PHYSICAL REVIEW C VOLUME 18, NUMBER 6 DECEMBER 1978

^{208}Pb(p,α)^{205}Tl reaction

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(Received 12 June 1978)

The ^{208}Pb(p,α)^{205}Tl reaction has been studied at $E_p = 35$ MeV. Excitation energies and angular distributions have been obtained for many new states in ^{205}Tl. Cluster model distorted-wave Born approximation calculations are shown to produce excellent fits to the angular distributions. Among the new states, four are given $(15/2,17/2)^+$ assignments and one is assigned as $(19/2, 21/2)^+$ on the basis of the distorted-wave Born approximation fits.

[NUCLEAR REACTIONS ^{208}Pb(p, α), E_p = 35 MeV; measured $\sigma(\theta)$; ^{205}Tl deduced levels; enriched target, DWBA analysis; compared with weak coupling model.]

I. INTRODUCTION

The spectra of nuclei near the ^{208}Pb double shell closure provide an unusually attractive testing ground for nuclear structure models. In particular, those nuclei which are three particles (a combination of nucleons and nucleon holes) away from the Z = 82, N = 126 boundary provide a sensitive test for empirical shell model calculations, where the two-body matrix elements are taken from the two particle spectra and the single particle energies are deduced from the levels of ^{207}Tl, ^{207}Pb, ^{209}Bi, and ^{209}Pb. Such a calculation for ^{205}Tl would proceed by taking the n–n interactions from the ^{206}Pb spectrum and the p–n interactions from the ^{206}Tl spectrum, while the proton and neutron hole energies would come from ^{207}Tl and ^{207}Pb. Extensive shell model calculations for three particle nuclei near ^{208}Pb have been presented by a Stockholm group, along with a wealth of data obtained from γ-ray decay experiments.[1-5] They find outstanding agreement especially for the high spin states. Their study has not included ^{205}Tl, which should be one of the simplest shell model calculations, presumably because the large neutron excess makes it a difficult nucleus to reach with fusion-evaporation reactions.

The ^{208}Pb(p,α)^{205}Tl reaction is ideal for locating high spin states in ^{205}Tl. Direct three nucleon transfer reactions on targets near ^{40}Ca have been found to populate high spin states that have simple shell model wave functions.[6] Total angular momentum transfers as large as 19/2 have been reported with good agreement between the experimental angular distributions and the shapes predicted by distorted wave Born approximation (DWBA) calculations. We can therefore expect to locate some of the high spin states in ^{205}Tl by comparing the experimental (p,α) angular distributions with DWBA calculations.

The low-lying states in ^{205}Tl may also be described with a weak, or intermediate, coupling model where an $s_{1/2}$ or $d_{3/2}$ proton hole is coupled to the 0^+, 2^+, and 4^+ states of ^{206}Pb. Once again the (p,α) reaction is an ideal way to locate the members of this coupling scheme because the "triton" pickup excites both the neutrons and protons. By comparison, proton pickup is a poor way to locate all the members of the scheme since nearly all the proton-hole spectroscopic factors will lie in one state, if the coupling is weak. By comparing the (p,α) results presented here to the (t,α) results of Flynn et al.,[7] we should be able to test the weak coupling scheme for the low-lying ^{205}Tl spectrum.

In the sections that follow, we will present the data obtained for the ^{208}Pb(p,α)^{205}Tl reaction at E_p = 35 MeV. The angular distributions will be compared with DWBA calculations to place limits on J^π values and to assign high spin state ℓ values. The resulting picture of ^{205}Tl will be discussed, in terms of simple empirical shell model calculations and weak coupling considerations.

II. EXPERIMENT AND DATA

A beam of 35 MeV protons from the Michigan State University cyclotron was used to bombard a 40 μg/cm target of isotopically enriched ^{208}Pb which was deposited by evaporation onto a 20 μg/cm^2 carbon foil. The lead thickness was determined by comparing the elastic scattering angular distribution to an optical model calculation. The reaction products were analyzed with an Enge split-pole spectrograph and the Markham-Robertson focal plane detector[8] backed by a plastic scintillator. The α particles were uniquely identified by their energy loss in the counter gas and by their time-of-flight relative to the cyclotron radio frequency. In addition to the counter spectra, one run was recorded on a photographic emulsion for the purpose of obtaining more precise excitation energies than could be derived from the counter data. The energy resolution for the plate run was about 15 keV full width at half maximum (FWHM).

Two typical counter spectra with an energy resolution of about 25 keV FWHM and collected for about the same charge are shown in Fig. 1. Two features of the data are evident. The first is the extreme forward peaking of the angular distributions for the low-lying states, as can be seen by comparing the size of the ground state peak in the upper and lower portions of the figure. The second is the emergence of the large peak in the back angle spectra.

