in ^{206}Pb at 0.803 MeV. The $\frac{3}{2}^+$ state in ^{205}Tl at 0.205 MeV does not show as many similarities. Finally, two states at 2.828 and 2.868 MeV in ^{206}Tl are observed to resonate strongly in the 0.205-MeV $\frac{3}{2}^+$ proton channel and thus have a dominant configuration

$$[\nu_n(g_{9/2})\psi_{3/2}{}^{+205}(0.205\ \text{MeV})]_{5^+4^+}.$$

These states are observed somewhat weakly in ^{205}Tl(d, p) so they also have a small amount of

$$[\nu_n(g_{9/2})\psi_{1/2}{}^{+205}(\text{ground state})]_{5^+4^+}$$

onfiguration. The dominant part of the latter configuration is contained in the two states at 2.581 and 2.594 MeV. The mixing of the two configurations is what allows one to see these states in the analog resonance decay. This selective nature of the analog decay limits to some extent the number of states one can observe but by the same manner limits the number of possible configurations that can be assigned to the states.

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Single-Hole Structure of Pb^{207}†

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The Pb$^{208}(p, d)$Pb^{207} reaction has been used with 20.00- and 22.00-MeV proton beams from the Yale MP tandem accelerator to study the low-lying neutron-hole levels of Pb^{207}. The finite-range, nonlocal distorted-wave Born-approximation (DWBA) analyses of the experimental (p, d) angular distributions indicate that the $\frac{1}{2}^-(3p_{1/2}{}^{-1})$ ground state, the $\frac{5}{2}^-(2f_{5/2}{}^{-1})$ 570-keV level, the $\frac{3}{2}^-(3p_{3/2}{}^{-1})$ 894-keV level, and the $13/2^+(\text{l}i_{13/2}{}^{-1})$ 1634-keV level are almost pure single-neutron-hole levels in the Pb^{208} core. The $2f_{7/2}$ neutron-hole strength, and particularly the $1h\frac{9}{2}$ neutron-hole strength, may be somewhat fragmented, although the $\frac{7}{2}^-(2f_{7/2}{}^{-1})$ 2334-keV level and the $\frac{9}{2}^-$, $(1h_{9/2}{}^{-1})$ 3430-keV level represent large fractions of their respective sum-rule neutron-hole strength. No evidence was found for j dependence in the Pb^{208} (p, d) angular distributions at $E_p = 20.00$ and 22.00 MeV.

I. INTRODUCTION

THE nucleus $_{82}$Pb$_{125}{}^{207}$ is one neutron less than the doubly magic nucleus $_{82}$Pb$_{126}{}^{208}$. In the simplest shell-model picture the low-lying levels of Pb^{207} are described as single neutron holes in the Pb^{208} core. These neutron holes consist of the shell-model orbitals in the $N = 83$–126 major shell, which are $3p_{1/2}$, $2f_{5/2}$, $3p_{3/2}$, $1i_{13/2}$, $2f_{7/2}$, and $1h_{9/2}$, in order of increasing excitation energy in Pb^{207}. All experimental evidence on Pb^{207} supports this simple shell-model picture in its qualitative and in most cases quantitative aspects.

Work on the electron-capture decay of Bi^{207},[1] studies of the α decay of Po^{211},[2] and neutron-pickup studies on Pb^{208} [3–9] find a $\frac{1}{2}^-(3p_{1/2}{}^{-1})$ ground state for Pb^{207}, a $\frac{5}{2}^-(2f_{5/2}{}^{-1})$ level at 570 keV, a $\frac{3}{2}^-(3p_{3/2}{}^{-1})$ level at 894 keV, a $\frac{13}{2}^+(1i_{13/2}{}^{-1})$ level at 1634 keV, a $\frac{7}{2}^-(2f_{7/2}{}^{-1})$ level at 2334 keV, and a $\frac{9}{2}^-(1h_{9/2}{}^{-1})$ level at 3430 keV. Pb$^{206}(d, p)$ [3,10] and Pb$^{207}(p, p')$ [11] reaction and scattering studies have also found levels in Pb^{207} which have a one-particle two-hole structure. The first two of these levels comprise the doublet near 2.6 MeV in excitation which arise from the coupling of the $p_{1/2}$

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† Work supported in part by the U. S. Atomic Energy Commission Contract No. AT (30-1) 3223.

* Present address: Physics Department, University of California, Los Angeles, Calif.

[1] E. K. Hyde, I. Pearlman, and G. T. Seaborg, *The Nuclear Properties of the Heavy Elements* (Prentice-Hall, Inc., Englewood Cliffs, N. J. 1964), Vol. II, p. 1008; and the references cited therein.

[2] Ref. 1, p. 550; and the references cited therein.

[3] P. Mukherjee and B. L. Cohen, Phys. Rev. **127**, 1284 (1962).

[4] C. Glashausser and M. E. Rickey, Phys. Rev. **154**, 1033 (1967).

[5] G. Muehllehner, A. S. Poltorak, W. C. Parkinson, and R. H. Bassel, Phys. Rev. **159**, 1039 (1967).

[6] W. P. Alford and D. G. Burke, Phys. Rev. **185**, 1560 (1969).

[7] K. Yagi, T. Ishimatsu, Y. Ishizaki, and Y. Saji, Nucl. Phys. **A121**, 161 (1968).

