States in ^{205}Pb excited via the ^{204}Pb(d,p) reaction. I. The "hole" states*

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The spectrum of ^{205}Pb is studied with the ^{204}Pb(d,p) transfer reaction at incident energies of 13.0 and 20.0 MeV. Angular distributions are obtained for 15 of the known single-hole fragments in ^{205}Pb below an excitation energy of 2.56 MeV. Spectroscopic strengths are extracted and these results compared with three theoretical calculations. Two of these reproduce the total spectroscopic strengths and centroid energies for the neutron hole states rather well.

[NUCLEAR REACTIONS ^{204}Pb(d,p) $0 < E_x \leq 2.56$ MeV; $E(d) = 13.0$ and 20.0 MeV; measured $\sigma(E_p, \theta)$, extracted S_{lj}, and compared them with several theoretical calculations.]

I. INTRODUCTION

There is ample evidence[1] that the general features of the low-energy spectra observed in the Pb region can be explained by a simple shell-model interpretation. Indeed, current investigative efforts are directed towards examining the deviations from the simple shell behavior, as for example manifested in the fragmentation of the single-particle (hole) shell-model states. When the systematics of such departures are at hand, a more sophisticated nuclear potential in this region should evolve. In this context the present paper and that immediately following report on a series of ^{204}Pb(d,p) experiments populating levels in ^{205}Pb from zero to 5.62 MeV of excitation. Ultimately, the entire spectrum will be viewed as a whole, but an immediate understanding of the data is best achieved through separate discussions of the low-lying and the higher-lying states. The demarcation line is 2.56 MeV excitation energy. At this energy it is experimentally observed that the stripped neutron is populating fragments of the $N=6$ major shell states (those occurring with the 127th neutron). Below 2.56 MeV the excited states can be interpreted as fragments of the $N=5$ major shell. The latter levels are treated here, while the $N=6$ fragments are discussed in the following paper.

The $N=5$ region of the ^{205}Pb spectrum has been intensely studied previously, both experimentally and theoretically. In particular, Bjerregaard *et al.*[2] performed the ^{204}Pb(d,p) experiment with 13.3 MeV deuterons. From their data they extracted 27 proton groups representing states in ^{205}Pb up to 4.2 MeV excitation; only five of the groups, however, corresponded to an energy less than 2.56 MeV. This region of the spectrum is also seen in the decay of ^{205}Bi ($\frac{9}{2}^-$ ground state). With a maximum energy of 2.703 MeV,[3,4] ^{205}Bi decays by electron capture to certain states in ^{205}Pb which then depopulate via γ emission. By measuring γ-γ coincidences and also the accompanying electron conversion spectrum, Hamilton *et al.*[3] were able to establish 26 levels in ^{205}Pb up to 2.607 MeV, with most of these being assigned a unique spin and parity. The angular-momentum selection rules for the initial weak decay and the succeeding γ decays favor the population of relatively high ($\geq\frac{5}{2}$) spin states except in the lowest excitation energy range. The ^{205}Bi results are complemented by the ^{204}Pb(n,γ) slow neutron capture experiments. The neutrons go into $\frac{1}{2}^+$ unbound states in ^{205}Pb for which the $E1$ selection rules allow decays to $\frac{1}{2}^-$ and $\frac{3}{2}^-$ bound states. Jurney, Motz, and Vegors[5] analyzed the γ spectrum and found that it did not follow the predictions of the statistical model; that is, there was a gap in the energy spectrum between 2.117 and 3.572 MeV. The higher energy γ decays were interpreted as representing the direct population of 16 low-lying states, all below 2.65 MeV except for one at 3.162 MeV. (The experiment was sensitive enough to detect the much weaker and lower energy $M1/E2$ transitions between the low-lying states, thereby accounting for the nonstatistical gap in the γ spectrum.) Either there are no $\frac{1}{2}^-$ or $\frac{3}{2}^-$ states above 2.65 MeV (except for one), or if there are, for some reason the direct decay to them is greatly inhibited. The (n,γ) data reveals low-spin states ($\frac{1}{2}^-,\frac{3}{2}^-$) between 0.8 and 2.5 MeV of excitation which were not seen in the ^{205}Bi decay. The experimentally determined low-lying spectrum of ^{205}Pb is listed in Table I. This table also summarizes other measurements

TABLE I. Known levels in ^{205}Pb below 2.7 MeV.