III. RESULTS

A. Levels Observed

The excitation energies deduced from the current (p,α) data are given in Table I along with those found in the literature. For the most part, the (p,α) energies were determined from the plate data. The calibration lines were taken from the low-lying states that have been

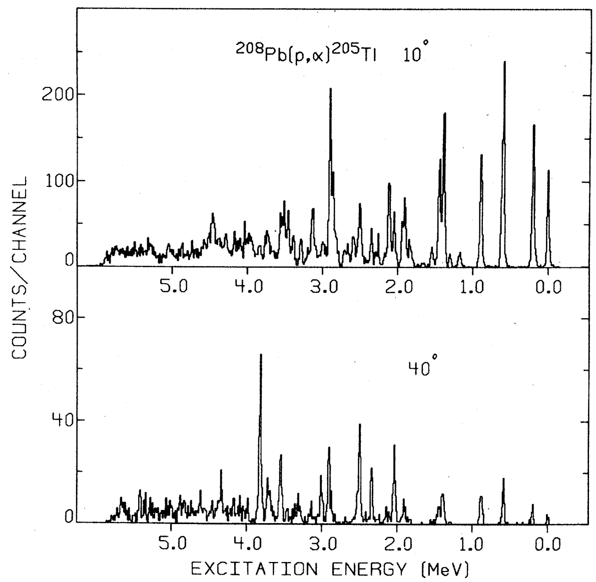

FIG. 1. Two counter spectra are shown for the reaction $^{208}Pb(p,\alpha)^{205}Tl$ at θ_L = 10° and 40°.

observed with a Ge(Li) detector in the (n,n'γ) experiment.[9] Since this procedure would require an extrapolation of the calibration curve to excitation energies 2.5 MeV above the last calibration line, data were taken on the $^{93}Nb(p,\alpha)^{90}Zr$ reaction to obtain calibration lines at higher excitations of ^{205}Tl. The run on ^{93}Nb was recorded on the same plate immediately after the corresponding run on the ^{208}Pb target. The excitation energies for those peaks that were too weak to appear on the plate were deduced from the counter data using the excitation energies determined from the plate data to calibrate the counter spectra. The uncertainties associated with the present work are ±3 keV below 2 MeV of excitation, ±5 keV from 2 to 3 MeV of excitation and ±8 keV above 3 MeV of excitation.

A primitive model of the (p,α) reaction which has often been called the "spectator" model treats the neutrons as being transferred as an inert zero coupled pair. Given this crude approximation, the $^{208}Pb(p,\alpha)^{205}Tl$ spectrum should look like the $^{206}Pb(t,\alpha)^{205}Tl$ spectrum. Although this is clearly not the case, we still might expect those states with large cross sections in the (t,α) reaction to be present in the (p,α) data. An examination of Table I shows that nearly every state observed in the (t,α) reaction[7,10] is found in the (p,α) data, with the exceptions of the 1.138 MeV and probably the 2.420 MeV levels. If the comparison is reversed we see that many states are observed in the (p,α) reaction that are not found in the (t,α) spectra. Most notable of these is the .925 MeV, $7/2^+$

TABLE I. Excitation energies of ^{205}Tl.

Excitation energy (MeV)									
(p,α)[a]	(p,α)[b]	(t,α)[c]	(t,α)[d]	(p,p')[b]	(d,d')[e]	(n,n'γ)[f]	(γ,γ')[g]	(γ,γ')[h]	J^π
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	$1/2^+$
0.204	0.20	0.205	0.20	0.207	0.203	0.204	0.211	0.206	$3/2^+$
0.620	0.62	0.614	0.62	0.622	0.616	0.620	0.623	0.615	$5/2^+$
0.925	0.92			0.924	0.920	0.925			$7/2^+$
		1.138	1.14	1.14	1.136	1.141	1.141	1.146	$3/2^+$
					1.174	1.181			
1.224		1.222	1.21			1.220		1.226	$1/2^+$
1.334		1.341	1.34	1.340	1.336	1.342	1.337	1.343	$3/2^+$
1.432	1.43	1.436	1.43	1.431	1.426	1.431	1.433	1.436	$(9/2^+)$
						1.435			$1/2^+$
								1.455	
1.484	1.48	1.491	1.48	1.48	1.479				$11/2^-$
						1.555	1.557	1.558	
1.568	1.58		1.58		1.579		1.575	1.576	$3/2^\pm,5/2^\pm,7/2^\pm$ [i]
					1.637				
1.685					1.668	1.712			
1.852	1.86	1.859	1.86		1.858				$5/2^+$ [i]
							1.874		
1.915	1.92								$11/2^-$ [i]
1.950		1.953	1.96				1.965	1.970	$5/2^+$ [i]
1.995							2.001	2.008	
2.054	2.04	2.044	2.04						$13/2^\pm,15/2^-$ [i]
							2.090	2.098	

TABLE I. (*Continued*)