[8] W. C. Parkinson. D. L. Hendrie, H. H. Duhm, J. Mahoney, J. Saundinos, and G. R. Satchler, Phys. Rev. **178**, 1976 (1969).

[9] G. R. Satchler, W. C. Parkinson, and D. L. Hendrie (to be published).

[10] W. Darcey, A. F. Jeans, and K. N. Jones, Phys. Letters **25B**, 599 (1967).

[11] G. Vallois, J. Saudinos, O. Beer, M. Gendrot, and P. Lopato, Phys. Letters **22**, 659 (1966).

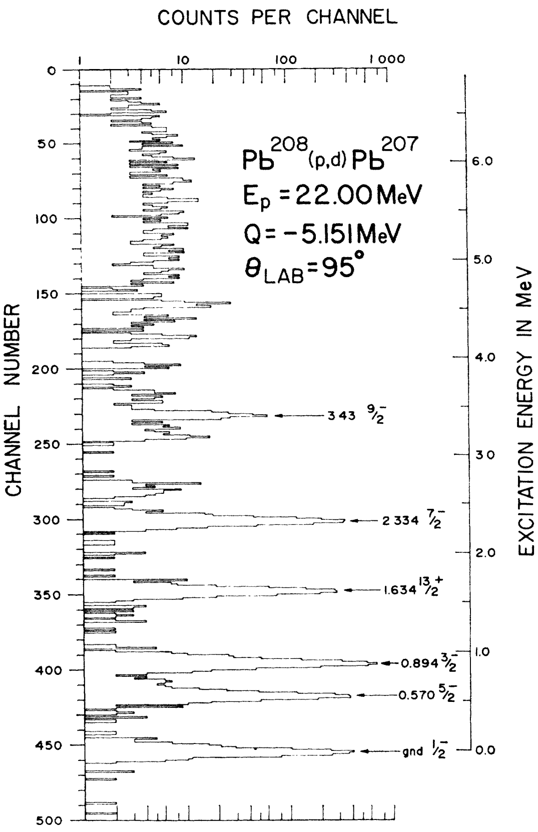

FIG. 1. Deuteron spectrum from the Pb^{208} (p, d) reaction with $E_p=22.00$ MeV and $\theta_{lab}=95°$.

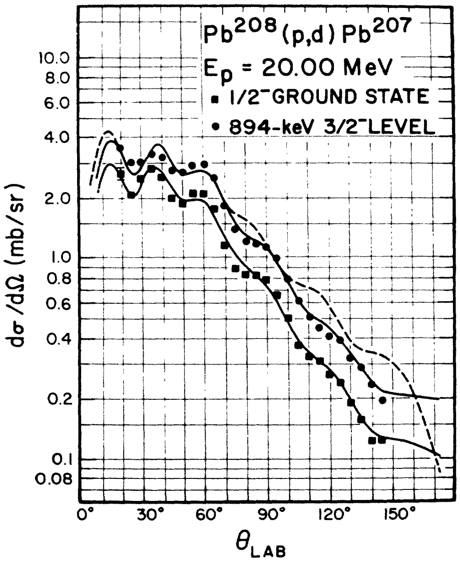

FIG. 2. Experimental $l_n=1$ (p, d) angular distributions to the $\frac{1}{2}^-(3p_{1/2}^{-1})$ ground state and to the $\frac{3}{2}^-(3p_{3/2}^{-1})$ 894-keV level of Pb^{207} at $E_p=20.00$ MeV. The solid curves are FRNL DWBA fits to the experimental data with a radial cutoff of 8.5 F. The dotted curve is a FRNL DWBA fit for the (p, d) transition to the $\frac{3}{2}^-$ level with no radial cutoff.

hole to the collective 3^- core excitation of Pb^{208}.[11] Most of the one-particle, two-hole levels have positive parity, while all the single-neutron-hole levels, except the $(1i_{13/2})^{-1}$ level at 1634 keV, have negative parity.

Our purpose in studying the $Pb^{208}(p, d)$ reaction with the Yale MP tandem accelerator was threefold. First, we wished to investigate the suitability of the (p, d) reaction for the study of single-neutron-pickup transitions in the lead region at the highest proton energies available. ($E_{p\,\max}=20$–22 MeV.) Two general criteria for the suitability of this neutron-pickup reaction mechanism are large cross sections, and easily distinguishable angular distributions for different values of the orbital angular momentum l_n of the picked-up neutron; in the $N=83$–126 major shell, the relevant values of l_n are 1, 3, 5, and 6. Similar studies of the $Pb^{208}(d, t)$ and $Pb^{208}(He^3, \alpha)$ neutron-pickup reactions have been reported.[5,6,8,9] As part of the present general study we wished to investigate to what degree the distorted-wave Born-approximation (DWBA) reaction-mechanism theory[12,13] reproduces the experimental $Pb^{208}(p, d)$ angular distributions, both in differential cross section shape and in absolute magnitude. If Pb^{208} has a closed neutron shell at $N=126$, and if the low-lying levels of Pb^{207} were indeed pure single-neutron-hole configurations, the spectroscopic factor S_{lj} for the transition to the neutron-hole state