E	J^π	^{205}Bi [a]	(n,γ) [b]	(p,d) [c]	(d,t) [d]	(p,t) [e]	(d,p) [f]	E	J^π	^{205}Bi [a]	(n,γ) [b]	(p,d) [c]	(d,t) [d]	(p,t) [e]	(d,p) [f]
		Reaction populating ^{205}Pb								Reaction populating ^{205}Pb					
0.0	$\frac{5}{2}^-$	X	X	X	X	X	X	1.764	$\frac{7}{2}^-$	X		X	X		X
0.0023	$\frac{1}{2}^-$	X	X	X	X	X	X	1.776	$\frac{7}{2}^-$	X				X	
0.262	$\frac{3}{2}^-$	X	X	X	X	X	X	1.813	$(\frac{1}{2}^-)$		X				
0.576	$\frac{3}{2}^-$	X	X	X	X	X	Y	(1.818)	$\frac{5}{2}^-$	X				X	
0.703	$\frac{7}{2}^-$	X				X		1.842	$(\frac{13}{2}^+)$	X		X			Y
0.761	$\frac{5}{2}^-$	X	X	X	X	X	Y	1.921	$(\frac{3}{2}^-)$		X			X	
0.803	$(\frac{3}{2}^-)$		X	X	X	X	Y	1.966	$\frac{9}{2}^-,\frac{7}{2}$	X				X	
0.987	$\frac{9}{2}^-$	X				X		2.089	$(\frac{3}{2}^-)$		X			X	
0.999	$(\frac{1}{2}^-)$		X	X	X	X	Y	2.120	$(\frac{1}{2}^-)$		X				
1.014	$\frac{13}{2}^+$	X		X	X	X	X	2.203	$\frac{11}{2}^+$	X				X	
1.044	$\frac{7}{2}^-$	X		X		X	Y	2.252	$\frac{7}{2}^+,\frac{9}{2}^+$	X[g]				X	X
1.265	$\frac{5}{2}^-$	X					Y	2.354	$(\frac{1}{2}^-)$		X	X		X	Y
1.374	$(\frac{3}{2}^-)$		X	X		X	Y	2.364	$(\frac{3}{2}^-)$		X				
1.499	$\frac{9}{2}^-$	X				X		2.487	$(\frac{3}{2}^-)$		X			X	
1.575	$\frac{7}{2}^-$	X		X		X		2.488	$\frac{9}{2}^+,\frac{7}{2}^+$	X				X	
1.594	$\frac{9}{2}^+$	X				X		2.521	$\frac{7}{2}^-$	X		X		X	
1.614	$\frac{7}{2}^-$	X		X	X	X	Y	2.556			X				
1.619	$(\frac{1}{2}^-)$		X					2.565	$\frac{9}{2}^+$	X		X		X	X
1.705	$\frac{11}{2}^-,\frac{9}{2}^-$	X				X		2.568			X				
1.756		X				X		2.607	$\frac{9}{2}^+$	X					X
1.759	$\frac{9}{2}^+$	X						2.635			X			X	

[a] References 3 and 4.
[b] Reference 5.
[c] Reference 6.
[d] Reference 7.
[e] Reference 8.
[f] Reference 2 and present work. Y indicates a level seen only in the present ^{204}Pb(d,p)^{205}Pb study.
[g] Spin assignment of Ref. 3 questioned in favor of $\frac{9}{2}^+$.

of direct reactions populating ^{205}Pb residual levels.[6-8]

Appropriate to the lead region are the single-particle and single-hole neutron shell-model states depicted in Fig. 1. The energy spacings of the particle states are as they appear in ^{209}Pb,[9] while those for the hole states come from the ^{208}Pb(p,d)-^{207}Pb spectrum.[10] The major shell gap of 2.7 MeV corresponds to the excitation of the nearly pure $2g_{9/2}$ fragment in ^{207}Pb by the (d,p) transfer.[11] The $^{205}_{82}$Pb$_{123}$ nucleus has a closed proton shell and three neutron holes in the $N=5$ major shell. According to the simple shell model, the three-hole ^{205}Pb ground state should have the configuration $|^{208}\mathrm{Pb}^{0+}_{\mathrm{g.s.}} \otimes (2f_{5/2}{}^{-1})(3p_{1/2}{}^{-2})\rangle_{5/2^-}$. Excited states should appear with spins and energies as given in Fig. 1. Of course, the residual interaction destroys this simplicity, but the first three states of ^{205}Pb do have the expected spins. In Table I, it is seen that most of the low-lying states in ^{205}Pb have negative parity, that obtained by the coupling of three negative parity holes. Only when configurations with one or three $1i_{13/2}$ holes are considered will there by positive parity states constructed from the $N=5$ major shell. Therefore, using only the hole states of Fig. 1 as a basis space, several authors have endeavored to reproduce the low-lying spectrum of ^{205}Pb. Three calculations which have given (d,p) spectroscopic factors to these states will now be briefly summarized.

