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^{194,196,198}Pt(p,t) reactions at 35 MeV

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The ^{194,196,198}Pt(p,t) reactions have been studied at a proton energy of 35 MeV using nuclear emulsion plates and a high-resolution position-sensitive proportional counter. Fifty states were observed in ^{194}Pt and ^{196}Pt and sixty-four in ^{192}Pt, many for the first time. Angular distributions were measured for many of these levels from 7° to 60° and the results were compared with zero-range distorted wave Born approximation calculations. Several new J^{π} assignments were made using distorted wave Born approximation and empirical shapes of transitions to well-known levels in Pt and Pb. No new levels, in particular, no new 0^+ levels, were seen below 1.5 MeV excitation. A new 0^+ level at 1.628 MeV was found in ^{192}Pt, and new levels tentatively assigned to be 4^+ were seen in all three final nuclei near 1.9 MeV with 15% of the ground state strength at 7° in the ^{196,198}Pt(p,t) reactions. Enhancement factors were calculated for simple two-neutron pickup configurations. A comparison is made between experimental (p,t) strengths and those calculated in the O(6) limit of the interacting boson approximation model for $L = 0$, 2 transitions.

[NUCLEAR REACTIONS ^{194}Pt(p,t), ^{196}Pt(p,t), and ^{198}Pt(p,t), E_p=35 MeV; measured $\sigma(E_t, \theta)$; deduced energies, J^{π}, and strengths; DWBA calculations, comparison with experiment; enhancement factors. Enriched targets, 7 keV resolution (plates); interacting boson approximation model.]

I. INTRODUCTION

The Pt isotopes lie in a transitional region between well-deformed rare-earth nuclei and the spherical nuclei near doubly magic ^{208}Pb. Since the Pt nuclei are not well described by either of the simple Bohr-Mottelson collective-model limits, the symmetric rotor or the harmonic vibrator, they provide a valuable testing ground for current models of collective nuclear motion.

It has been known for several years that a transition from prolate to oblate shapes occurs among the heavier Os and the lighter Pt nuclides.[1,2] For the heavier Pt nuclides ($^{192-198}$Pt) the quadrupole deformation parameter, β, has a value[3,4] of approximately 0.15, or about one half the value determined for the well-deformed rare earth nuclei and consequently these Pt isotopes exhibit few rotational features. Some of the features of the lowest energy levels of these nuclides can be interpreted in terms of a harmonic vibrator. However, a notable problem with this picture is the lack of a candidate for the 0^+ member of the 2-phonon triplet. Moreover, the platinum isotopes are farther away from closed shells than those nuclei for which vibrational models have been applied most successfully.

Because of the difficulty with harmonic vibrational models, various other collective models have been tried, such as the γ-unstable[5] or the asymmetric rotor[6] models. These models seem appropriate here because of the lack of low-lying excited 0^+ levels. The asymmetric rotor model in particular has recently enjoyed some success for odd-A nuclides in this region,[7-11] but neither this nor any of the standard limits of the collective model seem capable of describing the structure of the even-even nuclides. As a result, several attempts[12-14] have been made to treat this region by solving the full collective Hamiltonian, beginning with the pioneering work of Kumar and Baranger in which the parameters of the Hamiltonian were determined by using the pairing-plus-quadrupole model. These more complete treatments of the collective model have had considerably more success in accounting for the low-lying properties of the nuclides in the platinum-osmium region using a potential energy surface which implies a relatively γ-soft nucleus. Nevertheless, mathematical solutions for these models present formidable difficulties.

A simpler description of the nuclides in the platinum-osmium region has recently emerged from the interacting-boson approximation (IBA) model of Iachello and Arima.[15] In this model the nucleus is treated in terms of a set of bosons, one for each pair of neutrons or protons outside a closed shell. The bosons can be in either an L = 0 or L = 2 state and are allowed to interact. The most general Hamiltonian describing such a system possesses an SU(6) group symmetry. Particularly simple descriptions are possible when the Hamiltonian is symmetric with respect to subgroups of SU(6). The SU(5) subgroup, for example, corresponds approximately to the vibrational limit of the collective model, and SU(3) to the rotational limit. Another important subgroup of SU(6) is O(6), and Cizewski et al.[16] have shown that this limit accounts for most of the energy and decay properties of all positive parity levels below the pairing gap for ^{196}Pt. In fact, the structure of ^{196}Pt and most of the lighter mass even-even Os and Pt nuclides can be understood[16] by adding a small but gradually increasing symmetry-breaking term to the Hamiltonian as one goes farther away from the O(6) limit.

The majority of the experimental information on the heavier Pt isotopes has come from γ-ray studies following the ε, $\beta^{\pm}$ decay of Au and Ir isotopes.[17-22] There have also been several publications on γ-decay following neutron capture.[23-26] More recently the nature of the high-spin levels of the platinum nuclides up to spin 20^+ has been studied by (α,xnγ) in-beam γ-ray spectroscopy.[8,27-29]

There have been numerous inelastic scattering experiments[1,3,4,30-33] performed on the Pt nuclides, primarily by Coulomb excitation of the first 2^+ states. The bulk of the transfer reaction data is from one-neutron transfer studies of the odd platinum nuclei,[34-38] with the exception of an investigation of the ^{196}Pt(p,t) reaction in a search for strong L = 0 transitions in heavier nuclei.[39]

The present high-resolution (p,t) reaction study utilized a 35 MeV proton beam and was undertaken as a search for low-lying 0^+ levels in the even-even platinum nuclides, ^{192,194,196}Pt. The (p,t) reaction was chosen for the distinctive, diffraction-like shapes of the L = 0 transfers, which populate $J^{\pi} = 0^+$ levels in the residual nucleus when using even-even targets. These low-lying 0^+ states play an important role in distinguishing the models mentioned above, although additional information from transition rates and multipole moments is necessary.

In addition to the existence and energy of 0^+ states, the strength of the transition populating such states in a (p,t) reaction can also provide information on the shape of a nucleus, as was seen in the Sm isotopes.[40] If the ground states of the Os or Pt nuclei are relatively rigid in the γ direction and γ varies rapidly, strong $L = 0$ transitions populating excited 0^+ levels which have shapes similar to the target ground state might be observed. However, Sharma and Hintz[41] observe no strong transitions to excited 0^+ states in the Os(p.t) reactions, possibly because the γ shape parameter appears to be changing slowly.

A number of transitions were seen in the ^{194,196,198}Pt(p,t) reactions with $L \geq 2$ that were strong enough to yield complete angular distributions. Most of these were reproduced reasonably well by the calculations of the DWBA code DWUCK.[42] This along with empirical shapes has allowed several spin assignments to be confirmed and several tentative new assignments to be made. Such a procedure has not previously been carried out in this mass region due to the assumed influence of second-order effects on the shape of the angular distribution.

II. EXPERIMENTAL METHOD

The experiments were performed with the 35-MeV proton beam from the Michigan State University Cyclotron. Outgoing tritons were detected in the focal plane of an Enge split-pole spectrograph with a high-resolution, slanted cathode, position-sensitive proportional counter.[43] The tritons were identified using the energy loss in the counter, but to achieve low background spectra redundant particle identification was made by backing the counter with a plastic scintillator for time-of-flight information. Angular distributions were obtained from 7° to 60° in the laboratory. By using the dispersion matching technique[44] an energy resolution of about 15 keV full width at half-maximum (FWHM) was achieved (see Fig. 1). A 2° x 2° aperture was used in these experiments with $d\Omega = 1.2 \times 10^{-3}$sr. The targets used were rolled foils, approximately 650 μg/cm^2 thick and enriched to $\simeq 97\%$ for each isotope of platinum studied.

A separate set of high-resolution measurements was made using Kodak NTB-25 photographic emulsions. Exposures at three angles per nuclide were taken using thin, ion-sputtered targets of about 150 μg/cm^2. The platinum was sputtered onto a 20 μg/cm^2 carbon foil supported by one layer of formvar. The backing did not present a contamination problem because of the large negative Q value for (p,t) reactions on carbon and oxygen. The three angles, 7°, 22°, 33° which are at the first maximum, first minimum, and second maximum in the $L = 0$ angular distributions, were chosen for the identification of 0^+ levels. The resolution was optimized by using the dispersion matching technique. Fig. 2 shows a (p,t) plate spectrum with 7 keV FWHM resolution. The experimental data were normalized to the integrated beam current measured in a Faraday cup and also compared to the elastically scattered protons monitored at 90°. Disagreement between charge and monitor counter normalization was generally less than 5%. Absolute cross sections for all targets were obtained in a separate set of experiments by normalizing the angular distribution of elastically scattered protons to optical model predictions between 25° and 50°. The cross-section uncertainties are typically 15–20%. The optical model calculations were performed using the Becchetti-Greenlees[45] proton parameters given in Table I.

Peak areas and centroids were determined by the computer code AUTOFIT.[46] Excitation energies for each of 50 or 60 states observed in the three final nuclei were determined using a quadratic momentum vs. distance curve, fit to the energies of 6 or 7 previously well known states. The values of the excitation energies, resulting primarily from analysis of the 7° plate data, are listed in Tables II, III, and IV where the states used as calibration lines are indicated in each case. The errors in excitation energies are approximately 1 keV below 1.5 MeV and 0.1–0.2% above 1.5 MeV.