Excitation energy (MeV)									
(p,α)[a]	(p,α)[b]	(t,α)[c]	(t,α)[d]	(p,p')[b]	(d,d')[e]	(n,n'γ)[f]	(γ,γ')[g]	(γ,γ')[h]	J^π
2.124	2.12	2.112	2.12						$5/2^+$ [i]
2.182	2.18						2.163	2.166	$(11/2^\pm,13/2)^\pm$ [i]
							2.210		
							2.222	2.224	
2.286	2.30								$(11/2^-)$ [i]
		2.304					2.300	2.306	
2.318							2.315	2.319	
2.389	2.40								$15/2^+,17/2^+$
		2.420	2.43						
2.470		2.482	2.49	2.487	2.482				
2.537									
2.560	2.55						2.558	2.559	$(15/2^+,17/2^+)$
2.583		2.588	2.60						
2.632				2.625	2.623				$5/2^-,7/2^-$
							2.669		
2.702							2.705		
		2.714		2.716	2.716		2.723	2.722	
2.741			2.74				2.751	2.749	$5/2^-,7/2^-$
2.839									
2.881							2.896	2.893	$5/2^\pm,7/2^\pm$ [i]
2.917	2.90				2.933				$(11/2^\pm,13/2^\pm$ [i]
				2.97	2.974				
2.996									
							3.021	3.018	
3.072									
3.111									
3.133									$7/2^\pm,9/2^\pm$ [i]
3.159									
3.182				3.18	3.173		3.176	3.180	
				3.213					
3.273				3.256	3.259			3.259	
							3.289	3.288	$7/2^+,7/2^-$
								3.335	
3.363									$7/2^\pm,9/2^\pm$
3.427				3.414					$7/2^\pm,9/2^\pm$ [i]
3.511	3.48								
3.531				3.54					$15/2^+,17/2^+$
3.636									$9/2^+$
3.692	3.66								$15/2^+,17/2^+$ [i]

TABLE I. (*Continued*)

Excitation energy (MeV)									
$(p,\alpha)^a$	$(p,\alpha)^b$	$(t,\alpha)^c$	$(t,\alpha)^d$	$(p,p')^b$	$(d,d')^e$	$(n,n'\gamma)^f$	$(\gamma,\gamma')^g$	$(\gamma,\gamma')^h$	J^π
3.813									$19/2^+,21/2^+$ [i]
3.96									
3.99									

a) Present experiment
b) Ref. 11
c) Ref. 7
d) Ref. 10
e) Ref. 17
f) Ref. 9
g) Ref. 18
h) Ref. 19
i) Spin assignments made in the present experiment

state which is one of the largest peaks in the (p,α) data. This behavior is clear evidence for the importance of the transferred neutrons in the (p,α) reaction.

A comparison with the (p,p') column[11] also sheds some light on the role of the neutrons in many ^{205}Tl states. In particular two $\ell = 4$ transitions located at .925 MeV and 1.43 MeV are strongly populated by the (p,α) reaction. In addition, a large number of $\ell = 3$ (p,p') transitions are observed in the (p,α) spectrum. A summary of this comparison is found in Table II.

B. DWBA Calculations and J^π Assignments

Previously, spin and parity assignments have been made for two classes of states in ^{205}Tl. Those states which have large amplitudes for the coupling of an $s_{1/2}$ proton hole to the 2^+, 4^+, and 3^- states of ^{206}Pb have been located by inelastic scattering experiments.[11,12] The

TABLE II. Comparison of (p,p') and (p,α) Reactions to States in ^{205}Tl.

Excitation (from (p,p'))	L-(p,p')	$J^\pi(p,\alpha)$
0.00		
0.207	2	$3/2^+$
0.622	2	$5/2^+$
0.924	4	$7/2^+$
1.340	2	weak but consistent with $\ell=2$
1.43	4	$7/2^+$
1.48	5	$11/2^-$
2.487	3	weak
2.625	3	$5/2^-,7/2^-,7/2^+$
2.716	3	$5/2^-,7/2^-,7/2^+$
2.97	3	doublet
3.18	(3)	weak but consistent with $\ell=3$
3.256	3	(doublet)
3.414	≥ 5	$7/2^\pm,9/2$

proton hole states have been assigned from analyzing power measurements using the $^{206}Pb(\vec{t},\alpha)^{205}Tl$ reaction as shown in Table I. Although there are over 50 levels tabulated in Table I, there are only 9 which were listed as having definite spin-parity assignments from previous work, while many of the states observed in the proton pickup experiments are listed as either $5/2^+$ or $11/2^-$. It is especially important to clarify the spin assignments of the proton-hole states so that the centroids of the $d_{5/2}$ and $h_{11/2}$ hole strengths can be determined. At present only 5% of the $d_{5/2}$ strength and about half of the $h_{11/2}$ strength has been definitely assigned.

The angular distributions obtained from the (p,α) data can be used to make J^π assignments when they are compared to the shapes of DWBA calculations using mass three cluster form factors, if the predicted angular distributions have shapes that can be distinguished from one another. Otherwise limits on J^π values can be made if a number of j transfers have similar angular distributions.