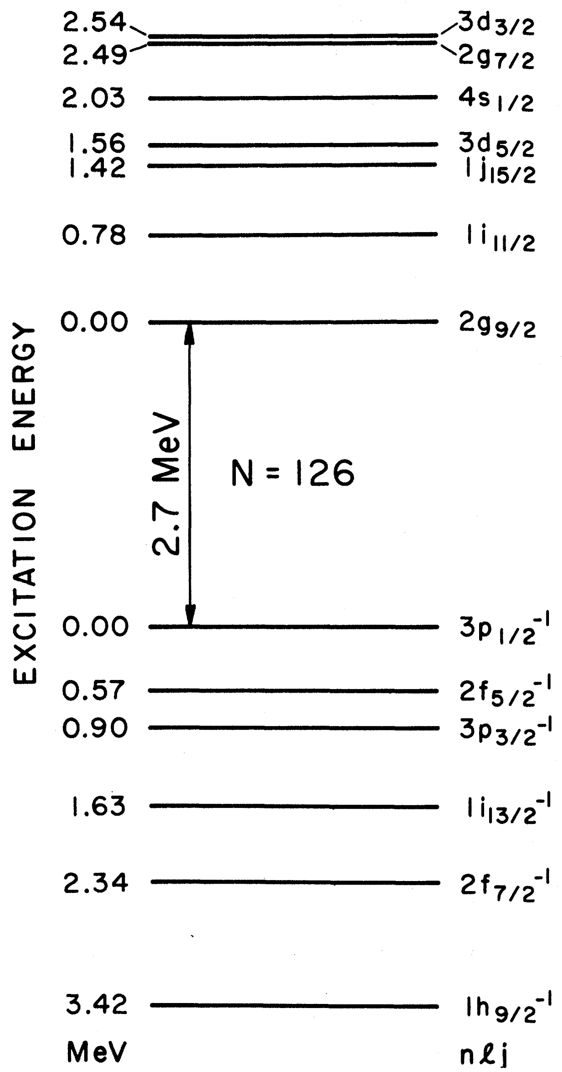

FIG. 1. The observed ordering of the neutron single-particle and single-hole orbits of the $^{208}_{82}Pb_{126}$ core (Ref. 11). The particle orbits constitute the $N=6$ major shell, and the hole orbits are in the $N=5$ major shell.

The calculation by Miranda[12] used a simple analytical residual interaction and did not include the deepest-lying $1h_{9/2}$ state. Miranda's force contained separate singlet-even and triplet-odd strengths, and core renormalization was simulated by weak nonlocality parameters in the 0, 2, and 3 terms of the multipole decomposition. The parameters of the interaction were varied to obtain the best fit to the spectrum below 1.5 MeV excitation.

A second calculation using the BCS formalism was made by Harvey and Clement.[13] The conventional BCS procedure was modified according to the inverse gap equation (IGE) method of Gillet, Green, and Sanderson[14] wherein the experimental hole energies of ^{205}Pb were taken to be quasiparticle-model energies rather than shell-model energies. The lighter lead isotopes from ^{203}Pb to ^{207}Pb were all considered, and the comparison of theory and experiment indicated that the lead region was particularly amenable to the IGE method, more so than the tin and nickel regions.

The last nuclear structure calculation to be mentioned here is that being performed by McGrory *et al.*,[15] using a Kuo-Brown type[16] "realistic interaction" similar to that reported by Kuo and Herling[17] for ^{210}Pb, ^{210}Bi, and ^{210}Po.

II. EXPERIMENTAL METHOD

These experiments utilized the Yale MP-1 tandem Van de Graaff accelerator to obtain 13.0 and 20.0 MeV incident energy deuterons. The outgoing proton groups were momentum analyzed with the laboratory's multigap spectrograph.[18] Nuclear emulsion photographic plates recorded the protons and the data were obtained by manual scanning. The target was 225 $\mu g/cm^2$ of ^{204}Pb (99.7% isotopic purity) evaporated onto 10 $\mu g/cm^2$ carbon foils. The target's thickness was measured by an α-stopping-power gauge and also by the Rutherford scattering of 4 MeV protons. The two methods agreed to within $\pm10\%$. The absolute cross sections are believed accurate to $\pm15\%$.

One 13.0 MeV exposure was taken, accumulating 2000 μC of charge. The photograph plates spanned the angular range 5° to 80° in 7.5° intervals; unfortunately technical difficulties caused the loss of the 35° data. The average energy resolution achieved was $\Delta E/E \approx 0.06\%$ (i.e., 9 to 11 keV).

Two 20.0 MeV measurements were made, utilizing 4000 and 10 200 μC exposures, respectively. The shorter run was taken to measure the enhanced yield of the ground-state group $[(d\sigma/d\Omega)_{max} = 2.5$ mb/sr$]$ which, for angles forward of 57.5°, saturated the plates in the longer run. Data were recorded in the angular range 5° to 115° in 7.5° intervals, although it turned out that most groups were too weak to be significant beyond 80°. For the 20 MeV runs, the $\Delta E/E$ resolution was somewhat worse than that at 13.0 MeV incident energy. Specifically, a doublet at 1.00 MeV of excitation which should have been resolved was not. More serious was the presence of contaminant elements on the target. A careful search turned up many proton groups from lighter elements moving through the ^{205}Pb spectrum. The majority of the ^{205}Pb groups are only weakly (~25 μb/sr) excited and thus were sometimes obscured in their angular distributions by contaminant lines. In Fig. 2 we show the low-lying ^{205}Pb spectrum as observed