III. DWBA ANALYSIS

The experimental angular distributions were compared with standard, zero-range distorted waves calculations using the code DWUCK.[42] Table I is a list of all optical

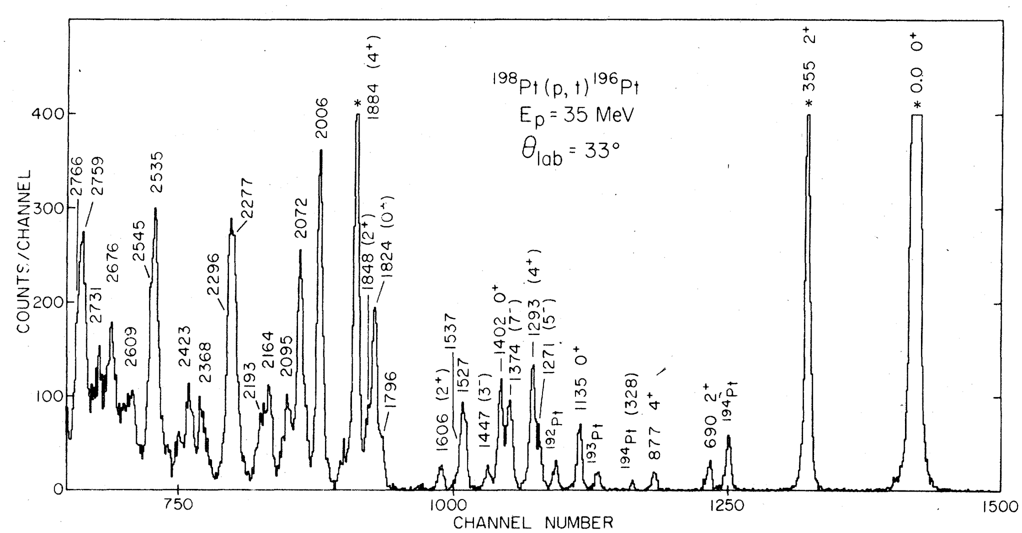

FIG. 1. Triton spectrum at 33° from the ^{198}Pt(p,t)^{196}Pt reaction. Data obtained with a position sensitive delay-line counter (FWHM $\simeq$15 keV) in the focal plane of the MSU Enge split-pole spectrometer. "*" above peak indicates peak height has been cut off at maximum value shown on vertical scale.

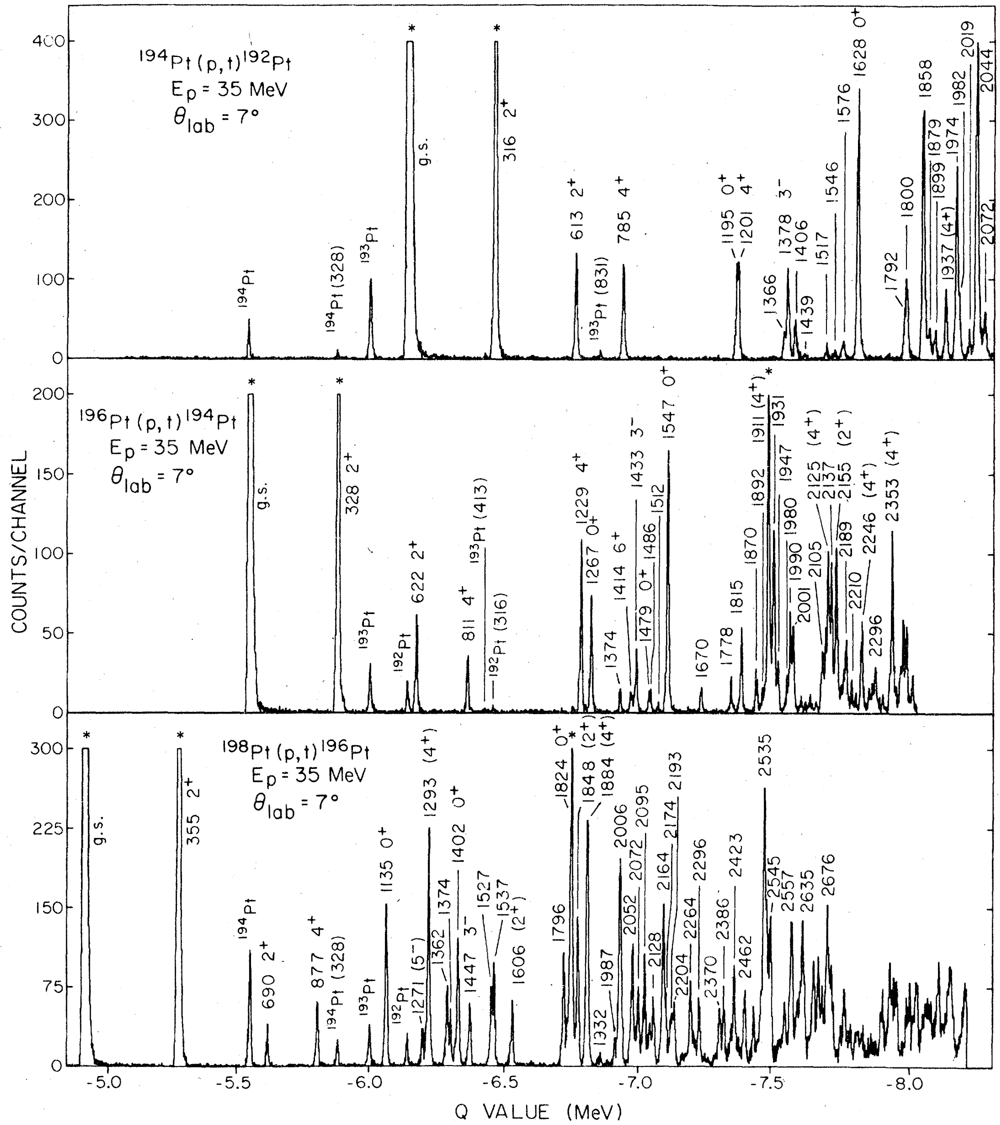

FIG. 2. Triton spectra at 7° from the $^{194,196,198}Pt(p,t)^{192,194,196}Pt$ reactions. Data obtained with nuclear emulsion plates (FWHM ≃ 7 keV) and the MSU Enge split-pole spectrometer. The spectra are plotted on a common Q value scale. "*" above peak indicates peak height has been cut off at maximum value shown on vertical scale.

model parameters used in the three reactions studied. Becchetti-Greenlees proton parameters were used in the entrance channel, and the triton parameters were taken from Flynn et al.[47] The wave functions were calculated for a Woods-Saxon potential with the usual prescription for the binding energy of each neutron, $0.5(S_{2n} + E_x)$. Here S_{2n} is the two-neutron separation energy and E_x is the excitation energy of the residual nucleus.

In order to test the effect of small changes in the optical model parameters, calculations were carried out using the Becchetti-Greenlees proton parameters for ^{208}Pb along with the ^{206}Pb triton parameters of Flynn et al. No major changes in the strength or shape were seen for any of the transitions calculated for the $^{196}Pt(p,t)$ reaction.

Since the platinum nuclides display low-lying collective excitations, one might expect that second-order or multistep effects, which are not accounted for in simple DWBA calculations, would play a role in determining the strength and shape of the angular distributions in (p,t) reactions as has been found for reactions on well deformed nuclei.[48] A possible explanation for the absence of such strong effects in the platinum nuclides may be the smaller value of the deformation parameter β_2(≃ 0.15 vs. ≃ 0.3 in rare earths). Since the strength of multistep couplings depends on terms involving various powers of β_2, the smaller value of β_2 may be enough to reduce many of the second-orde reaction steps. Further evidence for the predominance of the one-step mechanism is the absence in all three reactions studied of any strength (> 1 μb) populating the unnatural parity states, in particular the 3^+ level known to exist at ≃ 950 keV in $^{192,194,196}Pt$. Such transitions are forbidden to first-order in a one-step process. Previous work,[49] comparing DWBA with two-step coupled channels calculations for $^{62}Ni(p,t)$ and Cd(p,t) nuclei with

Table I. Optical model parameters.[a]

Parameter Set	Channel	V_R	r_R	a_R	W_v	W_{SF}	r_I	a_I	V_{SO}	r_{SO}	a_{SO}	r_C
1	$p+{}^{194}Pt$	52.9	1.17	0.75	5.0	5.4	1.32	0.647	6.2	1.01	0.75	1.17
	$t+{}^{192}Pt$	167.0	1.16	0.752	13.61	---	1.498	0.817	---	---	--	1.16
2	$p+{}^{196}Pt$	53.1	1.17	0.75	5.0	5.5	1.32	0.653	6.2	1.01	0.75	1.17
	$t+{}^{194}Pt$	167.0	1.16	0.752	12.55	---	1.498	0.817	---	---	--	1.16
3	$p+{}^{198}Pt$	53.2	1.17	0.75	5.0	5.6	1.32	0.658	6.2	1.01	0.75	1.17
	$t+{}^{196}Pt$	167.0	1.16	0.752	11.5	---	1.498	0.817	---	---	--	1.16
Bound State		V_n[b]	1.25	0.75	---	---	---	---	λ=25	1.25	0.75	---

[a] Definition of parameters in References 44 and 46.