The DWBA calculations were performed with the code DWUCK.[13] The optical parameters (see Table III) were the same as those used in the $^{206,208}Pb(\alpha,p)^{209,211}Bi$ work of Flynn et al.[14] The initial bound state geometrical parameters were chosen to be $r_o \simeq 1.22$ fm and $a \simeq .7$ fm. The parameters were varied slightly to test the stability of the calculations. The DWBA shapes were found to be insensitive to these small fluctuations and, in the end, the bound state parameters were chosen to be $r_o = 1.25$ fm and $a = .60$ fm, since these parameters seemed to produce slightly better fits to the experimental angular distributions of the known low-lying levels. The fits obtained with the method just described are shown in Figs. 2, 3, and 4. The excellent agreement between the DWBA calculations and the data lead us to believe that we can rely on DWBA calculations to determine J^π limits for previously unidentified states.

Before proceeding to compare the data to the DWBA curves, we wish to discuss the limits of the information that can be obtained in this manner. A very strong j dependence, resulting from the spin-orbit coupling in the proton optical potential, has been observed with the (p,α) reaction on lighter nuclei. However, in the DWBA calculations for $\ell = 2$ through 9 which are presented in Fig. 5, it is seen that j dependence is too small an effect to be observable for most ℓ transfers. The only possible exceptions are the $\ell = 2$, 4, and 5 cases. For the $3/2^+$, $5/2^+$ pair the maxima and minima come at very different angles. Unfortunately, these oscillations are located at large enough angles that they can only be observed for the very strongest peaks, which correspond to levels whose J^π is already known. The $7/2^+$, $9/2^+$ pair are distinguishable

TABLE III. Optical Model Parameters.

	V	r	a	W	r_i	a_i	W_D[a]	V_{so}[a]	r_{so}	a_{so}
p	- 52.7	1.22	.72	- 2.8	1.32	.65	32.4	-25.0	1.06	.68
α	-187.0	1.35	.57	-25.0	1.35	.52				
τ		1.25	.60							

[a]Includes factor of 4 used in DWUCK.[13]

by their slopes, the $9/2^+$ angular distribution being significantly flatter than the $7/2^+$ calculation. The major difference between the $\ell = 5$ transfers is that the $9/2^-$ angular distribution rises as one approaches zero scattering angle while the $11/2^-$ curve rolls over. Thus we will usually not be able to definitely assign a J value for a final state unless other experimental information is available.

Further limitations on our ability to make J^π assignments become evident if we compare calculations for the same j value but with different ℓ transfers, for example $j = 7/2^+$ and $7/2^-$. Such a comparison is given in Fig. 6. In most cases the results are indistinguishable for $j \leq 13/2$, the exception being the $j = 11/2$ case. Thus we will often not be able to distinguish between $5/2^+$, $5/2^-$, $7/2^+$, $7/2^-$ for a weak peak with poor statistics. The high spin

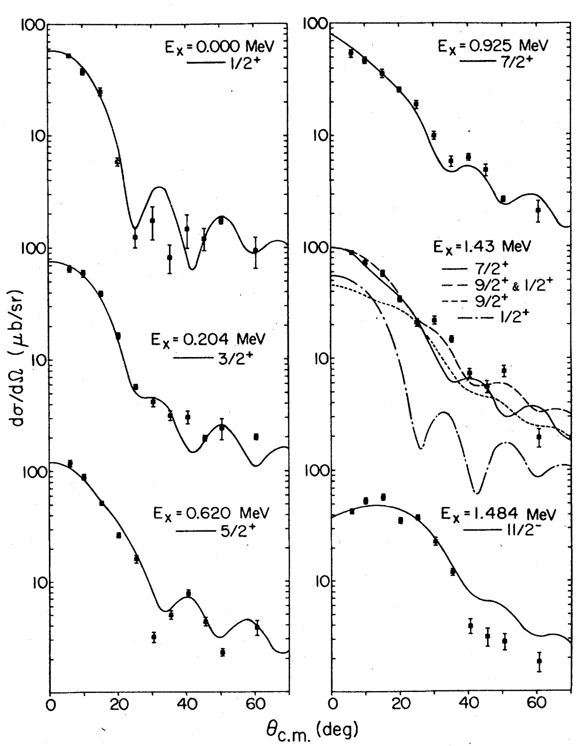

FIG. 2. Angular distributions for low lying states in ^{205}Tl. Fits are cluster model DWBA calculations performed for the indicated J^π values using the optical model parameters in Table III.