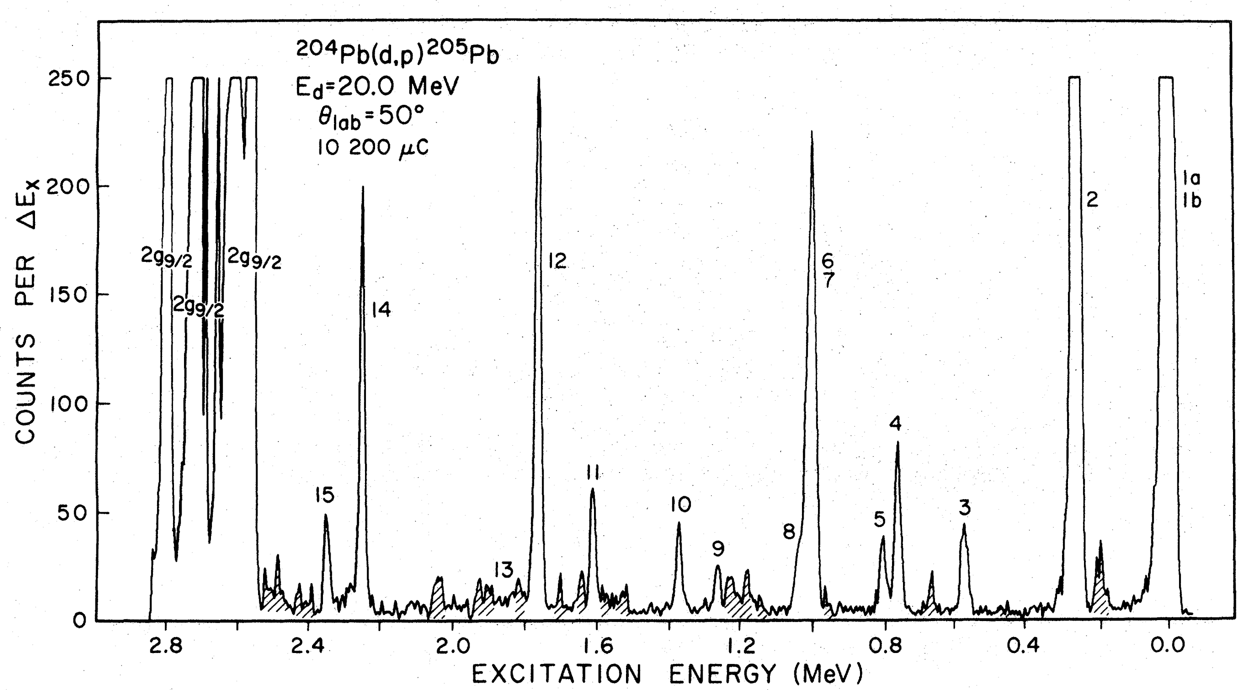

FIG. 2. The low-lying (d,p) spectrum of ^{205}Pb as observed with 20.0 MeV incident energy deuterons. The numbered groups correspond to levels in ^{205}Pb, while the shaded areas arise from contaminants.

at one angle in the 20.0 MeV measurement. [In Fig. 2 of the following paper we present the full (d,p) spectrum of ^{205}Pb, showing that the low-lying spectrum of ^{205}Pb is much less complex than the higher-lying spectrum.]

III. EXPERIMENTAL RESULTS

A total of 15 proton groups representing 16 levels in ^{205}Pb up to 2.56 MeV of excitation were deduced from these experiments. While all the groups in the spectrum are seen at both incident deuteron energies, 13.0 and 20.0 MeV, only six of the 13.0 MeV angular distributions have statistically significant yields. The experimental angular distributions of all the groups are given in Figs. 3 and 4 along with direct reaction fits to be discussed below. It should be pointed out that the long 20.0 MeV exposure was capable of detecting cross sections as low as 2 μb/sr (corresponding to an integrated yield of about 40 counts). Consequently, the present work constitutes a very sensitive test for the nuclear structure calculations summarized above. Comparing Table I and Fig. 2, it is seen that only about half the known low-lying states in ^{205}Pb are excited in the (d,p) reaction. All the excitation energies derived correspond to previously established states: no new levels in ^{205}Pb are proposed. Only five of the groups (including two doublets) are excited with peak cross sections greater than 100 μb/sr at 20.0 MeV incident energy; the remaining groups all have peak cross sections of less than 30 μb/sr.

The direct reaction code DWUCK[19] was used to predict distorted-wave Born approximation (DWBA) angular distributions; these were compared with the experimental differential cross sections. The choice of the d, p, and n potentials used in the analysis is explained in the following paper and listed in Table II of that paper. The calculated curves are shown in Figs. 3 and 4. The predicted shapes were fitted to the experimental differential cross section according to the usual equation[19]

$$\sigma^{\exp}(\theta) = N_0 S_{lj} \sigma_{lj}^{\mathrm{DW}}(\theta)\,, \tag{1}$$

where $\sigma^{\exp}$ is the experimental cross section, $\sigma_{lj}^{\mathrm{DW}}$ is the theoretical cross section, N_0 (=1.5) is the zero-range deuteron normalization factor obtained from the Hulthen wave function, and S_{lj} is the spectroscopic factor extracted from the fit to the data. Our spectroscopic factors, those of Bjerregaard *et al.*,[2] and the theoretical predictions are given in Table II. However, the spectroscopic factors derived from the 13.0 and 13.3 MeV data are subject to question because no account has been taken of resonance anomalies in the outgoing