[b] The neutron well depths were adjusted to give each orbit one-half the sum of the two neutron separation energy and the excitation energy of the residual nucleus.

collectivity similar to Pt, has shown that there are very small differences between the two reaction models in predicting shapes of angular distributions. The main effect of the two-step mechanisms was seen in the transition strengths. This may also explain the fact that the DWBA calculations reproduce the angular distribution shapes reasonably well in the platinum region, although coupled channel calculations have not been performed.

One method for obtaining spectroscopic information from two-nucleon transfer cross sections with DWBA calculations is to use an empirical normalization (D_0^2) to define an enhancement factor, ε, for the configuration which produces the strongest calculation for a given L transfer.[50,51] The relationship between the experimental cross-section and that calculated by DWUCK can be expressed as

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = 9.72\, D_o^2\, \varepsilon\, C^2 \times (2J+1)^{-1}\, \sigma^{LSJ}_{DWUCK}(\theta)$$

The factor D_o^2 is the normalization constant which results from making the zero-range approximation. A value of 2.2×10^5 MeV ^{2}F ^{3} was used in our calculations.[51] The constant 9.72 is derived from the choice of the size of the outgoing triton used in DWUCK and the range parameters of the two-body interaction. The isospin coupling coefficient, C^2, is unity for all transitions. The quantity J is the total angular momentum of the transferred neutron pair and $\sigma^{LSJ}_{DWUCK}(\theta)$ is the differential cross section calculated in DWUCK. In situations where one has approximate wave functions the factor ε is a measure of the adequacy of the wave functions used in calculating the form factor. A value of $\varepsilon = 1$ would indicate an ideal wave function description if all other assumptions were valid. In the present case ε represents the relative strength for a particular L-transfer expressed in arbitrary units (σ^{LSJ}_{DWUCK} calculated from the dominant 2-neutron configuration). This allows for the unfolding of kinematic factors which may favor a particular L transfer. The configurations used for each L transfer are footnoted in Tables II, III, and IV. As mentioned above, these configurations produced the greatest calculated strengths for their respective L transfer in each of the three reactions, ^{194,196,198}Pt(p,t).

IV. EXPERIMENTAL RESULTS

A. General Analysis

Tables II, III, and IV contain the excitation energies, cross-sections, and new J^π assignments for the three reactions studied, ^{194,196,198}Pt(p,t), in addition to results from previous work. The cross section is reported for the data taken at 7° using nuclear emulsions, as the resolution (≈7 keV FWHM) and low background allowed for the measurement of weakly excited and close lying states. We have reported energies and associated cross sections for approximately 50 levels in the ^{196,198}Pt(p,t) reactions and 64 in the ^{194}Pt(p,t)^{192}Pt reaction with about one-half of the levels being reported for the first time. Values for the enhancement factors, ε, are listed for those states where relatively complete angular distributions were obtained.

B. L = 0 Transitions

As expected, the L = 0 transitions were observed with the very characteristic diffraction pattern seen in most two-nucleon transfer reactions. This distinctive shape allows for reliable assignments of 0^+ levels in the final nucleus. Eleven L = 0 transitions were observed in the three reactions including the three ground state transitions and one transfer to a newly identified excited 0^+ level in ^{192}Pt. The L = 0 transitions are shown in Fig. 3, along with the DWBA calculations from the code DWUCK. The shapes of all these transitions are very similar. There is very little change from nucleus to nucleus in the phase of the distributions or in the peak-to-valley ratios. The same is true for the DWBA calculations, which show only slight deviations at forward angles. In general, the calculated shapes are independent of Q value or choice of the simple 2-neutron configuration used in computing the form factor.

The ground state transitions are by far the most intense transitions observed in all three reactions. The strongest excited 0^+ state in Pt is populated with only 8% of the strength of the ground state at 7°.

The 0^+ state at 1.195 MeV in ^{192}Pt, previously seen[17,18] in the decay of ^{192}Au, was unresolved from

Table II. States populated in ^{192}Pt.

Present Work $^{194}Pt(p,t)^{192}Pt$				Previous Results[a]			
				(α,α')[c]		γ-ray experiments[d]	
E_x (MeV)	J^π	$\sigma(7^o)$ (μb/sr)	ε[b]	E_x (MeV)	J^π	E_x (MeV)	J^π
0.0	0^+	971	5.1	0.0	0^+	0.0	0^+
0.316[e]	2^+	126	0.84	0.316	2^+	0.3165	2^+
0.613[e]	2^+	16	0.16	0.612	2^+	0.6124	2^+
0.785[e]	4^+	15	0.21	0.785	4^+	0.7845	4^+
1.195[e]	0^+	10	0.07			1.1951	0^+
1.201[e]	4^+	16		1.20	4^+	1.2010	4^+
1.366		4				1.3653	6^+
1.378[e]	3^-	16		1.378	3^-	1.3779	3^-
1.406		7				1.4062	
1.439		1				1.4391	$(1^+,2^+)$
1.517		2				1.5182	7^-
1.546		1					
1.576		4				1.5766	(2^+)
1.628	0^+	49	0.26				
1.792		6					
1.800		23(10°)					
1.858		43					
1.879		5				1.8804	
1.899		4					
1.937	(4^+)	11	0.32				
1.974		28					
1.982		9					
2.019 (3)		3					8^+
2.044	(doublet)	70				2.0479	
2.072		7				2.0741	
2.132		7				2.1301	
2.140		13					
2.153		8				2.1494	
2.166		19					
2.188		7					
2.204		17					
2.271		18					
2.308		25					
2.330 (3)		1				2.3356	
2.352		4					
2.358		7					
2.375		2				2.3755	
2.389		2					
2.411		6				2.4085	
2.428		15					
2.444		11					

Table II. (Continued).

Present Work ^{194}Pt(p,t)^{192}Pt				Previous Results[a]			
				(α,α')[c]		γ-ray experiments[d]	
E_x (MeV)	J^π	$\sigma(7^\circ)$ (μb/sr)	ε[b]	E_x (MeV)	J^π	E_x (MeV)	J^π
2.450		9				2.4533	
2.467		13				2.4722	
2.486		6					
2.492		8					
2.506		1					
2.526		6					
2.549		21					
2.556		11					
2.575		4					
2.588		6				2.5853	
2.605		7					
2.624		6					
2.646		18					
2.662		5					
2.671		3					
2.695		4					
2.704		6					
2.720		7					
2.729		10					
2.743		6					
2.754		6					
2.778		5					
2.786		4					

a The states above 2 MeV seen in this work and previous results are associated only because of similar energies.

b The enhancement factors were calculated with pickup configurations $(0p_{3/2})^2$ for L = 0, $(2p_{3/2} \otimes 1f_{7/2})$ for L = 2, and $(1f_{5/2} \otimes 2p_{3/2})$ for L = 4.

c References 4, 30.

d References 8, 18, 19, 27, 28.

e Used as calibration point with energy taken from Nuclear Data Sheets B9, 195 (1973). Uncertainties in excitation energy are approximately 1 keV below 1.4 MeV and 0.1% above 1.4 MeV, except as indicated.

the 4^+ level at 1.201 MeV in the proportional counter data used for angular distributions. The spin of this level was confirmed using the three point angular distributions taken with nuclear emulsions. The new 0^+ level seen in ^{192}Pt at 1.628 MeV was populated with 5% of the strength of the ground state at 7°.

Three excited 0^+ states were populated in the ^{196}Pt(p,t)^{194}Pt reaction. All three states were previously seen[18,20,22] in the decay of ^{194}Au. The level at 1.479 MeV is very weakly excited (<0.5% of the ground state at 7°) and was resolved only in the plate data. The L = 0 nature of the transition populating this state was also confirmed by the three point angular distribution. The levels at 1.267 and 1.547 MeV were excited with considerably more strength, 3 and 6% respectively of the ground state strength at 7°, and the 1.547 MeV level was the only excited 0^+ state seen in the earlier (p,t) study of Maher et al.[39] There are two higher energy 0^+ levels known[18,22] in ^{194}Pt at 1.8936 MeV and 2.086 MeV. We observe a level weakly populated at 7° in the plate data with an energy of 1.892 MeV but an angular distribution was not obtained. We populate no state

Table III. States populated in ^{194}Pt.