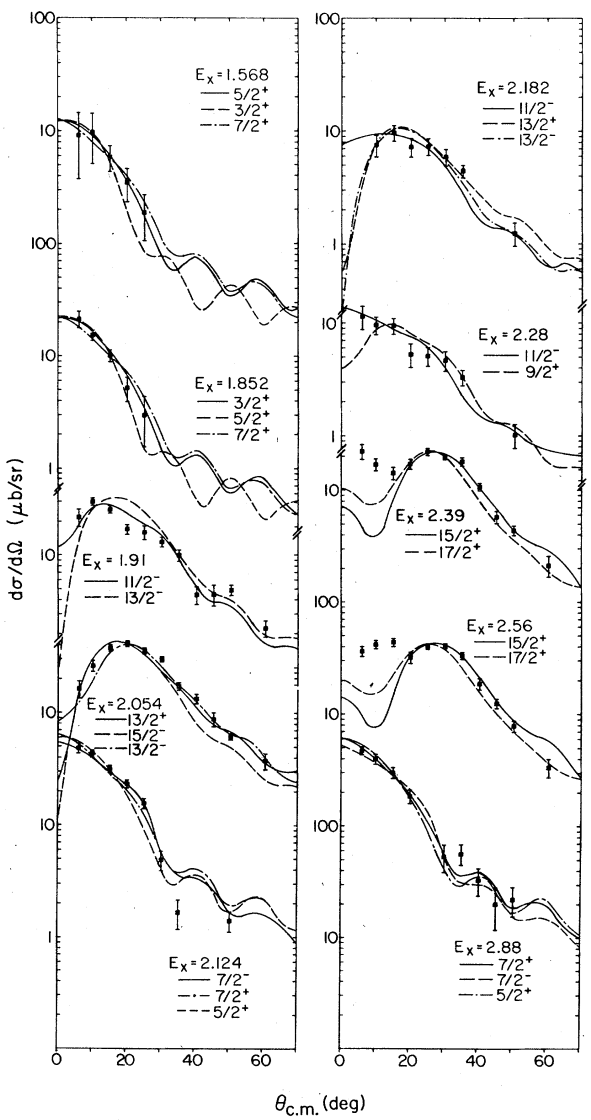

FIG. 3. Angular distributions for states in ^{205}Tl. Fits are cluster model DWBA calculations performed for the indicated J^π values using the optical model parameters in Table III.

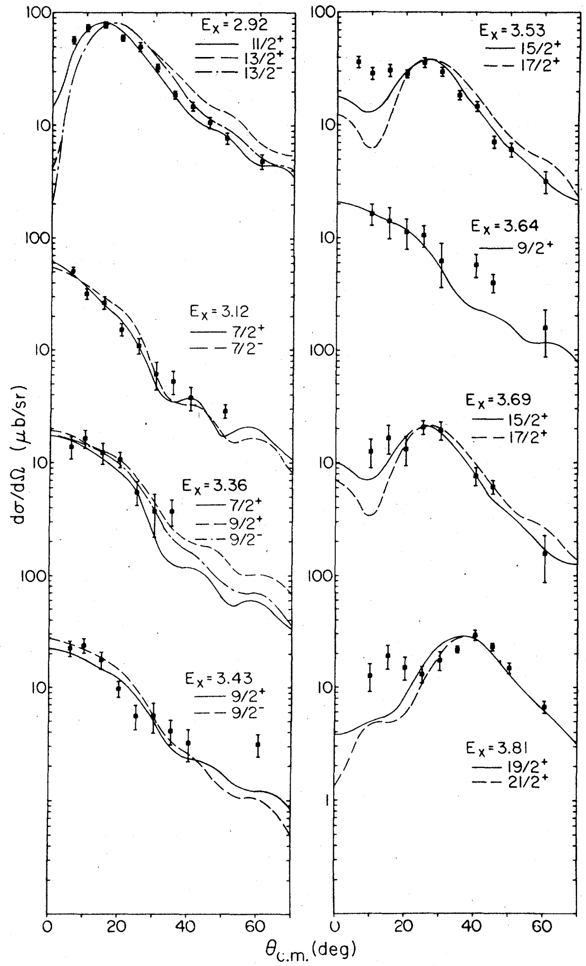

FIG. 4. Angular distributions for highly excited states in ^{205}Tl. Fits are cluster model DWBA calculations performed for the indicated J^π values using the optical model parameters in Table III.

assignments ($j \geq 15/2$) will be reasonably safe since the position of the broad maximum in these angular distributions moves about 5° each time the ℓ value increases by one.

The angular distributions and DWBA calculations for many of the previously unknown states are given in Figs. 3 and 4.

Four of the five levels that were given questionable J^π assignments in the (t,α) work (Ref. 7) are found in Figs. 3 and 4. We can see that the only assignments that can be made that are consistent with both experiments are 1.852 MeV; $5/2^+$, 1.915 MeV; $11/2^-$, and 2.124 MeV; $5/2^+$. A level observed in the (t,α) study at 1.95 MeV was only seen at forward angles in the present experiment and no angular distribution is therefore plotted. However, the angular distribution falls steeply with angle, which is characteristic of a state with low spin, so that combined with the results from the (t,α) experiment an assignment of $J^\pi = 5/2^+$ is indicated. The remaining peak in the (t,α) data at 2.588 MeV is part of an unresolved triplet centered at 2.56 MeV in our data. Using this information the new spectroscopic strength obtained from Ref. 7 is about 1.7 for the $d_{5/2}$ hole.