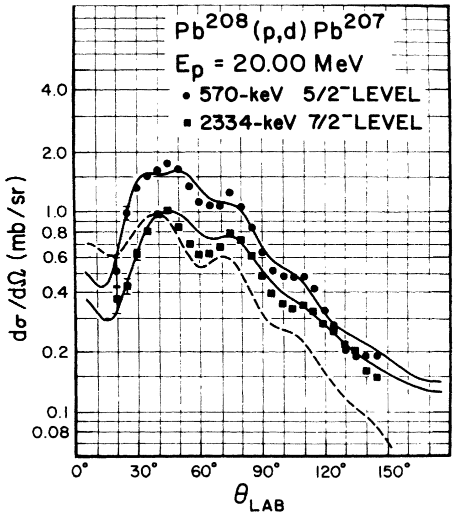

FIG. 3. Experimental $l_n=3$ (p, d) angular distributions to the $\frac{5}{2}^-(2f_{5/2}^{-1})$ 570-keV level and to the $\frac{7}{2}^-(2f_{7/2}^{-1})$ 2334-keV level of Pb^{207} at $E_p=20.00$ MeV. The solid curves are FRNL DWBA fits to the experimental data with a radial cutoff of 8.5 F. The dotted curve is a FRNL DWBA fit for the (p, d) transition to the $\frac{7}{2}^-$ level with no radial cutoff.

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[12] R. H. Bassel, R. M. Drisko, and G. R. Satcher, Oak Ridge National Laboratory Report No. ORNL-3240 and Suppl., 1962 (unpublished).

[13] G. R. Satchler, Nucl. Phys. 55, 1 (1964).

with quantum numbers l and j should equal $(2j+1)$, where $S_{lj}=\sigma(\text{expt})/\sigma_{lj}(\text{DWBA})$. Here $\sigma_{lj}(\text{DWBA})$ is the single-particle DWBA cross section.

Our second aim was to search for possible fragmentation of the $N=83$–126 neutron-hole strength in the level structure of Pb^{207}. For this reason, we required excellent statistical accuracy (3%) for all the strong peaks in the deuteron spectrum. The third goal of these studies was the measurement of the $Pb^{208}(p, d)$ angular distributions to include the larger angles (~150°–160°) and thereby to search for a possible j dependence similar to that which has been reported for (d, p) and (p, d) reactions on lighter nuclei.[14–18] For neutron-pickup transition in the $N=83$–126 shell there are two situations involving possible j-dependent effects, namely, two $l_n=1$ transitions ($j=\frac{1}{2}$ and $\frac{3}{2}$) and two $l_n=3$ transitions ($j=\frac{5}{2}$ and $\frac{7}{2}$).

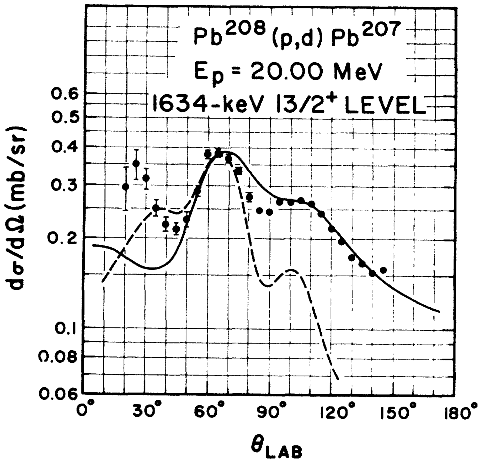

FIG. 4. Experimental $l_n=6$ (p, d) angular distribution to the $13/2^+(1i_{13/2}^{-1})$ 1634-keV level of Pb^{207} at $E_p=20.00$ MeV. The solid curve is a FRNL DWBA fit to the experimental data with a radial cutoff of 8.5 F, while the dotted curve is a FRNL DWBA fit with no radial cutoff.

II. EXPERIMENTAL PROCEDURE

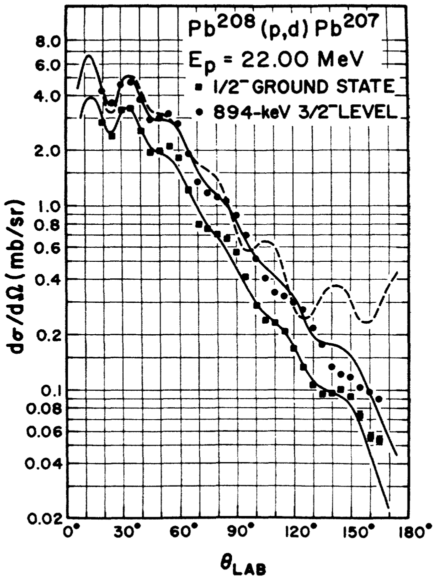

FIG. 5. Experimental $l_n=1$ (p, d) angular distributions to the $\frac{1}{2}^-(3p_{1/2}^{-1})$ ground state and to the $\frac{3}{2}^-(3p_{3/2}^{-1})$ 894-keV level of Pb^{207} at $E_p=22.00$ MeV. The solid curves are FRNL DWBA fits to the experimental data with a radial cutoff of 8.5 F. The dotted curve is a FRNL DWBA fit for the (p, d) transition to the $\frac{3}{2}^-$ level with no radial cutoff.