Present Work ^{196}Pt(p,t)^{194}Pt				Previous Results[a]			
				Charged-Particle Experiments[c]		γ-ray Experiments[d]	
E_x (MeV)	J^π	$\sigma(7^\circ)$ (μb/sr)	ε^b	E_x (MeV)	J^π	E_x (MeV)	J^π
0.0	0^+	801	3.6	0.0	0^+	0.0	0^+
0.328[e]	2^+	159	1.3	0.329	2^+	0.3285	2^+
0.622[e]	2^+	18	0.16	0.626	2^+	0.6221	2^+
0.811[e]	4^+	9	0.10	0.818	4^+	0.8112	4^+
1.229[e]	4^+	30	0.63	1.235		1.2295	4^+
1.267[e]	0^+	20	0.08			1.2671	0^+
1.374	$(4^+,5^-)$	4	0.26			1.3736	$(6^+,5^-)$
1.414	6^+	5	0.10			1.4116	6^+
1.433[e]	3^-	12	1.3	1.435	3^-	1.4325	3^-
1.479 (2)	0^+	3	0.03			1.4792	0^+
1.486 (2)		3				1.4853	7^-
1.512 (3)		2				1.5119	2^+
1.547[e]	0^+	46	0.26	1.551	0^+	1.5472	0^+
1.670		5				1.6706	2^+
1.778		6				1.7787	$(1,2,3)^+$
1.815		14				1.817	(3^-)
1.892		5		1.89		1.8936	0^+
1.911	(4^+)	71	1.9				
1.931		42				1.9302	$(1,2,3)^+$
1.947		10				1.9845	
1.990	$(6^+,7^-)$	9	(0.91,3.6)			1.9938	
2.001		17					
2.031		3		2.03			
2.062		4		2.08		2.0638	$(1,2,3)^+$
2.105		16		2.08		2.1091	$(1,2)^+$
2.125	(4^+)	37	0.57	2.13			
2.137		30		2.13		2.1409	
2.155	(2^+)	38	0.27			2.1580	$(1,2^+)$
2.189		18					
2.210		6					
2.224		4		2.22			
2.246	(4^+)	18	0.43				
2.277		6					
2.284		6				2.2873	$1,2^+$
2.296	$(7^-,8^+)$	10					
2.353	(4^+)	37	0.87				
2.532	(2^+)	28	0.33				
2.566	(6^+)	11(10°)	0.56	2.56			
2.580		27					

Table III. (Continued).

Present Work $^{196}Pt(p,t)^{194}Pt$				Previous Results[a]			
				Charged-Particle Experiments[c]		γ-ray Experiments[d]	
E_x (MeV)	J^{π}	$\sigma(7^{o})$ (μb/sr)	ε^{b}	E_x (MeV)	J^{π}	E_x (MeV)	J^{π}
2.595		16					
2.638	(4^+)	29	0.61				
2.700	(6^+)	18	0.61				
2.757		30					
2.815		12					
2.840		7					
2.871		13					
2.895		7					

a The states above 2 MeV seen in this work and previous results are associated only because of similar energies.

b The enhancement factors were calculated with pickup configurations $(0p_{3/2})^2$ for L = 0, $(2p_{3/2} \otimes 1f_{7/2})$ for L = 2, $(0i_{13/2} \otimes 1f_{7/2})$ for L = 3, $(1f_{5/2} \otimes 2p_{3/2})$ for L = 4, $(2p_{3/2} \otimes 0i_{13/2}$ for L = 5, $(1f_{5/2} \otimes 1f_{7/2})$ for L = 6, and $(2p_{1/2} \otimes 0i_{13/2})$ for L = 7.

c References 3, 30, 34, 39.

d References 18, 20, 22, 23, 27, 28, 31.

e Used as calibration point with energy taken from Nuclear Data Sheets B7, 95 (1972). Uncertainties in excitation energy are approximately 1 keV below 1.4 MeV and 0.1% above 1.5 MeV, except as indicated.

within 20 keV of the 2.086 MeV level.

Three excited 0^+ states were again observed in the $^{198}Pt(p,t)^{196}Pt$ reaction at energies of 1.135, 1.402, and 1.824 MeV. All three levels have been previously reported although the spin of the state at 1.402 MeV was assigned as $(0^+, 1^+, 2^+)$ in the decay of ^{196}Au and in the neutron capture experiment by Samour et al.[25] A recent (n,γ) study of ^{196}Pt by Cizewski et al.[16] also assigns the spin as 0^+ for the 1.402 MeV level.

It is significant that no new 0^+ levels were seen below 1 MeV in any of the three Pt isotopes studied. Implications of this absence will be discussed later.

C. L = 2 Transitions

In contrast to the situation for (p,t) reactions measured at lower energy in this mass region,[39,41] the L = 2 transitions observed in the present study appear to be sufficiently characteristic to allow spin assignments to be made. Transitions to the known first and second 2^+ levels have quite similar angular distributions. The major difference appears near 18° where the angular distribution for the second 2^+ has a more pronounced oscillation than for the first 2^+ as seen in Fig. 4. The remainder of the distributions for the excited 2^+ levels have approximately the same shape as the second 2^+ distribution. This small deviation in shapes seen in all three reactions may indeed be indicative of some small multistep effects affecting the shapes. As mentioned earlier, the small magnitude of the effect may be due to the rather small values of the β_2 deformation parameter for the Pt nuclides. The sensitivity of the angular distributions to changes in the two-neutron configuration indicated by the DWBA calculations shown in Fig. 4 could also account for the variation of 2^+ shapes observed.

In the $^{194}Pt(p,t)^{192}Pt$ reaction only two 2^+ levels were populated with enough intensity to extract a complete angular distribution from the data. These were the first and second 2^+ states at 0.316 and 0.613 MeV, the spin for both of which have been well established in earlier studies. Two levels at 1.439 and 1.576 MeV which have been previously assigned[17,27] as $(1^+, 2^+)$ and 2^+ respectively were weakly excited at forward angles.

Four 2^+ levels were populated in the $^{196}Pt(p,t)^{194}Pt$ reaction, with energies of 0.328, 0.622, 2.155, and 2.532 MeV. The two lowest energy levels have been seen in earlier studies, while the state at 2.155 MeV was reported as $(1,2)^+$ in Ref. 14 and is tentatively assigned as 2^+ in the present study. The new level at 2.532 MeV is also tentatively assigned as 2^+. This level may be part of a broad state seen at 2.55 MeV in the $^{195}Pt(d,t)$ data and at 2.56 MeV in the $^{194}Pt(d,d')$ study.[34] As in the $^{194}Pt(p,t)$ reaction, several known 2^+ levels were only weakly populated and angular distributions were not obtained for these.

In addition to the first (0.355 MeV) and second (0.690 MeV) 2^+ levels, two higher lying levels were populated in the $^{198}Pt(p,t)^{196}Pt$ reaction. These levels are at 1.606 and 1.848 MeV and have been assigned as 2^+. They have been confirmed in a recent (n,γ) experiment.[16]

Table IV. States populated in ^{196}Pt.

Present Work ^{198}Pt(p,t)^{196}Pt					Previous Results[a]			
					Charged-Particle Experiments[c]		γ-ray experiments[d]	
E_x (MeV)		J^π	σ (7°) (μb/sr)	ε[b]	E_x (MeV)	J^π	E_x (MeV)	J^π
0.0		0^+	852	3.7	0.0	0^+	0.0	0^+
0.355[e]		2^+	272	2.2	0.356	2^+	0.3557	2^+
0.689[e]		2^+	10	0.12	0.684	2^+	0.6889	2^+
0.877[e]		4^+	13	0.12	0.878	4^+	0.8770	4^+
1.135[e]		0^+	29	0.11	1.15		1.1352	0^+
1.271[e]		5^-	7				1.2705	$(4,5^-)$
1.293		(4^+)	43	0.77	1.290			
1.362			8				1.3617	$1^+,2^+)$
1.374		$(6^+,7^-)$	15	0.94			1.374	$(6,7)^-$
1.402		0^+	22	0.15			1.4027	$0^+,1^+,2^+$
1.447[e]		3^-	13	0.81	1.462	(3^-)	1.4471	3^-
1.527			11					
1.537			17					
1.606		(2^+)	10	0.09			1.6045	$0^+,1,2^+$
1.675	(2)		1				1.677	2^+
1.796			22					
1.824[e]		0^+	71	0.32			1.8234	0^+
1.848		(2^+)	27	0.22			1.8471	$0^+,1,2$
1.884		(4^+)	116	2.1	1.88			
1.932			2					
1.987	(10)		5					
2.006			45					
2.052			19					
2.072			17					
2.095			20					
2.114			7					
2.128			12				2.1289	$1^-,2^+$
2.164			28				2.1627	$0^+,1,2$
2.174			9				2.1744	2^+
2.193			9				2.1908	$0^+,1,2$
2.204			11					
2.264			16				2.2641	$1,2^+$
2.277			5					
2.296		$(7^-,8^+)$	12					
2.370			10					
2.386			11		2.39			
2.423			21					
2.440			4				2.442	$0^+,2^+$
2.462			14				2.468	1^+

Table IV. (Continued).

Present Work $^{198}Pt(p,t)^{196}Pt$				Previous Results[a]			
				Charged-Particle Experiments[c]		γ-ray experiments[d]	
E_x (MeV)	J^{π}	σ (7°) (μb/sr)	ε[b]	E_x (MeV)	J^{π}	E_x (MeV)	J^{π}
2.521		12					
2.535		50					
2.545		26				2.548	$0^+,2^+$
2.557		28		2.57			
2.609		13		2.60			
2.627		10					
2.635		27		2.64			
2.655		12		2.64			
2.666		11		2.67		2.662	$0^+,2^+$
2.676		20					
2.759		13					
2.766		23					
2.779		20					

a The states above 2 MeV seen in this work and previous results are associated only because of similar energies.

b See footnote b in Table III.

c References 3, 34.

d References 21, 24, 25, 26.

e Used as calibration point with energy taken from Nuclear Data Sheets B7, 395 (1972). Uncertainties in excitation energy are approximately 1 keV below 1.8 MeV and 0.1% above 1.8 MeV, except as indicated.