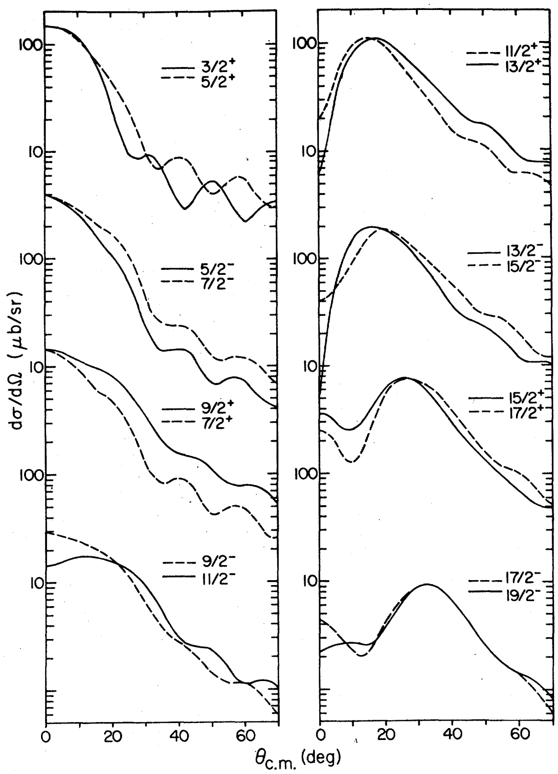

FIG. 5. Cluster model DWBA calculations for ℓ-transfers of 2 through 9. Each pair of curves plotted on the same scale represents the pair of j-transfers, $J_{tr} = \ell_{tr} \pm 1/2$, associated with a given ℓ-transfer.

Many states observed in the ^{205}Tl(p,p') reaction are present in the (p,α) data. This correspondence was previously demonstrated in Ref. 10. In our work we have obtained the angular distributions for many of these levels. A comparison of the ℓ transfers deduced from the (p,p') data and the (p,α) best DWBA fits is given in Table II. The agreement is very good with the exception of the 3.414 MeV state where the (p,α) data suggests that this state should be observed as an $\ell = 3$ or 4 transition in inelastic scattering.

A peak at 1.43 MeV has been observed in both the inelastic scattering[11] and proton pickup experiments.[7,10] Flynn et al.[7] have assigned $J^\pi = 1/2^+$ for this state on the basis of (t,α) analyzing power measurements while a strong $\ell = 4$ transition is observed in the (p,p') experiment.[11] The resolution of this discrepancy may be found in the (n,n'γ) decay scheme which includes two levels at 1.431 MeV and 1.435 MeV.[9] The (p,α) angular distribution for this peak (see Fig. 2) cannot be fit by either $\ell = 4$ DWBA curve. The only way to explain the small oscillations in the angular distribution is to sum the $1/2^+$ and $9/2^+$ DWBA calculations. Thus our data indicates that there are indeed two states at about 1.43 MeV with J^π's of $1/2^+$ and $9/2^+$. One of these states contains a portion of the $s_{1/2}$ hole strength while the other is probably the $9/2^+$ state that belongs to the $(\pi s_{1/2}^{-1} \times {}^{206}\mathrm{Pb}(4^+))$ configuration.

The most interesting of the new states are the high spin states, such as the one that stands out in the back angle spectrum shown in Fig. 1. Four angular distributions are best fit with $\ell = 8$ calculations and another appears to be