Proton beams of 20.00 and 22.00 MeV from the Yale MP tandem accelerator were used to bombard a self-supported, isotropically enriched Pb^{208} target, 700 μg/cm^2 in areal density. The beam intensities used in this experiment varied from ~10 nA at the most forward angle (20°) to ~800 nA at the larger angles. A ΔE-E telescope of silicon surface-barrier detectors and a particle-identifier system of the Landis-Goulding type[19] fabricated in this laboratory were used to identify and determine the energies of the deuteron and triton groups. The deuteron groups were stored in 512 channels of a 1024-channel analyzer while the

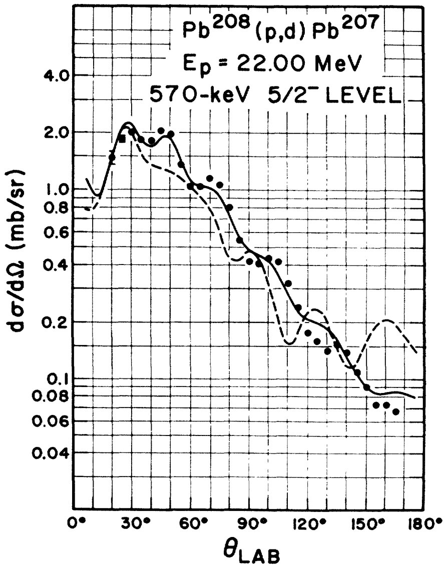

FIG. 6. Experimental $l_n=3$ (p, d) angular distribution to the $\frac{5}{2}^-(2f_{5/2}^{-1})$ 570-keV level of Pb^{207} at $E_p=22.00$ MeV. The solid curve is a FRNL DWBA fit to the experimental data with a radial cutoff of 8.5 F, while the dotted curve is a FRNL DWBA fit with no radial cutoff.

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[14] L. L. Lee, Jr., and J. P. Schiffer, Phys. Rev. Letters **12**, 108 (1964).

[15] L. L. Lee, Jr., and J. P. Schiffer, Phys. Rev. **136**, 405 (1964).

[16] J. P. Schiffer, L. L. Lee, Jr., A Marinov, and C. Mayer-Boricke, Phys. Rev. **147**, 829 (1966).

[17] R. Sherr, E. Rost, and M. E. Rickey, Phys. Rev. Letters **12**, 420 (1964).

[18] C. A. Whitten, Jr., E. Kashy, and J. P. Schiffer, Nucl. Phys. **86**, 307 (1966).

[19] F. S. Goulding, D. A. Landis, J. Cerny, and R. J. Pehl, Nucl. Instr. Met. **31**, 1 (1964).

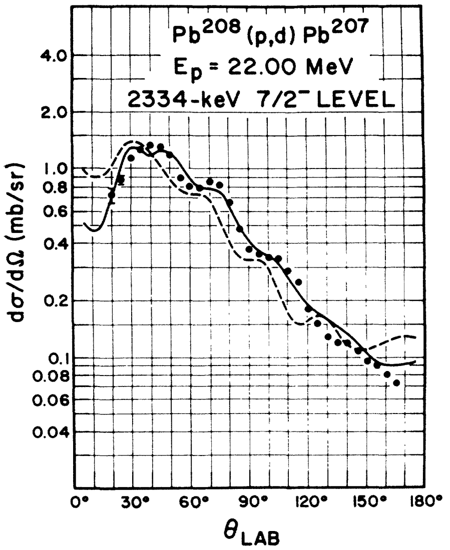

FIG. 7. Experimental $l_n=3$ (p, d) angular distribution to the $\frac{7}{2}^-(2f_{7/2}^{-1})$ 2334-keV level of Pb^{207} at $E_p=22.00$ MeV. The solid curve is a FRNL DWBA fit to the experimental data with a radial cutoff of 8.5 F, while the dotted curve is a FRNL DWBA fit with no radial cutoff.

triton groups, which were analyzed separately and which will be reported elsewhere,[20] were stored simultaneously in the second 512 channels. The particle telescope subtended a solid angle of approximately 1.4×10^{-3} sr; the angular resolution was approximately 2°. During all runs the condition of the Pb^{208} target was monitored by detecting elastically scattered protons at 90° to the incident beam. Throughout a long series of runs the ratio of elastically scattered proton monitor counts to integrated beam charge remained constant; no evidence of any target deterioration was detected.

We obtained absolute cross sections for the $Pb^{208}(p, d)$ reaction at 20.00 and 22.00 MeV by first measuring elastic proton-scattering yields on Pb^{208} at 7.00 MeV between 60° and 90°, where the scattering is purely Coulomb in character. Under identical conditions of target thickness and detector geometry we then measured the pickup-reaction cross sections at proton energies of 20 and 22 MeV. A very conservative estimate of the error in our absolute $Pb^{208}(p, d)$ cross sections at these energies is $\pm10\%$.

TABLE I. $Pb^{208}(p, d)Pb^{207}$ total cross sections for incident proton energies of 20.00 and 22.00 MeV.