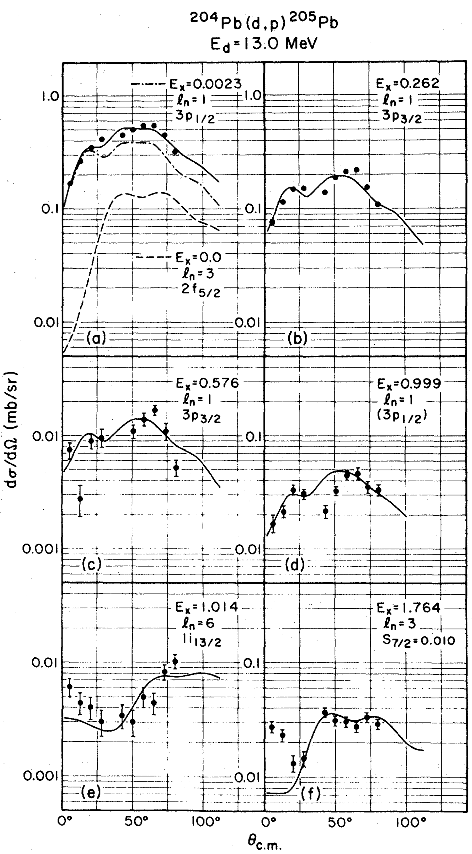

FIG. 3. (a) – (f) Fits to the strongest ^{204}Pd(d,p) ^{205}Pb hole-state angular distributions at E_d = 13.0 MeV. Even with 2000 μC of charge, the other groups are too weakly excited to have meaningful angular distributions.

channel. These resonances are discussed in the following paper. The analysis of the 20.0 MeV data is free from that criticism. It should also be noted that spectroscopic factors from the present analysis may not be directly comparable to those predicted by the more complex theoretical descriptions,[12,13,15] since the theoretical form factors are not necessarily similar to those given by the separation-energy procedure used here.

Neglecting temporarily the fits to the $\frac{7}{2}^-$ groups, the quality of the fits is generally good. Ignoring the 1.764 MeV $\frac{7}{2}^-$ state, the quoted spectroscopic factors for our 13.0 and 20.0 MeV data are in fair agreement with each other.

One immediately apparent result available from Table II concerns the $\frac{13}{2}^+$ state at 1.014 MeV of excitation. Near this state, at 0.999 MeV, we observe the population of a level via an $l_n = 1$ transfer, an assignment that has been only tentatively established heretofore.[5,7] Unaware of this 0.999 MeV level and not having resolved the doublet, Bjerregaard *et al.*[2] mistakenly analyzed the proton group as a singlet $1i_{13/2}$ transfer which was then assigned an erroneously large spectroscopic factor. This doublet was completely resolved in our 13.0 MeV work but not quite in the 20.0 MeV data. Nonetheless, the existence of an $l_n = 1$ transfer is plainly evident at both incident energies [Figs. 3(d), 3(e), and 4(f)] along with the shape of the l_n = 6 transfer to the $1i_{13/2}$ state whose spectroscopic factor is now reduced a factor of 2 from the Bjerregaard value.

A second doublet unresolved in the spectrum is that of the $\frac{5}{2}^-$ ground state and the 2.3 keV $\frac{1}{2}^-$ state. The resulting proton group's angular distribution was taken to be the sum of an $l_n = 3$ shape and an $l_n = 1$ shape, with each group weighted by the spectroscopic factor to the corresponding member of the doublet. Unfortunately, the empirical shapes at both incident energies [Figs. 3(a) and 4(a)] are dominated by the $l_n = 1$ member, making the extraction of the $2f_{5/2}$ spectroscopic factor more difficult.

An angular distribution which is fitted well is that of the 2.252 MeV state, assigned a $\frac{7}{2}^+$ spin and parity in the study of the ^{205}Bi decay.[3] As such, this state would be reached via an $l_n = 4$ transfer and this is confirmed by the fit displayed in Fig. 4(m). The $\frac{7}{2}^+$ assignment (based on a weak coincidence) is not absolutely conclusive.[20] There exists a small chance that the 2.252 MeV state is $\frac{9}{2}^+$. Such a spin, also allowed by the $l_n = 4$ transfer, is more consistent with the evidence presented in the following paper. [Briefly it is concluded in that paper that the (d,p) spectroscopic strengths for the $N = 6$ major shell orbits are concentrated narrowly about the centroids. In that case, it is much more likely that the 2.252 MeV state is being populated through a $2g_{9/2}$ mixture 0.4 MeV away from its centroid, rather than by a $2g_{7/2}$ component 3.5 MeV away from its centroid.]