D. L = 3 Transitions

The 3^- octupole vibrational state was populated in each (p,t) reaction as shown in Fig 4. In the $^{194}Pt(p,t)$ reaction the 3^- state at 1.378 MeV and the 6^+ state at 1.366 MeV were not completely resolved, although the contribution to the cross section from the L = 6 transfer is thought to be small. As shown in Fig. 4, the L = 3 DWBA fits were quite poor, missing the first maxima by as much as 10°. Again this may be the result of inelastic effects, as the 3^- state is strongly populated in inelastic scattering studies.[30,34,52] In fact, this rather strong population of the 3^- levels is somewhat unexpected. These states were very weak in the Pb(p,t) reactions, which is expected since the 3^- state is basically particle-hole in nature, while (p,t) excites 2-particle, 2-hole states.

E. L = 4 Transitions

The spin assignments from L = 4 transitions required special attention in this study, due to the seemingly uncharacteristic shape of the angular distribution populating the well known first 4^+ level in all three reactions. This shape differs from the shape seen in both the simple two-neutron DWBA calculations and the Pb(p,t) data of Lanford.[53] As shown in Fig. 5, these angular distributions for the first 4^+ levels have no distinct maximum at 15°, but continue to rise toward forward angles and also show a pronounced minimum at 30°. A look at the angular distribution for the other known 4^+ levels (1.229 MeV in ^{194}Pt and 1.201 MeV in ^{192}Pt) shows a shape characterized by a distinct maximum near 15° more closely resembling that calculated in DWBA and in the Pb(p,t) reactions. It was the latter shape that was used to make spin assignments for possible high-lying 4^+ levels.

In addition to the first 4^+ state, at least two more excited 4^+ states were seen in each reaction, and in the $^{196}Pt(p,t)$ reaction six more such states have been tentatively identified. The 1.201 MeV level in ^{192}Pt, a known 4^+ state, was not resolved from the 1.195 MeV 0^+ level although the shape is distorted slightly by the weakly populated 0^+ level, as shown in the plate data. A possible third 4^+ level in ^{192}Pt was seen at 1.937 MeV, although its interpretation as a 3^- state cannot be ruled out, as the DWBA calculations for L = 4 and L = 3 are quite similar. The assignment is tentatively made as 4^+ because of the appearance of possible 4^+ levels near this energy in ^{194}Pt and ^{196}Pt. Also, the empirical shape of the L = 3 angular distributions for the three known 3^- levels is considerably "flatter" at forward angles (see Fig. 4).

In addition to the known 4^+ level at 1.229 MeV, five new levels were populated in ^{194}Pt with the same basic L = 4 shape at energies of 1.911, 2.125, 2.246, 2.353, and 2.638 MeV and have been tentatively assigned as 4^+ levels.

In ^{196}Pt two levels were populated by transitions whose angular distribution shape is that of an L = 4 transfer. The level at 1.293 MeV may have been observed in inelastic alpha scattering (1.290 MeV) but was not assigned spin or parity. The L = 4 DWBA fit is not as good as others seen in the ^{196}Pt(p,t) reaction, but this deficiency is partially due to analysis difficulties in unfolding the contribution from the nearby 5^- level at 1.271 MeV. The trend in the other two Pt nuclei studied would suggest this is the second 4^+ level. The level at 1.884 MeV in ^{196}Pt was populated very strongly with the shape of an L = 4 transfer and completes a series of new 4^+ levels seen at $\approx$1.9 MeV in all three (p,t) reactions. This level may be the same state seen in the (d,d') study[34] at 1.88 MeV.

F. L $\geq$ 5 Transitions

Only limited success was achieved with assigning J^π values to states populated by L transfers greater than 4. Although the DWBA calculations showed the first maxima shifting approximately 5–10° towards backward angles as the transferred angular momentum increased, there was only one known higher spin state populated with a complete angular distribution for comparison. This was the 6^+ level in ^{194}Pt at 1.414 MeV. The other known levels with spins greater than 4 were either unresolved in the data (1.486 MeV 7^- in ^{194}Pt and 1.271 MeV 5^- in ^{196} Pt), or too weakly populated for a complete angular distribution (1.517 MeV 7^- and 2.019 MeV 8^+ in ^{192}Pt). Nevertheless, several spin assignments have been proposed for levels in ^{194}Pt and ^{196}Pt as shown in Fig. 5.

In ^{194}Pt a level at 1.374 MeV was populated, which has been assigned as a 5^- level in (α,xn) reactions[27,28] and as (6^+) or ($4,5^-$) in ^{194}Au decay[18] and triple neutron capture.[23] From the present (p,t) results a clear distinction cannot be made between L = 4 and L = 5 transfer. As a result the state has been assigned ($4^+,5^-$) from the natural parity selection rule. The level at 1.414 MeV, a known 6^+ state, is well reproduced by the L = 6 calculation, particularly in the angular region about the maximum.

This agreement leads us to propose two additional levels to be assigned as 6^+, at 2.566 and 2.700 MeV. As shown in Fig. 5, they are fit quite well by the theory. Levels at 1.990 and 2.296 MeV have been assigned J^π values ($6^+,7^-$) and($7^-,8^+$), respectively. A unique assignment was not possible because of the similarity of the shapes for the calculated L transfers involved in each case.

In the ^{198}Pt(p,t) reaction, two high-spin levels have been identified, at energies of 1.374 and 2.296 MeV. The first level was assigned as $(6,7)^-$ in the decay[21] of ^{196}Ir, and the (p,t) data indicate it to be either a 6^+ or 7^- state. From the (p,t) natural parity selection rule, this is therefore most likely a 7^- state and may be related to the 7^- state observed at 1.518 MeV in ^{192}Pt and 1.485 MeV in ^{194} Pt. The second level, at 2.296 MeV, is fit very well by the L = 7 calculation, but is again assigned as ($7^-,8^+$).

V. RELATIVE REACTION STRENGTHS

The triton spectra shown in Fig. 2 for the three reactions show many of the same overall features. The

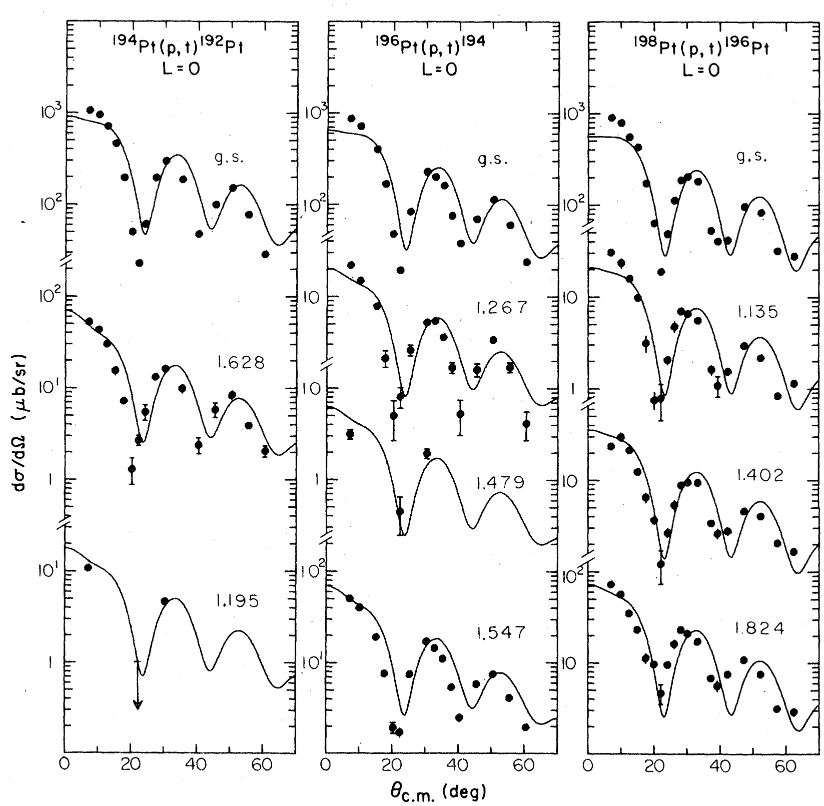

FIG. 3. L=0 angular distributions for the ^{194,196,198}Pt(p,t) reactions. The curves are the result of DWBA calculations using the optical model parameters of Table I. Energies are given in keV.

Table V. Integrated cross sections[a] for transitions in ^{194,196,198}Pt(p,t) and cross section ratios relative to the ground state of ^{192}Pt. Calculations in the 0(6) limit of the IBA model[b] for the L=0 and L=2 transitions, normalized to the ^{192}Pt g.s. and the ^{192}Pt 2_1^+ transitions are also shown.

