignments.

TABLE IV. $\pi h_{9/2}-\nu^{-1}h_{9/2}$ multiplet.

Excitation energy (keV)	S ($l=5$)
3280.7	0.33
3370.6	0.57
3420.6	1.81
3472.7	1.28
3533.0	0.59
3549.8	0.30
3573.6	1.79

The summed $l=5$ strength for levels in this region amounts to almost 70% of the strength observed in the ^{208}Pb$(p,d)^{207}$Pb, $l=5$ transition.

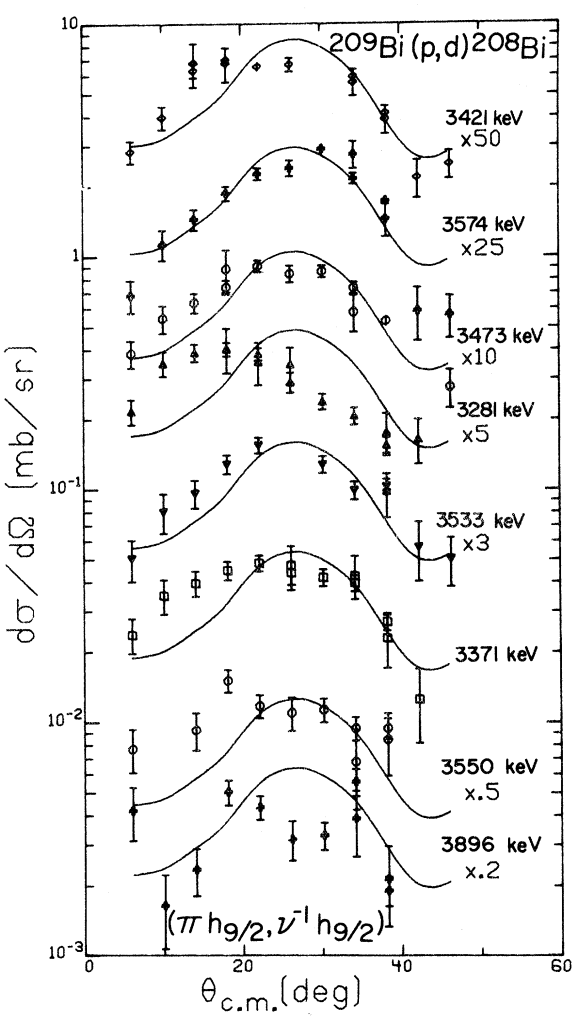

FIG. 10. Angular distributions for the $\pi h_{9/2}, \nu^{-1}h_{9/2}$ multiplet. The solid lines are the angular distribution for the $\nu^{-1}h_{9/2}$ state in ^{207}Pb from the ^{208}Pb$(p,d)^{207}$Pb reaction.

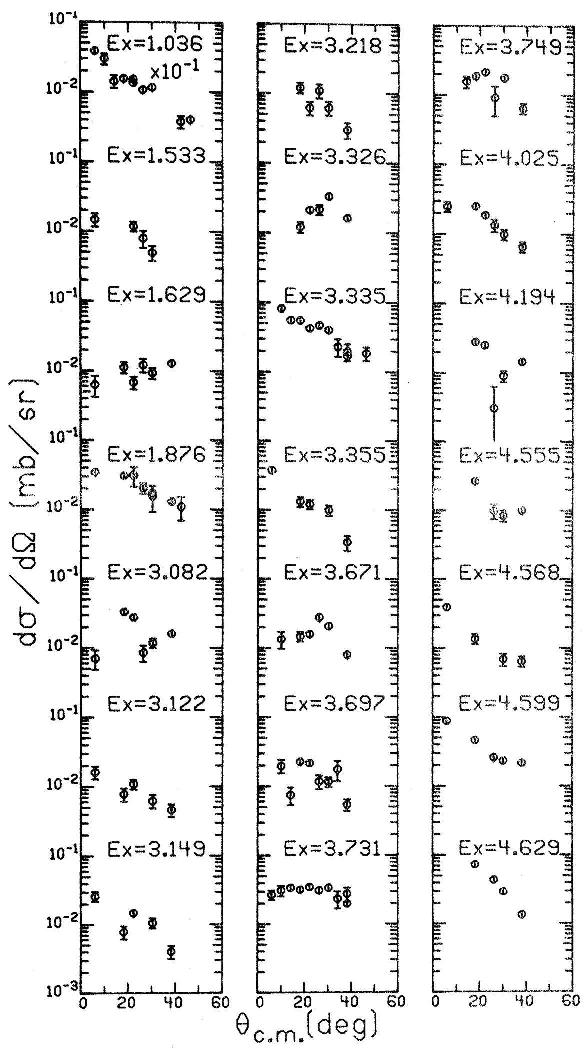

FIG. 11. Angular distributions of states observed in this work and not shown in other figures.

Miscellaneous States

There are more than 20 other states noted in Table I which do not fit into the multiplet picture already discussed. Most of these states occur above 3-MeV excitation energy. Some of the states below 3 MeV, for example the 1.036-MeV 4^+ state and the state at 1.876 MeV ($l=1$), have already been discussed. Angular distributions for these miscellaneous states are shown in Fig. 11. Many of the states are quite weak and the angular distributions are limited to a few angles.