The worst fit to the experimental angular distributions is that for the main $2f_{7/2}$ fragment at 1.764 MeV of excitation [Figs. 3(f) and 4(k)]. The other observed $2f_{7/2}$ fragments at 1.044 and 1.614 MeV [Figs. 4(g) and 4(j)] are also poorly fitted, although these angular distributions are not as well measured. The predicted $2f_{7/2}$ shape is completely out of phase with the forward-angle shape of the 1.764 MeV group which exhibits a broad maximum starting near 0°. Surprisingly the data at angles greater than $\theta = 42.5°$ appear to be reasonably fitted. Several explanations can be advanced for this failure but are found to be wanting. The most obvious is contaminant interference, especially by an $l_n = 0$ transfer. However, the maximum is too broad to sustain this theory. Moreover, none of the identified contaminant ele-

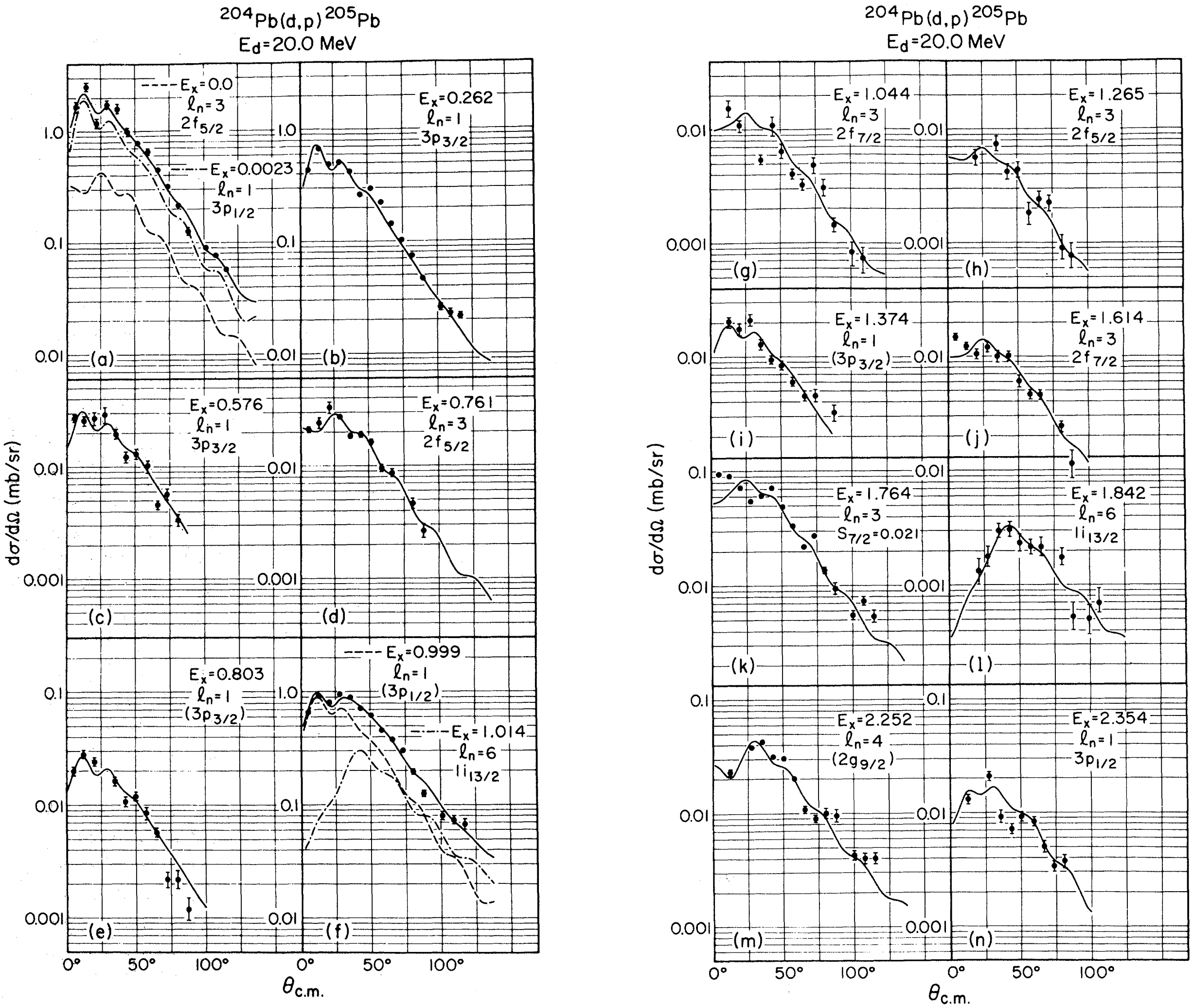

FIG. 4. (a) – (n) Fits to all the ^{204}Pb(d,p) hole-state angular distributions observed at $E_d = 20.0$ MeV.

ments would produce an $l_n = 0$ line at this energy in the spectrum, and it is difficult to believe that some undiscovered contaminant element could give such a strong group at this point in the spectrum and not give another group elsewhere. Neither is the fault likely to lie with the optical parameters, since the same parameters predict very well the observed shapes of the other hole states ($l_n = 1$, 3, and 6) and also of the particle states ($l_n = 0$, 2, 4, 6, and 7). Finally the possibility of a doublet was considered and rejected since we found no combination of l_n shapes which would fit the forward-angle shape without also destroying the fit to the back-angle points.