J^π	^{194}Pt(p,t)^{192}Pt				^{196}Pt(p,t)^{194}Pt				^{198}Pt(p,t)^{196}Pt			
	E (keV)	σ_{exp} (mb)	σ/σ_{192} (exp)	σ/σ_{192} 0(6)	E (keV)	σ_{exp} (mb)	σ/σ_{192} (exp)	σ/σ_{192} 0(6)	E (keV)	σ_{exp} (mb)	σ/σ_{192} (exp)	σ/σ_{192} 0(6)
0_1^+	0.0	73.8	1.0	1.0	0.0	61.0	0.83	0.90	0.0	57.8	0.78	0.76
0_2^+	1195	1.36	0.02	0.0004	1267	1.42	0.02	0.0003	1135	1.72	0.02	0.0002
0_3^+	1628	3.77	0.05	0.040	1479	0.23	0.003	-c-	1402	2.56	0.03	0.067
0_4^+	---	---	---	0.008	1547	4.00	0.05	0.039	1824	5.50	0.07	0.032
0_5^+	---	---	---		1892[d]	0.39	0.005	0.016	---	---	---	---
2_1^+	316	11.0	0.15	0.15	328	13.6	0.18	0.14	355	20.1	0.27	0.14
2_2^+	613	1.67	0.02	0.029	622	1.72	0.02	0.013	689	0.97	0.01	0.001
2_3^+	1439[d]	0.1	0.001	0.018	1512[d]	0.1	0.001	0.021	1362[d]	0.25	0.003	0.048
3^-	1378	3.03	0.04		1433	2.58	0.03		1447	2.10	0.03	
4_1^+	785	1.42	0.02		811	0.95	0.01		877	1.03	0.01	
4_2^+	1201	2.35	0.03		1229	5.63	0.08		1293	6.72	0.09	
4_3^+	1937	1.79	0.02		1911	14.8	0.20		1884	18.4	0.25	

a Integration performed between 7° and 60°. Uncertainties are 10-15%.

b Reference 59.

c See text.

d These states were not identified in this experiment as 0^+ or 2^+ levels. However, their 7° cross sections have been used to scale their total cross section with that of the ground state or 2_1^+ for comparison with the calculations for the 0(6) limit of the IBA.

most notable are: strong population of the ground state and first 2^+ level in the residual nucleus; several excited L = 0 transitions; an increasing population of the 4_2^+ and 4_3^+ levels as the mass of the target increases. Table V displays for each reaction the integrated differential cross section from 7° to 60° for the more strongly populated levels below 2 MeV. These same trends from ^{194}Pt(p,t) to ^{198}Pt(p,t) are seen in the enhancement factors, ε extracted from the DWBA calculations mentioned above. These values are listed in Tables II, III, and IV. Since these calculations used only a simple 2-neutron wave function, values differing from unity suggest the absence of correlations in the wave function. As expected, the ground state transitions are the most enhanced with an ε of 5.1 in ^{194}Pt(p,t) and 3.7 in ^{198}Pt(p,t). While the ground state population is decreasing with increasing A, the enhancement of the first 2^+ level and third 4^+ is increasing with A from 0.84 to 2.2, and 0.32 to 2.1 respectively. Although ε was not calculated for the 4_2^+ level in ^{192}Pt, Table V shows the total cross section of this state also increases with A. In addition, the enhancement of the 4_1^+, 2_2^+, 3^-, and the excited 0^+ levels remains relatively constant in all three reactions.

These same general trends, decreasing ground state population and a general increase in population of excited states with increasing A, were seen in the (p,t) reactions on the Pb nuclides.[53] This was interpreted as an indication of an increase in the two-particle coherence of the wave functions as one moves away from the closed shell. The decreasing ground state population from ^{192}Pt to ^{196}Pt is not as dramatic as that seen in the Pb data, but this is understandable from a simple pairing-vibration model.[50] If the creation and annihilation operators for the two-neutron pick-up are treated as boson operators, then the strengths of the transitions are related to the number of pairs of neutrons (phonons) or holes, in the final state, relative to the nearest closed shell. For ^{202,204,206}Pb, the strengths of the ground state transitions should be in the ratio 3:2:1, while for ^{194,196,198}Pt the ratio would be 6:5:4. This is consistent with the experimental Pt ratio of 6.1:5.0:4.7, with 15–20% uncertainties on these numbers. Arima and Iachello[54] have noted that both finite dimensionality effects and an increase in collectivity as one proceeds into a shell are important and give quantitative predictions for these effects with the IBA; however, the uncertainties on our measured ground state strengths are too large for us to observe such an effect.

VI. DISCUSSION

A. General

One of the long standing problems in trying to describe the Pt nuclides within the framework of a nuclear model has been the apparent lack of a 0^+ level near 700 keV.

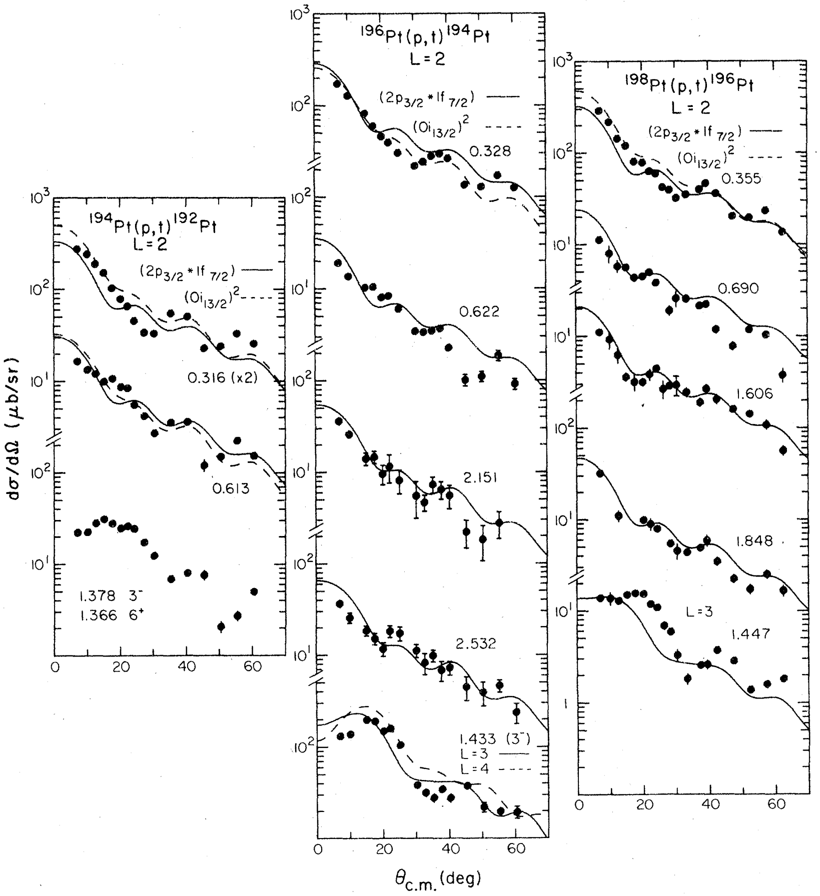

FIG. 4. L=2 and L=3 angular distributions for the ^{194,196,198}Pt(p,t) reactions. The curves are the result of DWBA calculations using the optical model parameters of Table I. Energies are given in keV.

Early attempts to characterize these nuclei were usually made within a vibrational picture, because of the nearly equal level spacings below 1 MeV. These attempts were unsuccessful primarily because the lowest 0^+ level has neither the decay properties nor the energy compatible with a 2-phonon 0^+ state.

The asymmetric rotor model has also been applied in this region because it predicts an inversion of the 2^+_2 and 4^+_1 levels as well as the lack of a low-lying excited 0^+. But again, the 0^+ levels present a problem, as the model predicts no excited 0^+ state unless new degrees of freedom are introduced.

The asymmetric rotor model has had considerable success in describing the odd-A nuclei, although predictions from coupling a particle to a triaxial core have been shown to be experimentally indistinguishable thus far from those obtained by a variety of other approaches,[10,11] including that involving a γ-unstable core. Three Coulomb excitation studies have been performed on the Pt nuclides, and the results have been compared to various models: Lee et al.[31] see evidence for a stable triaxial shape; Baktash et al.[32] favor the model of Kumar and Baranger; the third study proved inconclusive.[33]

The pairing-plus-quadrupole model of Kumar and Baranger has had considerable success in predicting the prolate to oblate shape transition, but only addresses the lower energy levels and their transitions. It also predicts the potential energy surface to be γ-soft. This is one of several predictions of γ-soft potentials in the Pt-Os region, in apparent disagreement with some experimental evidence, cited above, for rigid triaxial shapes. An underlying difficulty in static potential calculations may be neglect of the zero-point vibration motion.[55] If the zero-point energy is larger than the deformation energy (shallow minimum in the potential) then the static shape of the nucleus in the ground state fades in significance when dynamic motion (vibration) is considered.

One of the primary reasons for the current reaction study was to search for low-lying 0^+ states that could be interpreted as the "missing" 0^+ state of the 2-phonon triplet in a vibrational model interpretation. Although (p,t) transitions to 2-phonon states are forbidden in first-order, these states have been seen[56] in (p,t) reactions on Cd and Pd, probably due to two-step transfers and/or anharmonic terms in the vibrational potential. We see no evidence for low energy L = 0 transitions populating a 0^+ level in any of the three reactions, ^{194,196,198}Pt(p,t). In fact, we see no new levels populated below ≃1.5 MeV with a cross-section ≳1 μb/sr at forward angles, about 0.1% of the ground state population. (In Cd, the relative (p,t) strength ratio for $0^+_2/0_{g.s.}$ is ≃0.25%.)