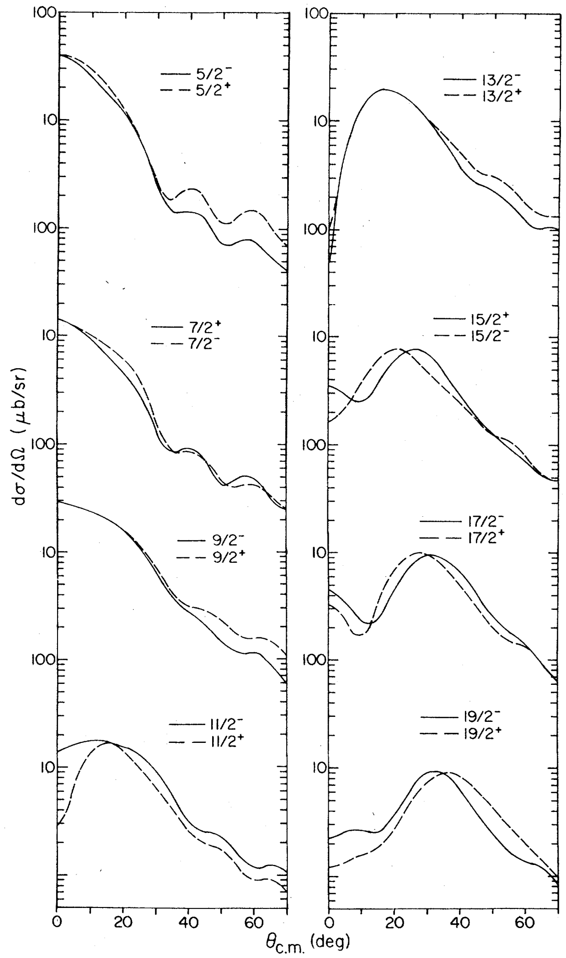

FIG. 6. Cluster model DWBA calculations for j–transfers from 5/2 to 19/2. Each pair of curves plotted on the same scale represents the pair of ℓ–transfers, $\ell_{tr} = J_{tr} \pm 1/2$, which can lead to a given j–transfer.

a state with $\ell = 10$. The $\ell = 8$ transitions are located at 2.39, 2.56, 3.53, and 3.69 MeV. The state at 2.56 MeV is part of an unresolved triplet. A state at 3.51 MeV, not resolved from the 3.53 state, appears to be a state of low spin that causes the forward angle points of the 3.53 state angular distribution to be too high. The $\ell = 10$ transition is observed to a state at 3.81 MeV excitation. The broad maximum in the angular distribution is reproduced very well by the DWBA calculation, but the forward angle data points are above the calculation. Although there are a number of possible explanations for this forward angle failure, the difficulty of extracting an accurate peak area from the forward angle spectra for this state is probably the major problem. In the small angle spectra we must extract the area of a small peak riding on a background of dense low spin states. It is therefore likely that areas obtained from these data will be too large, since they will contain area which is part of the low spin state background. As the angle increases the low spin state cross-sections drop rapidly, while the high spin state cross-section increases, so that the areas near the high spin state maximum are accurate.

IV. DISCUSSION

At first glance the low-lying spectrum of ^{205}Tl looks very much like a weak coupling scheme for an $s_{1/2}$ proton hole and the strong collective states of ^{206}Pb. The strongest states are the $1/2^+$ ground state, the $3/2^+$, 204 keV, and $5/2^+$, 620 keV states, which might be associated with the $\pi s_{1/2}^{-1} \times {}^{206}\mathrm{Pb}(2_1^+)$ configuration and the $7/2^+$, 925 keV and $9/2^+$, 1430 keV states which could be the $\pi s_{1/2}^{-1} \times {}^{206}\mathrm{Pb}(4_1^+)$ states. Further, evidence in favor of this scheme is the strong population of the $3/2^+$, $5/2^+$, $7/2^+$, and $9/2^+$ states in inelastic scattering experiments.

A closer look, however, reveals two significant deviations from this simple model. The first problem is that the excitation energies in ^{205}Tl are much too small. Using the known excitation energies in ^{206}Pb, the centroid of the $3/2^+$, $5/2^+$ pair in ^{205}Tl is predicted to be located at an excitation of 800 keV while the centroid in ^{205}Tl is about 400 keV. The centroid of the $7/2^+$, $9/2^+$ pair is at about 1.12 MeV while the 4^+ in ^{206}Pb has an excitation energy of 1.68 MeV. We see that the deviations are of the order of –400 to –500 keV.

The second problem is the spectroscopic factors obtained with proton pickup experiments. These should be 2.0 for the ground state and zero for all the excited states belonging to the weak coupling scheme. Flynn et al.[7] have found some $s_{1/2}$ strength in two higher levels, a large spectroscopic factor for the $\pi d_{3/2}^{-1}$ component of the 204 keV state, and a small, but non-zero, spectroscopic factor for the $d_{5/2}$ proton hole component of the $5/2^+$ state.

We must conclude that these states are significantly mixed and hence the weak coupling model must be abandoned. It is still tempting to try to use a similar phenomenological approach where the basis states are taken to be $\pi s_{1/2}^{-1} \times {}^{206}$Pb, $\pi d_{3/2}^{-1} \times {}^{206}$Pb, and $\pi d_{5/2}^{-1} \times {}^{206}$Pb and diagonalize the appropriate matrices, assuming that the mixing is caused by a particle-phonon interaction. One immediate consequence of this scheme is that more states are included. Table IV gives the number of states of a given J^π in this basis. Including the data of all the experiments, we find that all three low-lying $1/2^+$ states have been observed, three of the five predicted $3/2^+$ states are known, and four of the six $5/2^+$ states have been found. In addition, one $7/2^+$ and one $9/2^+$ state have been observed. The agreement may be even better if the 1.685 MeV state should prove to be a $3/2^+$ or $5/2^+$ state. Preliminary calculations in this basis have been performed for the $1/2^+$ states of ^{205}Tl by E.R. Flynn and R.E. Anderson.[15] They obtain very good agreement

TABLE IV. Coupling Model Predictions.