It is believed that the problem is related to the fragmentation of the $2f_{7/2}$ orbital, a phenomenon which also occurs in ^{207}Pb. In that nucleus, the main $2f_{7/2}$ fragment occurs at 2.34 MeV excitation and can also be reached weakly via the (d,p) reaction as seen by Moyer, Cohen, and Diehl.[11] The ^{207}Pb $\frac{7}{2}^-$ angular distribution was not well fitted with the standard DWBA prediction. For ^{207}Pb Hamamoto[21] has suggested a splitting of the $2f_{7/2}$ orbital through admixture with the configuration $|^{208}\mathrm{Pb}^{3^-}_{2.62\ \mathrm{MeV}} \otimes 1i_{13/2}{}^{-1}(1.6\ \mathrm{MeV})\rangle_{7/2^-}$. Recently a ^{208}Pb$(p,d)$ ^{207}Pb study[22] has found a $\frac{7}{2}^-$ state at 4.14 MeV which is believed to be the other fragment resulting from the mixing. If such a splitting mechanism is present in ^{207}Pb, it is likely to carry over into ^{205}Pb. As a matter of fact the three ^{205}Pb calculations[12,13,15] predict substantial fragmentation of the $2f_{7/2}$ state and this prediction

TABLE II. The low-lying (d,p) spectrum of ^{205}Pb.

No.	Exp. E_x [g] (MeV)	nlj [h]	Exp. spectroscopic factors 13.3 [a] (MeV)	13.0 [b] (MeV)	20.0 [c] (MeV)	Theoretical values Miranda [d] E_x (MeV)	S_{lj}	McGrory [e] E_x (MeV)	S_{lj}	Harvey [f] E_x (MeV)	$\sum S_{lj}$
1a	0.0	$2f_{5/2}$	0.37	0.26	0.27	0.0	0.24	0.07	0.18	0.0	0.19
1b	0.0023	$3p_{1/2}$	0.70	0.61	0.83	0.070	0.53	0.0	0.64	0.0	0.62
2	0.262	$3p_{3/2}$	0.15	0.12	0.15	0.26	0.09	0.21	0.17	0.25	0.27
3	0.576	$3p_{3/2}$		0.006	0.007	0.47	0.0004	0.75	0.005	0.60	
	0.703	$2f_{7/2}$			<0.001 [i]	0.82	0.0002	0.91	0.000	0.77	j
4	0.761	$2f_{5/2}$		0.018	0.014	0.84	0.0003	0.88	0.006	0.73	
5	0.803	$3p_{3/2}$		0.003	0.004	0.99	0.005	1.02	0.02	0.91	
6	0.999	$(3p_{1/2})$	k	0.034	0.042	1.36	0.019	0.80	0.005	0.68	
7	1.014	$1i_{13/2}$	0.093 [k]	0.045	0.040	0.86	0.0013	1.12	0.027	1.03	0.021
8	1.044	$2f_{7/2}$			0.004 [l]	1.02		1.13	0.001	0.88	j
9	1.265	$2f_{5/2}$			0.004	1.34	0.004	1.37	0.000	1.22	
10	1.374	$3p_{3/2}$			0.004	1.24	0.001	1.35	0.004	1.37	
11	1.614	$2f_{7/2}$		0.004	0.004 [l]	1.63	0.0004	1.58	0.004	1.59	j
12	1.764	$2f_{7/2}$	0.013	0.010	0.021 [l]	1.77	0.0003	1.76	0.023	1.82	j
13	1.842	$1i_{13/2}$			0.004	1.93		2.09	0.001	1.85	
14	2.252	$(2g_{9/2})$			0.01						
15	2.354	$(3p_{1/2})$			0.006 [l]						

[a] Reference 2.
[b] Present work, ±18%.
[c] Present work, ±15%.
[d] Reference 12.
[e] Reference 15.
[f] Reference 13.
[g] References 3 and 4.
[h] Quantum numbers for transfer used in DW calculation.
[i] Level probably absent.
[j] Harvey and Clement predict that the total $2f_{7/2}$ strength equals 0.029 with the calculated 1.82 MeV level taking the most strength.
[k] Bjerregaard *et al.* assigned all the strength of this doublet to the $1i_{13/2}$ member.
[l] Angular distributions poorly fit.

is borne out by the results of the present experiment.

Granting that the $2f_{7/2}$ single-hole state is more severely admixed with other possible configurations, the resulting form factor is probably not well described by the simple separation-energy procedure. Whether the form factor uncertainty is responsible for the marked failure of the $2f_{7/2}$ to match the predicted angular distribution is, however, not clear. Since the $l_n = 3$ transfer is actually the "matched" momentum value, the surface region is most important in the transition matrix element. In this region of the nucleus, the separation-energy procedure guarantees the correct radial dependence although not the overall normalization. Hence, any radical changes in the predicted angular distribution would have to be the result of gross errors in the interior parts of the separation-energy form factor.