A second result of the experiments is the absence of any strong L = 0 transitions populating excited L = 0 levels. As mentioned earlier, a strong L = 0 transition (≃50–100% of the ground state strength) might have indicated a shape isomeric level in the residual nucleus related to the γ degree of freedom. This would imply a stable triaxial

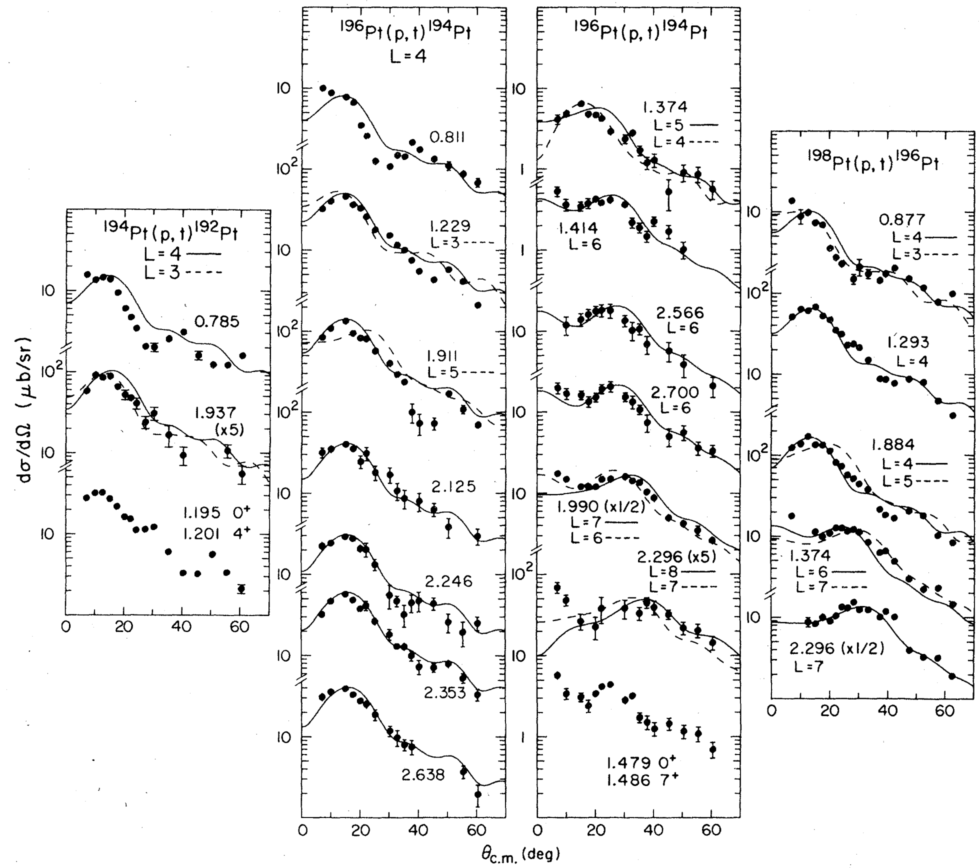

FIG. 5. $L \geq 4$ angular distributions for the ^{194,196,198}Pt(p,t) reactions. The curves are the result of DWBA calculations using the optical model parameters of Table I. Energies are given in keV.

minimum in the potential. Since no transition was observed that was stronger than 10% of the total ground state cross section, the data seem to be consistent with an interpretation of these nuclei as being soft, with shallow minima in the potential surface.

Tables II, III, and IV show three or four excited 0^+ levels weakly populated in each of the three (p,t) reactions studied. Most of these 0^+ states are not easily interpreted within current models for this region. The energy is too high in the Pt region (≈1.2 MeV) for the first excited 0^+ state to be a member of the 2-phonon triplet in a strict vibrational sense, although the pairing-plus-quadrupole model predictions of Kumar and Baranger[12] are quite reasonable: 1.207, 1.101, and 1.018 MeV for ^{192,194,196}Pt excited 0^+ states respectively. The cross section for populating the first excited 0^+ state in (p,t) is 2–3% of the ground state in each reaction, rather weak for it to be considered the "β-vibrational" state of a symmetric rotor, as the typical cross-section for the first excited 0^+ levels in deformed nuclei is approximately 5–10% of the ground state. Some of the higher energy 0^+ states may carry more of the β-vibrational strength, as they are populated by stronger L = 0 transitions.

One interpretation of the 0^+ levels may be as the K = 0, two γ-phonon bandhead of a symmetric rotor, as seen[41,57] in ^{188,190,192}Os. The energy of these 0_2^+ levels is quite close to the Bohr-Mottelson prediction of twice the single γ-phonon bandhead (≈625 keV in Pt). Existing branching data for the decay of the first excited 0^+ state in $^{190-196}$Pt also supports this phonon interpretation with the ratio

$$(B(E2)0_2^+ \to 2_2^+)/(B(E2)0_2^+ \to 2_1^+) >> 1 \ .$$

B. Interacting Boson Approximation

Recently a description of even-even nuclei in terms of a system of interacting bosons which can occupy two levels with angular momentum L = 0 and L = 2 has been proposed by Arima and Iachello.[15] The six components of these two states provide a basis for the representation of the SU(6) group, and by using the symmetry relations of the subgroups, SU(3), SU(5), and O(6), analytical solutions for the energy levels and several dynamic properties can be obtained straightforwardly for nuclei near these limits. It has recently been shown[16] that ^{196}Pt may be an excellent example of the O(6) limiting symmetry of the interacting boson approximation (IBA) model. The O(6) limit reproduces the approximate energy for all collective levels below 2 MeV as well as the approximate branching ratios deexciting each level. Moreover, it predicts no 0^+ level with 2-phonon components near the 4_1^+ and 2_2^+ level, and it has no equivalent to the 3-phonon 2^+ level. Small perturbations from this limit also account for the 0–2–2 sequence of states and their changing decay patterns as a function of A in the Os–Pt region,[16] both consequences of a slowly increasing symmetry breaking term. Such A-dependent deviations from the O(6) limit are in fact predicted to occur within the more complete SU(6) representation of the IBA.

Prior to the introduction of the O(6) limit of the IBA, we had explored the SU(5) vibrational limit as applied to the Pt iostopes. It is interesting to note that poor results were obtained for the energy levels and B(E2) values in SU(5) unless the first excited 0^+ state observed in each nucleus is presumed to correspond to the higher-lying 3–phonon 0^+ state in the O(5) limit, rather than the 2–phonon excitation. The O(6) limit accounts naturally for this "3-phonon" character of the lowest 0^+ state in Pt and Os isotopes, while the "2–phonon" 0^+ state retreats to somewhat higher energy. The problem of the "missing" low-lying 0^+ state in the Pt isotopes is thus resolved.

With the apparent success of the O(6) limit in accounting for the spectroscopic properties of the shape-transitional Pt isotopes, it is perhaps not surprising, as Casten has noted,[16] that the macroscopic model which has a spectrum and decay properties most similar to the O(6) limit is the deformed, γ–soft oscillator model of Wilets and Jean.[5]

It has been shown by Arima and Iachello[54] that the IBA model provides a natural framework for a unified description of 2–nucleon transfer reactions across a complete shell. The ease of associating the IBA with 2–nucleon transfer reactions is due to the inherent coupling in this model of pairs of fermions to bosons with angular momentum 0 and 2, or s and d bosons. Although present studies have centered primarily on L = 0 transitions, further calculations are underway on L = 2 transitions. It is also possible to treat higher L transfers by coupling bosons to form higher order operators, or alternatively by adding g bosons (L = 4). We have restricted our discussion to the L = 0, 2 transitions at this time. Ref. 54 investigates 2–nucleon transfer reactions in the SU(5) (vibrational) and SU(3) (rotational) limits, while we present here features of the (p,t) reactions near the O(6) limit.

The operators for the (p,t) reaction can be expressed in terms of creation and annihilation operators for the s and d bosons, $s^+(d^+)$ or s(d) depending on whether one is near the end or beginning of a shell. This change of operators is due to a change from particles to holes in describing the system. For the L = 0 transitions in (p,t) reactions the operator, to first order, has the form[54]

$$T_{+\nu}^{(0)} = \alpha_\nu s_\nu^\dagger (\Omega_\nu - N_\nu - n_{d\nu})^{1/2} .$$

In this notation a distinction is made between boson operators for neutrons ($s_\nu^\dagger$) and protons, as the calculations discussed below have been performed[58] using a code which allows for the two types of bosons. Other quantities in the operator are a strength factor, α_ν; the effective neutron pair degeneracies of the sub-shell in question, Ω_ν; the neutron pair number, N_ν; the neutron d–boson number, $n_{d\nu}$. The factor

$$[\Omega_\nu - N_\nu - n_{d\nu}]^{1/2}$$

is a result of the finite dimensionality of the shells. The eigenfunctions in the O(6) limit have a particular quantum number, τ, which is related to the expectation value of the number of d bosons, $\langle n_d\rangle$. For L = 0 transitions it can be shown there is a $\Delta\tau = 0$ selection rule which requires that the average number of d bosons does not change. Thus, the relative strengths of these transitions can be predicted by a check of the O(6) wave functions for the 0^+ states. For example, in the ^{198}Pt(p,t)^{196}Pt reaction the ground states for both nuclei have $\tau = 0$ or $\langle n_d\rangle \simeq 2$, while the first and second excited 0^+ states in ^{196}Pt have $\tau = 3$ ($\langle n_d\rangle \simeq 3$) and $\tau = 0$ ($\langle n_d\rangle \simeq 2$) respectively. Thus, in the O(6) limit the strongest L = 0 transitions would be the ones populating the ground state and <u>second</u> excited 0^+. This is indeed what is seen experimentally as shown in Table V. For the reactions in this study the second excited 0^+ state is more strongly populated except for the 1479 keV level in ^{194}Pt. However, the 1479 level in ^{194}Pt may not be a collective state, but could be of single particle nature,[59] since it lies near the pairing gap for the Pt nuclides ($2\Delta \simeq 1500$ keV).