J^π	Number of States Predicted	Number of States Observed (plus possible)
$1/2^+$	3	3
$3/2^+$	5	3 (1)
$5/2^+$	6	4 (2)
$7/2^+$	5	1 (6)
$9/2^+$	4	1 (3)
$11/2^+$	2	(1)
$13/2^+$	1	(3)

with both the experimental excitation energies and proton pickup spectroscopic factors. They are currently extending these calculations to include all the possible states. A comparison of the relative strength of states excited in the (t,α), (p,p'), and (p,α) reactions implies that the .620 MeV, $5/2^+$, .925 MeV, $7/2^+$, and 1.43 MeV, $9/2^+$ states must have large $\pi s_{1/2}^{-1} \times {}^{206}Pb(2^+$ and $4^+)$ components.

If the high spin states of ^{205}Tl could be described as a proton hole in the $s_{1/2}$ orbit coupled to the high spin spectrum of ^{206}Pb we would expect a pair of $\ell = 12$ transitions at about 4.03 MeV and a pair of $\ell = 10$ transitions at about 3.96 MeV. Although an $\ell = 12$ transfer has not been observed, we have located a state with $\ell = 10$ at 3.81 MeV, i.e., at approximately the excitation energy expected. We cannot say where the $\ell = 8$ levels should lie because there have not been any 8^+ assignments made in ^{206}Pb. An estimate of these energies can be made by using the values obtained by Kuo and Herling[16] who performed shell model calculations for the two-particle nuclei near Pb using residual interaction matrix elements deduced from the Hamada-Johnston potential. They predict that the lowest 8^+ state should be located about 50 keV below the 10^+ state, no matter which core polarization approximation is chosen. Thus there should be a pair of $\ell = 8$ transitions near 3.9 MeV. Two $\ell = 8$ transfers are observed about 300 keV lower than this value. Thus this simple model, which predicts a number of $\ell = 8$ to 12 transfers between ≃ 3.7 MeV and 4.3 MeV excitation, is generally supported by the data. Apparently there is some mixing that is unaccounted for, as evidenced by the low excitation energies of the $\ell = 8$ transitions. The $\ell = 12$ transitions that have not been observed may be missing either because they are not resolved or are only weakly excited at this bombarding energy.

The simple model discussed above is nearly equivalent to the empirical shell model concept. Since the ^{206}Pb 8^+, 10^+, and 12^+ states are pure $\nu(i_{13/2})^{-2}$ configurations, the weak coupling assumption amounts to performing the shell model calculation for pure $\pi s_{1/2}^{-1}\, \nu(i_{13/2})^2$ configurations, neglecting the p–n interactions and taking the proton hole energy to be the difference in the ground state energies of ^{206}Pb and ^{205}Tl. A proper calculation would include the p–n interactions, and take the $\pi s_{1/2}^{-1}$ energy to be the ground state energy of ^{207}Tl relative to ^{208}Pb. In this instance an empirical calculation is not likely to work since the $(\pi s_{1/2}^{-1}\, \nu i_{13/2}^{-1})$ 6^+ and 7^+ configurations are split among a number of unidentified levels in ^{206}Tl. Kuo and Herling[16] predict that one 6^+ and one 7^+ may have as much as 70% $(\pi s_{1/2}^{-1}\, \nu i_{13/2}^{-1})$. Given the lack of data for ^{206}Tl, it seems unlikely that a least squares determination of the p–n residual matrix elements can be made. This leaves only the theoretical approach which can be carried out using the matrix elements determined by Kuo and Herling.

The (p,α) data for the $\ell = 8$ transitions clearly show that the basis states used in the above discussion are far too restricted. Given either of the approaches discussed above, there can only be two final states with $\ell = 8$ and they will be near 4 MeV of excitation. The data show four $\ell = 8$ transfers, two of which occur very low in excitation energy. If all the active orbitals are considered, there are a great number of states with $\ell = 8$. A large scale shell model investigation of ^{205}Tl is required before further statements can be made about these low-lying $\ell = 8$ transitions.

V. SUMMARY

Data for the $^{208}Pb(p,\alpha)^{205}Tl$ reaction at $E_p = 35$ MeV have been presented. DWBA calculations have been shown to fit the shapes of the experimental angular distributions. Using these fits we have been able to clarify some previously ambiguous J^π assignments and make some new assignments. We have also been able to identify five high spin states, four of which have $\ell = 8$ and one of which has $\ell = 10$. The excitation energies of the ^{205}Tl spectrum have been discussed in terms of a weak coupling model and a simple shell model. Both models qualitatively reproduce many features of the data, but there are some failures, such as the observation of more low-lying $\ell = 8$ transitions than predicted. We conclude that large scale quantitative shell model calculations are required before these data can be fully understood.

VI. ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No. Phy 78–01684 and the U.S. Department of Energy.

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