Level in Pb^{207}	σ_t (mb) $E_p=20.00$ MeV	σ_t (mb) $E_p=22.00$ MeV
1/2⁻ ground state	12.6	11.8
5/2⁻ 570 keV	9.3	9.4
3/2⁻ 894 keV	17.7	18.3
13/2⁺ 1634 keV	3.2	3.4
7/2⁻ 2334 keV	5.9	6.7
9/2⁻ 3430 keV	···	0.68
	$\Sigma\,\sigma_t=48.6$ mb	$\Sigma\,\sigma_t=50.2$ mb
	5 levels	6 levels

III. EXPERIMENTAL DATA AND DISCUSSION

A typical deuteron spectrum for the $Pb^{208}(p, d)$ reaction at an incident proton energy of 22.00 MeV and a laboratory angle of 95° is shown in Fig. 1. Five levels in Pb^{208} are excited strongly: the $\frac{1}{2}^-(3p_{1/2}^{-1})$ ground state, the $\frac{5}{2}^-(2f_{5/2}^{-1})$ 570-keV level, and $\frac{3}{2}^-(3p_{3/2}^{-1})$ 894-keV level, the $\frac{13}{2}^+(1i_{13/2}^{-1})$ 1634-keV level, and the $\frac{7}{2}^-(2f_{7/2}^{-1})$ 2334-keV level. The $\frac{9}{2}^-(1h_{9/2}^{-1})$ level at 3430 keV is excited with moderate strength; all other levels in Pb^{207} up to an excitation energy of approximately 6 MeV are only weakly excited in the $Pb^{208}(p, d)$ reaction at $E_p=20.00$ and 22.00 MeV. Three levels are known to exist in Pb^{207} at excitation energies near 2700 keV, consisting of the $\{(Pb^{208}3^-)\nu 3p_{1/2}^{-1}\}$ $\frac{5}{2}^+$, $\frac{7}{2}^+$ doublet at 2610 and 2655 keV, respectively[11]; and the $\frac{9}{2}^+$, $2g_{9/2}$ one-particle–two-hole state at 2740 keV.[3,10] The deuteron spectrum of Fig. 1 shows that these levels are excited in the (p, d) reaction, but their strength is approximately 1/50–1/100 the strength of the single-neutron-hole levels of Pb^{207}.

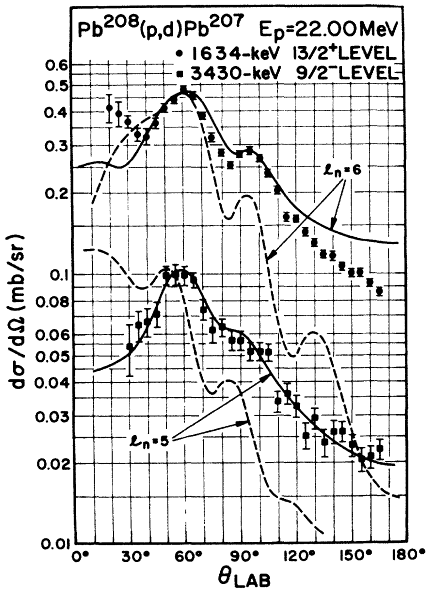

FIG. 8. Experimental $l_n=6$ (p, d) angular distribution to the $13/2^+(1i_{13/2}^{-1})$ 1634-keV level of Pb^{207}; and the experimental $l_n=5$ (p, d) angular distribution to the $\frac{9}{2}^-(1h_{9/2}^{-1})$ 3430-keV level of Pb^{207} at $E_p=22.00$ MeV. The solid curves are FRNL DWBA fits to the experimental data with a radial cutoff of 8.5 F. The dotted curves are FRNL DWBA fits with no radial cutoff.

Figures 2–8 present the experimental $Pb^{208}(p, d)$ angular distributions for the low-lying neutron-hole

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[20] G. E. Holland, C. A. Whitten, Jr., Nelson Stein, and D. A. Bromley (to be published).

TABLE II. DWBA parameters used in the analysis of the $\mathrm{Pb}^{208}(p, d)$ angular distributions.

$$V(r)=U_c(r)-V_0(1+e^x)^{-1}-iW_0(1+e^{x'})^{-1}+i4W_D(d/dx')(1+e^{x'})^{-1}+(h/m_\pi c)^2V_{so}\boldsymbol{\sigma}\cdot\mathbf{l}r^{-1}(d/dr)(1+e^x)^{-1},$$

where

$$U_c(r)=(Ze^2/2r_{0c}A^{1/3})[3-(r/r_{0c}A^{1/3})^2],\qquad r<r_{0c}A^{1/3}\qquad U_c(r)=Ze^2/r,$$

$$r>r_{0c}A^{1/3},\qquad x=(r-r_0A^{1/3})/a,\qquad x'=(r-r_0'A^{1/3})/a'.$$

	V_0	r_0	r_{0c}	a	W_0	W_D	r_0'	a'	V_{so}
Proton parameters[a]	53.5	1.25	1.25	0.65	...	7.5	1.25	0.76	...
Deuteron parameters[b]	108.6	1.057	1.25	1.059	...	12.7	1.478	0.636	...

Neutron well:

$$U_n(r)=-V_0[1-(\lambda/ra)(h/2m_pc)^2\boldsymbol{\sigma}\cdot\mathbf{l}d/dx](1+e^x)^{-1},$$
$$x=(r-r_{0n}A^{1/3})/a,$$
$$a=0.65\ \mathrm{F},\qquad r_{0n}=1.25\ \mathrm{F},\qquad \lambda=25.0.$$

V_0 is calculated from the shape of $U_n(r)$ and the binding energy of the picked-up neutron: $B_n(p, d)=[2.225-Q(p, d)]$ MeV.