A few groups of states merit further mention. A close doublet of two states occurs at 3.122 and 3.149 MeV with similar angular distributions ($l=1$).

Another close doublet occurs at 3.335 and 3.355 MeV where both members have angular distributions consistent with an $l=0$ transfer (Fig. 11). Such a doublet with configuration ($\pi h_{9/2}$, $\nu s_{1/2}{}^{-1}$) might be expected in this region since an $l=0$ transition is observed at an excitation energy of 3.304 MeV in the ^{208}Pb$(p,d)^{207}$Pb reaction. For this configuration the two states would have spins 4^- and 5^- with a cross section ratio of 1.22 expected. However, the observed ratio of cross sections is instead close to 3.0 probably implying that the strength is split among more than two levels.

At energies above 4 MeV, only a few states stand out and they have either $l=3$ or $l=1$ angular distributions (Fig. 11). Three states are observed at 4.025, 4.555, and 4.629 MeV with $l=3$ distributions, which presumably have a dominant configuration of ($\pi h_{9/2}$, $\nu f_{7/2}{}^{-1}$) and are based on the fragment of the $f_{7/2}$ strength observed in the ^{208}Pb(p,d) reaction at 4.546-MeV excitation energy. Two other states at 4.568 and 4.599 MeV are also observed in this region but these have a predominantly $l=1$ distribution.

V. ABSOLUTE COMPARISON OF ^{208}Pb(p,d) AND ^{206}Bi(p,d) REACTIONS

In view of the possible 25% discrepancy in absolute cross section indicated in the (d,t) reaction on ^{208}Pb and ^{209}Bi, and also because of the intrinsic interest in such a comparison, the cross sections for the (p,d) reactions on ^{208}Pb and ^{209}Bi were compared under the same experimental conditions. The particles in the spectrograph focal plane were detected in a single resistive wire-proportional counter, while a NaI monitor counter at a scattering angle of 90° detected the elastically scattered protons to monitor target thickness and charge-collection efficiency. A dead-time correction was made by feeding the monitor pulses into channel zero of the analog-to-digital converter and recording this with the data. The targets of ^{208}Pb and ^{209}Bi, of thicknesses 6.7 mg/cm^2 and 15.1 mg/cm^2, respectively, were placed successively in the beam leaving all other conditions the same. The (p,d) cros cross sections for the ground state of ^{207}Pb and the 5^+, 4^+ ground-state doublet in ^{208}Bi were measured at six angles between 16 and 32° in the laboratory. At least 100 000 counts were taken for each peak. The cross section for each target was calculated by normalizing their respective yields to the monitor and the ratio of cross sections for ^{208}Pb and ^{209}Bi was then calculated. There appears to be a very slight angular dependence to the ratio which averages at 1.08 ± 01. If one assumes that the difference in the elastic scattering from ^{208}Pb and ^{209}Bi at 90° is given by Becchetti-Greenlees optical parameters[10] (viz 2%), then the ratio of (p,d) cross sections is reduced to 1.06.

The elastic scattering measurements between 32 and 52° also cast some doubt on the reliability of the Becchetti-Greenlees prediction of the difference in the ^{208}Pb and ^{209}Bi elastic cross sections. The ratio of elastic scattering on ^{208}Pb to ^{209}Bi varies from about +4 to −7% over the angular range measured whereas the predictions only range from 0 to − 2%. If one assumes that the flat region of the angular distribution around 40° is given most accurately by the calculation, then this would reduce the (p,d) ratio by 3.5% to 1.05 instead of the 2% implied by the 90° elastic data. The conclusion is that the ^{208}Pb(p,d) cross section appears to be only about 5% higher than the ^{209}Bi(p,d) cross section. However there remains some uncertainty in this number because of the uncertainty in the difference in the elastic cross sections. A check on the target thickness using an α gauge gave consistent values but the errors in these measurements were too great (± 6%) to draw more definitive conclusions.

VI. CONCLUSIONS

The results from the ^{209}Bi(p,d) ^{208}Bi experiment are generally in good agreement with previous measurements from the (d,t) reaction.[2,3] In a few cases some spin assignments do not check; in particular the 2^- member of the $i_{13/2}$ multiplet was not observed at the previously given position. The position of this state is important because its location is strongly dependent on the strength of the tensor part of the two-body force in nuclei.[1] The absolute cross section for the ^{209}Bi$(p,d)^{208}$Bi ground-state 5^+, 4^+ $p_{1/2}$ doublet and ^{208}Pb(p,d)-^{207}Pb ground-state transition agreed to within ± 5%. There was some indication that the ^{208}Bi spectroscopic factors relative to ^{207}Pb were slightly larger than the weak-coupling predictions for the higher l- transfers. Apart from the $(\pi h_{9/2}, \nu^{-1} h_{9/2})$ multiplet, one of the few exceptions to the weak-coupling predictions occurs in the $(\pi h_{9/2}, \nu^{-1} p_{3/2})$ multiplet where there is significant mixing with nearby 4^+ and 3^+ states. However, this mixing is accurately predicted by Kuo's calculations.[6] In general, the agreement of the present results and the weak-coupling-model predictions for ^{208}Bi is very good.

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