A second explanation (which would not preclude the uncertainties in the form factor) is that the $\frac{7}{2}^-$ transitions in ^{205}Pb (and ^{207}Pb) are symptomatic of the contributions of processes more complicated than the one-step transition. Processes involving inelastic scattering as well as transfer have recently been demonstrated to be important for certain weaker transitions in the rare-earth region,[23] although no experimental evidence has so far confirmed their effect in direct reactions on the lead region. However, by analogy with the strongly collective rotational states which participate during rare-earth direct reactions it is possible that the strongly collective 3^- vibration in ^{204}Pb (2.62 MeV, 35 Weisskopf units)[24] is inducing an interference effect which could distort the angular distribution. Two-step sequential transfers have also been suggested[25] in this region; however, the influence of multistep processes does not seem to be important for other states formed by coupling single-particle states to core vibrations. At this time these remarks are speculative since no calculations of either effect have been attempted. In any event, the discrepancy in the fit to the 1.764 MeV angular distribution is undeniable.

IV. COMPARISON OF THEORY WITH EXPERIMENT

The comparison of any absolute experimental spectroscopic factor with the corresponding theoretical prediction cannot be very precise. Uncertainties about the reaction mechanism calculation (especially for the 13 MeV data) and also the error limits placed on the absolute cross section can be invoked to cover an extended margin of error. Less subject to such qualifications are the relative spectroscopic factors and the overall magnitude and distribution of excitation. In that spirit, the comparison of the spectroscopic factors listed in Table II will be discussed.

All of the three calculations cited state that the first three states in ^{205}Pb should nearly exhaust their respective available spectroscopic strengths. This clearly is what is observed experimentally. Considering the uncertainties mentioned above, experiment and theory are within the limits of agreement. The calculation of McGrory[15] and of Harvey and Clement[13] also appear to be successful in their estimation of the fragmentation of the $1i_{13/2}$ and $2f_{7/2}$ hole states. With respect to these states, the older Miranda calculation[12] underestimates the observed spectroscopic strength. One success of the Miranda calculation, however, is in the description of the lowest-lying $\frac{7}{2}^-$ state at 0.703 MeV. Miranda and also Rao[26] have calculated that near this energy should lie a $\frac{7}{2}^-$ level based mainly on the first 2^+ core vibration (of moderate collectivity, ~9 Weisskopf units[24]). Confirmation of such collectivity comes from the ^{205}Bi decay work.[3] By a branching ratio of 99.9% the 0.703 MeV state $E2$ decays to the $\frac{5}{2}^-$ ground state completely eschewing a similarly allowed decay to the 0.262 MeV $\frac{3}{2}^-$ state. An appealing view is the assumption that the 0.703 MeV level is mainly $|^{204}\mathrm{Pb}^{2+}_{0.899} \otimes 2f_{5/2}\rangle_{7/2^-}$, for which only the core participates in the transition leaving the odd neutron as a spectator. As such, the state should not be populated by a direct (d,p) reaction on the 0^+ target. Our experiment offers confirmation that this state is very weakly populated (if at all).

V. SUMMARY

With a very high sensitivity to small cross sections, this study has examined the low-lying states of ^{205}Pb as seen in the ^{204}Pb(d,p) reaction. Even so, no new states were found and less than half the known states of ^{205}Pb in this region could be excited appreciably. The data show a clear division of the available spectroscopic strength, with one experimental level taking at least 90% of the observed spectroscopic strength for the $2f_{5/2}$, $3p_{1/2}$, $3p_{3/2}$, and $1i_{13/2}$ hole states. On the other hand, the $2f_{7/2}$ orbital shows much more splitting, and the deepest-lying $1h_{9/2}$ state is not seen. (However, it is possible that some $h_{9/2}$ hole strength is obscured by transitions populating the $2g_{9/2}$ particle states at 2.8 MeV.) In contrast to the upper three holes, the three most-bound holes are much more weakly excited, indicating that these subshells are almost completely filled in ^{204}Pb. A correction for a previous $i_{13/2}$ misassignment reinforces this conclusion.

With one exception, the experimental angular distributions were fitted reasonably well with a direct-reaction calculation. The deviant group was that from the main $2f_{7/2}$ fragment at 1.764 MeV of excitation. There is no satisfying explanation at this time to resolve this and a similar discrepancy in ^{207}Pb. Possibly multiple-step processes involving the highly collective 3^- states are responsible.

In view of what is to be presented in the following paper, the three-hole excitation spectrum of ^{205}Pb is quite sparse. Apart from the five strongest fragments, the proton groups all have peak cross sections of less than 30 μb/sr. In the following paper, it will be shown that nearly all the groups from the high-lying spectrum, in contrast, exceed 100 μb/sr at their maximum. It is almost inconceivable that any of these groups could come from hole-state fragments (l_n = odd), for if they did, a very large shift in the hole-state's centroid energy would be implied. Such a shift would have no physical basis, and would be inconsistent with the distribution of excitation as it has been observed here.

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