[a] Reference 24.

[b] P. E. Hodgson, Advan. Phys. **15**, 329 (1966). The deuteron parameters listed in Table II are found on p. 411 of Hodgson's article; G. R. Satchler (private communication).

levels of Pb^{207} at incident proton energies of 20.00 and 22.00 MeV. At $E_p=20.00$ MeV the (p, d) angular distributions were measured from $\theta_{\mathrm{lab}}=20°–145°$, while at $E_p=22.00$ MeV the (p, d) angular distributions were measured from $\theta_{\mathrm{lab}}=20°–165°$. The $\mathrm{Pb}^{208}(p, d)$ transition to the $\frac{9}{2}^-$ $(1h_{9/2}^{-1})$ level at 3430 keV was only measured at $E_p=22.00$ MeV.

Three qualitative features may be noted regarding the experimental (p, d) angular distributions at $E_p=20.00$ and 22.00 MeV. First, with the exception of the transition to the $\frac{9}{2}^-(1h_{9/2}^{-1})$ 3430-keV level, the peak cross section for each (p, d) transition to the low-lying neutron hole levels of Pb^{207} is quite large—varying between approximately 0.5–5.0 mb/sr. Second, each $\mathrm{Pb}^{208}(p, d)$ angular distribution shows pronounced structure and the various values of the neutron orbital angular momentum transfer l_n, $l_n=1$, 3, 5, and 6, are readily distinguished from one another. Third, an inspection of Figs. 2 and 5 ($l_n=1$; $j=\frac{1}{2}$ and $\frac{3}{2}$) and Figs. 3, 6, and 7 ($l_n=3$; $j=\frac{5}{2}$ and $\frac{7}{2}$) shows no evidence for any pronounced j dependence in the $\mathrm{Pb}^{208}(p, d)$ neutron-pickup transitions. Absence of j-dependent effects in the $\mathrm{Pb}^{208}(p, d)$ angular distributions was also observed by Glashausser and Rickey at $E_p=28.0$ MeV[4] and by Yagi *et al.* at $E_p=55.0$ MeV.[7]

Table I presents the total (p, d) cross sections at 20.00 and 22.00 MeV for the transitions studied in this experiment. The (p, d) cross sections at angles less than 20° for both energies and greater than 145° at 20 MeV and greater than 165° at 22 MeV were not measured in this experiment and were estimated using DWBA curves. In all cases the measured angular range accounts for more than 90% of the total cross section. The total (p, d) cross section to the five low-lying neutron-hole states of Pb^{207} is 48.6 mb at $E_p=20.00$ MeV, while at $E_p=22.00$ MeV the total (p, d) cross section to the six low-lying neutron-hole states of Pb^{207} is 50.7 mb. A conservative estimate of the error in these total cross-section measurements is ±10%. The total reaction cross section for protons on lead was measured by Pollock and Schrank[21] at $E_p=16.4$ MeV with the result $\sigma_R=1330\pm180$ mb, and by Gooding[22] at $E_p=34\pm2.5$ MeV with the result $\sigma_R=1775\pm120$ mb. Also, Makino *et al.*[23] have measured a total reaction cross section of 2100 ± 110 mb for 29-MeV protons on gold ($Z=79$). These total reaction cross-section measurements would indicate that the total $\mathrm{Pb}^{208}(p, d)$ cross section for neutron pickup transitions from the $N=83–126$ major shell at $E_p=20.00$ and 22.00 MeV is about 3% of the total proton reaction cross section at these energies.

IV. DWBA ANALYSIS AND SPECTROSCOPIC INFORMATION

In order to obtain spectroscopic factors from the experimental $\mathrm{Pb}^{208}(p, d)$ angular distributions, DWBA analyses were performed using the Oak Ridge computer code JULIE. The proton and deuteron optical-model parameters used in these analyses, as well as the bound-neutron well parameters, are presented in Table II. The proton optical-model parameters were taken from the work of Perey,[24] while the deuteron parameters were obtained from a review by Hodgson. Since the computer code did not include spin-orbit coupling for large l_n transfer, the spin-orbit couplings in both proton and deuteron optical-model potentials were set equal to zero in the DWBA calculations presented in this paper. This procedure was checked for the low l_n transfers ($l_n=1$ and 3) by including a proton spin-orbit strength $V_{so}=7.5$ MeV in a few cases; its effect was found to be small both on the magnitude and on the shape of the DWBA predicted

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[21] R. E. Pollock and G. Schrank, Phys. Rev. **140**, B575 (1965).

[22] T. J. Gooding, Nucl. Phys. **12**, 241 (1959).

[23] M. O. Makino, C. H. Waddell, and R. M. Eisberg, Nucl. Phys. **50**, 145 (1964).

[24] F. G. Perey, Argonne National Laboratory Report No. ANL-6848, Vol. I, p. 114, 1964 (unpublished).

TABLE III. $Pb^{208}(p, d)Pb^{207}$ spectroscopic factors at $E_p = 20.00$ and 22.00 MeV. The spectroscopic factors labeled T were obtained from the ratios of the experimental *total* (p, d) cross sections listed in Table I and the FRNL DWBA *total* cross sections. The spectroscopic factors labeled P were obtained from the ratios of the experimental and FRNL DWBA cross sections when a "best fit" was obtained between the two curves at the peak position of each angular distribution. The fits used are presented in Figs. 2–8.