The stronger population of the second excited 0^+ state relative to the first in Pt(p,t) reactions has not been satisfactorily explained by any other model. The results of calculations using the $T_{+\nu}^{(0)}$ operator given above are shown in Table V. The strengths are calculated in the O(6) limit with a small quadrupole-quadrupole boson interaction which breaks the pure O(6) symmetry and accounts for the changing properties of these nuclei as the O(6) to rotor transition progresses. These calculations also reproduce the increasing strengths for the ground state to ground state transitions as A decreases, a trend which extends to the ^{190}Pt(p,t)^{188}Pt reaction as well.[60]

For the L = 2 transitions the operator becomes somewhat more complex as a change in seniority of 0, ±2 is allowed. The L = 2 operator can be expressed as[59]

$$T_{+\nu}^{(2)} = (\alpha_\nu d_\nu^\dagger + \beta_\nu [d_\nu^\dagger d_\nu s_\nu^\dagger]^{L=2} + \gamma_\nu [d_\nu^\dagger d_\nu d_\nu]^{L=2})\, A$$

where the change in seniority for each term is +2, 0, –2 respectively. Here α_ν, β_ν, and γ_ν are relative strength factors for each coupling of s and d bosons and A is a finite dimensionality factor similar to that for $T_{+\nu}^{(0)}$. Calculations have been carried out[58] using only the first and second terms of this operator with β_ν chosen to be 0.08. The results are shown in Table V. The governing selection rule is $\Delta\tau = +1$, which would allow only the population of the lowest of the first three 2^+ levels in the strict O(6) limit, since the ground state wavefunction has $\tau = 0$ and the first 2^+ state has $\tau = 1$, while 2_2^+ has $\tau = 2$ and 2_3^+, $\tau = 4$. The addition of the small symmetry breaking term will allow some population of the other 2^+ levels as well due to the mixing of the wavefunctions.

For relative populations within a nucleus, the general agreement of the IBA model calculations for the L = 2 transitions is very reasonable, but the calculation does not predict the proper trends from one nucleus to the next. For example, the model predicts a virtually constant 2_1^+ population while experimentally the 2_1^+ state population increases almost twofold from ^{192}Pt to ^{196}Pt. The calculations also predict a decrease in strength for populating the second 2^+ as A increases, while experimentally one observes a constant strength. Calculations are currently underway to adjust the sign and magnitude of β_ν and γ_ν to reproduce the experimentally observed trends as a function of A. It should be noted that the small values calculated for the higher L = 2 transitions may have rather large uncertainties, as higher order terms not included in $T_{+\nu}^{(2)}$ may then have a non-negligible contribution.

C. L = 4 Transitions

Although the IBA provides an adequate first order description of L = 0 and L = 2 transitions, an extension of this method to describe L = 4 transitions has not yet been carried out. Thus, an IBA interpretation of the transitions populating the 4^+ levels in ^{192,194,196}Pt is not available.

There is an example of another strong L = 4 transition, similar to those observed in this work, which was seen with 40% of the ground state transition strength[61] in the ^{204}Hg(p,t)^{202}Hg reaction at $E_p = 17$ MeV. It has been noted by Breity <u>et al.</u>[62] that DWBA calculations seem to indicate large in <u>phase</u> ($2p_{3/2} \otimes 1f_{5/2}$) and ($1f_{7/2} \otimes 2p_{1/2}$) neutron components in the transfer form factor. By using the ^{206}Pb 4_2^+ wavefunction of Vary and Ginocchio[63] with the ($1f_{7/2} \otimes 2p_{1/2}$) amplitude enhanced by a factor of 2 to 3, the cross section for the 4_2^+ state surpasses that of the first 4^+. In the present study these same two configurations provided the greatest calculated strengths for all $L = 4$ transitions and the $(2p_{3/2} \otimes 1f_{5/2})$ configuration was used in calculating the enhancement factors. The suggestion that the lack of large 4^+ cross sections in the lighter Hg isotopes may be due to a depletion of the $2p_{1/2}$ orbital may apply to the lighter Pt nuclides as well. Since these nuclides are farther away from the $N = 126$ shell closure, decreasing occupancy of the $1f_{5/2}$ orbital now becomes a factor rather than the $2p_{3/2}$ orbital. Thus, this same effect may explain the generally decreasing strength of the 4^+ levels as A decreases (see Table V).

One possible explanation for the 4_3^+ levels may be that they are the bandhead for the $K = 4$ component of the 2-phonon γ vibrations of the symmetric rotor. These states are also seen in Os(p,t) studies of Ref. 41 at an energy near 1.2 MeV. There are problems with this interpretation for the Pt isotopes though, as the energy ($\simeq$1.9 MeV) is much too high for the Bohr-Mottelson vibrational picture mentioned above. The energies are only slightly better explained in the triaxial rotor model, where they can be determined from the sum rule

$$\sum_{i=1}^{3} E(4_i^+) = 5E(3^+) \quad ,$$

giving $E(4_3^+) \simeq 2.5$ MeV in the Pt isotopes. However, additional problems arise from this interpretation due to the strengths of the 4^+ transitions in ^{196,198}Pt(p,t). Because (p,t) transitions to 2-phonon states are forbidden to first order in a pure vibrational model, such states should be only weakly populated as a result of multistep effects and anharmonicities in the vibrational potential. In the Cd region,[52] the population of 2 phonon states is typically 1–5% of the ground state population. Similarly, in Os(p,t) the strength of the 4^+ transition is $\simeq$1–2% of the ground state. However, in ^{196,198}Pt(p,t) the strength of this 4_3^+ transition is $\simeq$15% of the ground state while only in ^{194}Pt(p,t) is it as low as 1% of the ground state strength. Thus, a uniformly simple interpretation of the $K^\pi = 4^+$ bandheads as γ vibrational states in the ^{192,194,196}Pt isotopes seems questionable.

Recently, Bagnell et al.[64] have argued from calculations explaining the strength of the 4_3^+ states in the ^{191,193}Ir(t,α)^{190,192}Os reactions that these states could be described as single phonon hexadecapole vibrations in the Os isotopes. This interpretation is also used to describe these states as seen in a recent (α,α') experiment.[65] It is probable that these 4_3^+ states have both two γ-phonon and hexadecapole vibrational components. In ^{194,196}Pt the strength of the $L = 4$ (p,t) transition may indicate a substantial hexadecapole component. These same states are also observed in the (p,p') reaction[52] with considerable strength.

Such apparent dissimilarities between shape-transitional Os and Pt isotopes are perhaps not so surprising, however. Casten et al.[66] have noted in a recent letter that the prolate-oblate shape transition in Os isotopes apparently occurs rather definitively near ^{192}Os, so that ^{194}Os displays identifiable oblate shape characteristics. The even-A Os isotopes $A \leq 190$ studied in (p,t) reactions are still manifestly prolate in character. In contrast, the γ-soft or perhaps triaxial character of the Pt shape transition is already evident[67] in ^{188}Pt, and seemingly persists at least through ^{196}Pt with little evidence for a well developed oblate, rotational system. In view of these considerations, it is perhaps unreasonable to expect parallel behavior in (p,t) reaction patterns in Pt and Os isotopes.

VII. SUMMARY

The angular distributions for most transitions populating levels below 2 MeV in the ^{194,196,198}Pt(p,t) reactions at 35 MeV have been measured. A DWBA analysis was performed for each reaction and enhancement factors were calculated. The DWBA calculations along with empirical shapes from this study allow several new spin assignments to be suggested. No new 0^+ states below 1 MeV were observed in any of the reactions studied, however, and no strong $L = 0$ transfers to excited states were seen. The latter observation can be regarded as consistent with the expected γ softness of these nuclei. A new 0^+ level was found at 1.628 MeV in ^{192}Pt, and new levels near 1.9 MeV are tentatively assigned as 4^+ in each residual isotope. These 4^+ states are populated with increasing (p,t) strength as a function of A, until in ^{196}Pt the strength is 15% of the ground state strength at 7°. The transition populating the second 4^+ level in each nucleus is also quite strong, and in ^{198}Pt(p,t), the strength to the 4_2^+ level is about 10 times that populating the 4_1^+ level. The character of these strongly populated 4_2^+ and 4_3^+ states is still not well understood and needs further study.

Finally, and perhaps most important, we note that the O(6) limit of the IBA model of Arima and Iachello provides a qualitative explanation of $L = 0$ and $L = 2$ (p,t) strengths, particularly the observation that the second excited 0^+ state is populated more strongly than the first excited 0^+ state in each reaction. It is planned to combine the (p,t) data reported here with Pt(p,p') data[52] recently obtained in our laboratory to provide further significant tests of the O(6) limit of the IBA model in this mass region.

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