	20.00 MeV				22.00 MeV			
	$R_c = 0.0$ F		$R_c = 8.5$ F		$R_c = 0.0$ F		$R_c = 8.5$ F	
Level in Pb^{207}	T	P	T	P	T	P	T	P
$1/2^-$ ground state	2.1	2.2	2.2	2.2	2.2	2.2	2.2	2.1
$5/2^-$ 570 keV	4.9	4.3	6.1	6.2	4.9	4.0	5.9	6.1
$3/2^-$ 894 keV	3.6	3.7	4.1	4.0	3.6	4.0	4.0	4.0
$13/2^+$ 1634 keV	13.5	9.4	15.0	14.5	8.7	6.5	12.8	13.4
$7/2^-$ 2334 keV	4.5	3.6	6.1	6.7	3.7	3.4	5.6	6.0
$9/2^-$ 3430 keV	···	···	···	···	2.7	2.2	6.1	6.1

(p, d) angular distributions. The deuteron optical-model parameters used by Muehllehner *et al.*[5] in an analysis of $Pb^{208}(d, p)$ and $Pb^{208}(d, t)$ angular distributions were also tried in several of the present DWBA (p, d) calculations. The fits to the experimental data using their deuteron parameter set were of comparable quality to the fits obtained with the corresponding set presented in Table II.

The DWBA (p, d) calculations were first performed with the zero-range, local (ZRL) JULIE computer program. It was found that for *all* l_n transfers the best fits to the experimental (p, d) angular distributions were obtained with a radial cutoff of 8.5 F. This corresponds to a radial cutoff about 1 F outside the nuclear surface ($1.25\, A^{1/3} = 7.4$ F). For the $l_n = 6$ transition to the $\frac{13}{2}^+$ 1634-keV level, an acceptable fit could be obtained only if a radial cutoff of about 8.5 F was used.

In the final DWBA calculations, the effects of a finite-range neutron-proton interaction and of nonlocal potentials for the incoming proton, outgoing deuteron and bound-neutron wave functions were included by using the local-energy approximation. The range of nonlocality was 0.85 F for the bound-neutron wave function and the incoming proton wave and was 0.54 F for the outgoing deuteron wave. The range of the neutron-proton interaction was taken as 1.25 F. The finite-range nonlocal (FRNL) effects were included by multiplying correction factors into the neutron wavefunction, or form factor, using the computer program FANLFR.[25] As a function of the radial cutoff the shapes of the FRNL DWBA (p, d) angular distributions were found to be quite similar to the zero range local (ZRL) DWBA (p, d) angular distributions. As in the ZRL calculations the best fits to the experimental (p, d) angular distributions for *all* l_n transfers were obtained with a radial cutoff of 8.5 F. At this radial cutoff the main effect of the FRNL calculations was to increase the magnitude of DWBA (p, d) cross sections by about 20% over that obtained with the ZRL calculations. This is to be expected since at 8.5 F the only effects left for the FRNL correction factors are the renormalization due to the constant C from the renormalization of the bound-neutron wave function, and the asymptotic value of the finite-range correction which is a few percent above unity.[26] Figures 2 through 8 present the FRNL DWBA fits to the experimental data. The solid curves are the DWBA (p, d) calculations with a radial cutoff of 8.5 F. The fits to the data are quite good over the entire range of angles. The dotted curves in Figs. 2–8 are the FRNL DWBA fits with no radial cutoff. Particularly for the high l_n values, the fits to the experimental data without inclusion of the cutoff are decidedly inferior to those which include the cutoff.

Table III presents the (p, d) spectroscopic factors obtained from the FRNL DWBA analysis with $R_c =$ 0.0 and 8.5 F. These spectroscopic factors were obtained both from the ratios of the *total* experimental (p, d) cross sections with the *total* DWBA cross sections (labeled T in Table III) and also from the ratios of the experimental and DWBA cross sections when a "best fit" was obtained between the two curves at the peak position of each angular distribution (labeled P in Table III). The fits used to obtain the P spectroscopic factors are presented in Figs. 2–8. Both procedures give almost identical results for $R_c =$ 8.5 F. The most striking result of this analysis is the fact that with $R_c = 8.5$ F we obtain spectroscopic factors for the four lowest-lying levels of Pb^{207} which are almost identically $(2j+1)$—the result which would be expected if these levels were pure single-neutron holes in the Pb^{208} core. The absolute value, but not the shape, of the DWBA angular distribution is dependent upon the value chosen for the radius parameter r_{0n} of the bound-neutron wave function and upon the assumption of nonlocality for the bound-neutron wave function. If local, rather than nonlocal bound-neutron

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[25] J. K. Dickens (unpublished).

[26] G. R. Satchler (private communication).

wave functions are used in the DWBA analysis, the DWBA cross sections for all the transitions decrease by $(21\pm3)\%$, and the spectroscopic factors increase by the same factor. Also, decreasing r_{0n} from 1.25 to 1.20 F reduces the DWBA cross sections by 30–40%, and thus increases the spectroscopic factors by the same amount. However, the relative ratios of the spectroscopic factors are quite insensitive to the value of r_{0n} or the assumption of nonlocality for the bound-neutron wave function. Thus the result that

$$S_{1,1/2}:S_{3,5/2}:S_{1,3/2}:S_{6,13/2}=2:6:4:14$$

to within 10% is rather conclusive evidence that the four lowest-lying levels of Pb^{207} are almost pure single-neutron holes in the Pb^{208} core. This conclusion is in accord with the results of other recent neutron-pickup studies on Pb^{208}.[5–9]

Table III shows that with $R_c=8.5$ F the experimental spectroscopic factors for the $\frac{7}{2}^-$ 2334-keV level and the $\frac{9}{2}^-$ 3430-keV level are, respectively, 20 and 40% less than the value $S_{lj}=2j+1$ which would be expected if these levels were pure single-neutron-hole states. The other recent neutron-pickup studies on Pb^{208} [5–9] give somewhat conflicting results for the spectroscopic strengths to these two levels. The $Pb^{208}(He^3, \alpha)$ work at 28 MeV [6] and 47.5 MeV [9] find that the $\frac{7}{2}^-$ 2334-keV level represents all of the $2f_{7/2}$ strength $S\sim8$, while the $\frac{9}{2}^-$ 3430-keV level represents about 60% of the $1h_{9/2}$ strength, $S\sim6$. The $Pb^{208}(p, d)$ studies at 55 MeV [7] find that both levels represent about 85% of their respective neutron-hole strengths; while the $Pb^{208}(d, t)$ studies at 14.8, 20.1, and 24.8 MeV [5] find that the 2334-keV level represents about 75% of the total $2f_{7/2}$ strength, $S\sim6$, and that the 3430-keV level represents all of the $1h_{9/2}$ strength, $S\sim10$. The $Pb^{208}(d, t)$ studies at 50 MeV [8] find that the 2334-keV level represents 75–85% of the total $2f_{7/2}$ strength, $S=6.0$–6.8, while the 3430-keV level represents 65–90% of the $1h_{9/2}$ strength, $S=6.4$–9.0.

Some fragmentation of the $2f_{7/2}$ and $1h_{9/2}$ neutron-hole strength might be expected, since many $\frac{7}{2}^-$ and $\frac{9}{2}^-$ levels would be expected at excitation energies above about 4 MeV in Pb^{207}, and some mixing should occur with the simple single-neutron-hole configurations. Some $\frac{7}{2}^-$ and $\frac{9}{2}^-$ configurations in Pb^{207} would be built on the collective negative-parity levels of Pb^{208} coupling with the $1i_{13/2}$ neutron hole. As an example, the Pb^{208} 2.614-MeV 3^- level would couple with the $1i_{13/2}$ neutron hole to give a multiplet of levels, with both a $\frac{7}{2}^-$ and $\frac{9}{2}^-$ member, at an excitation energy of about 4.25 MeV. Other $\frac{7}{2}^-$ and $\frac{9}{2}^-$ configurations in Pb^{207} would be based on the collective positive-parity levels of Pb^{208} coupling with the $3p_{1/2}$, $2f_{5/2}$, and $3p_{3/2}$ neutron holes in Pb^{207}. As an example, the collective 4^+ level in Pb^{208} would couple with the $3p_{1/2}$ neutron hole to give a $\frac{7}{2}^-$, $\frac{9}{2}^-$ doublet at an excitation energy of about 4.30 MeV.[27] In their $Pb^{208}(p, d)$ experiment at 55 MeV, Yagi *et al.*[7] assign a probable value of $l_n=3$ for the (p, d) transition to a level at 4.55 MeV in Pb^{207}. In their experiment, the strength of the 4.55-MeV level is approximately $\frac{1}{6}$ that of the $\frac{7}{2}^-$ level at 2334 keV, so that this level would account for most of the missing $2f_{7/2}$ neutron-hole strength. In the $Pb^{208}(He^3, \alpha)$ experiment of Alford and Burke at 28 MeV,[6] many Pb^{207} levels above an excitation energy of 3 MeV are excited with a strength $\sim1/10$ to 1/20 that of the 3430-keV $1h_{9/2}^{-1}$ level. However, no attempt was made to assign l_n values to these transitions.

V. SUMMARY

The (p, d) reaction at $E_p=20.00$ and 22.00 MeV has proved to be a very suitable reaction for studying single-neutron transitions in the lead region. The (p, d) cross sections are large, and the various values of l_n are easily distinguished from one another. With a radial cutoff of about 8.5 F, FRNL DWBA calculations are able to fit the experimental (p, d) angular distributions quite well; and the spectroscopic factors which are extracted with these DWBA calculations are quite reasonable on the basis of the known structure of the low-lying levels of Pb^{207}. The $\frac{1}{2}^-$ ground state, the $\frac{5}{2}^-$ 570-keV level, and $\frac{3}{2}^-$ 894-keV level, and the $\frac{13}{2}^+$ 1634-keV level of Pb^{207} are almost pure neutron-hole configurations in the Pb^{208} core. There is some evidence that the $2f_{7/2}$ neutron-hole strength, and particularly the $1h_{9/2}$ neutron-hole strength, ij somewhat fragmented. No evidence was found for s dependence in the $Pb^{208}(p, d)$ angular distributions at $E_p=20.00$ and 22.00 MeV.

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[27] N. Auerbach and N. Stein, Phys. Letters **28B**, 628 (1969).