Negative parity states of even-A Pt isotopes from proton inelastic scattering

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Negative parity states of ^{194,196,198}Pt are studied via the analysis of previously reported (p,p') data. The results suggest that two-quasiparticle configurations built on the nonexcited core play significant roles in the 7_1^- states, as predicted by the semidecoupled model and suggested by electron-capture data. It is also found that the 3_1^- states can be understood in an octupole vibrational picture. The latter result highlights an anomaly in the behavior of octupole states in the Pt-Hg region.

I. INTRODUCTION

High-spin negative parity states of even-A Pt and Hg isotopes have been explained by Toki *et al.*[1] in terms of the "semidecoupled" model. In this model, the negative parity states are composed of two-quasiparticle ($2qp$) configurations coupled to collective excitations of the core as well as $2qp$ configurations built on the ground state of the core. The presence of core-excited components in the negative parity states is experimentally supported[1] by the observation of collective $E2$ transitions of 30–40 Weisskopf units (W.u.) between these states.[2–9]

To date, the principal source for evidence that core ground-state configurations play a significant role in the negative parity states has been the data of Petry *et al.*[10] on the electron-capture decay of the 7^+ isomers of even-A Tl isotopes. These investigators found that the first forbidden transitions from isomers of ^{192,194,196,198}Tl to 7_1^- states of Hg daughters are favored over allowed decays to 6_1^+ states. They suggested an explanation for this observation based on the assumption of $\nu(i_{13/2}^{-1}p_{1/2})$ structure for the daughter 7_1^- states. If the 7^+ isomers of the parent nuclei have $\nu i_{13/2}\ \pi s_{1/2}$ structure, then decay to the 6^+ states of the daughters would require highly hindered $\pi s_{1/2}\rightarrow\nu i_{13/2}$ transitions while the decay to a $\nu(i_{13/2}^{-1}p_{1/2})$ $J^\pi=7^-$ state would go via the slightly hindered $\pi s_{1/2}\rightarrow\nu p_{1/2}$ transition.

The $2qp$ configurations that could provide core ground-state contributions in Pt and Hg can be partially determined from the structure of the even-A Pb isotopes. Since the excitation energies[11] of 7_1^- states of Pb are, on the average, about 400 keV above those of the Hg isotones and 700 keV above the energies of Pt isotones, the $\nu(i_{13/2}^{-1}p_{1/2})$ configuration, which plays the largest role in the Pb 7_1^- states[11–15] should also be admixed substantially into 7_1^- states of Hg and Pt. In addition, the $\pi(h_{11/2}^{-1}d_{3/2})$ configuration, which is not available to the Pb isotopes, might also be expected to contribute in Hg and Pt. Regarding this last point, it should be noted that Toki's calculation[1] predicted that 25% of the 7^- state in ^{190}Pt consisted of the $\pi(h_{11/2}^{-1}d_{3/2})$ configuration, while less than 21% resides in all of the neutron $2qp$ configurations.

Measurements of the lifetimes of such states [which yield $B(E2)$ matrix elements between excited states] cannot help identify such configurations. Electron-capture decays indicate the presence of particular configurations, but depend somewhat on knowledge of the parent nucleus. Inelastic scattering provides independent information on the relative importance of proton and neutron configurations which connect directly to the ground state, as well as others that enter via coupled channels.[16–18] In this work, we examine previously reported proton inelastic scattering data[19] for Pt to investigate its potential for use in studying the structure of the Pt isotopes. Section II will focus on the 7^- states, specifically the implications of 35 MeV (p,p') data for the 7_1^- state of ^{196}Pt.

One apparent failure of the semidecoupled model is its inability to predict the energies of octupole states in ^{198,200}Hg. In fact, the behavior of octupole states in this region is highly anomalous and seems to present an interesting theoretical challenge. In Sec. III, matrix elements for excitation of the 3_1^- states of ^{194,196,198}Pt will be extracted from the same data[19] and discussed in terms of the anomalous systematic behavior of 3_1^- states in the $Z=78-82$ region.

II. STUDY OF 7_1^- STATE OF ^{196}Pt

In this section, we will examine the proton inelastic scattering data of Deason *et al.*[19] for the excitation of the 7_1^- state of ^{196}Pt in the context of simple hypothetical configurations which resemble those used in the semidecoupled model. The first set consists of couplings of other low-lying states having $J<7$ (corresponding to $2qp$-excited core configurations) to the g.s. and the 7^- state. A state composed entirely of these configurations would be excited via processes of two steps or more. The second set consists of the shell-model particle-hole states $\pi(h_{11/2}^{-1}d_{3/2})$ and $\nu(i_{13/2}^{-1}p_{1/2})$. Because of the shell struc-

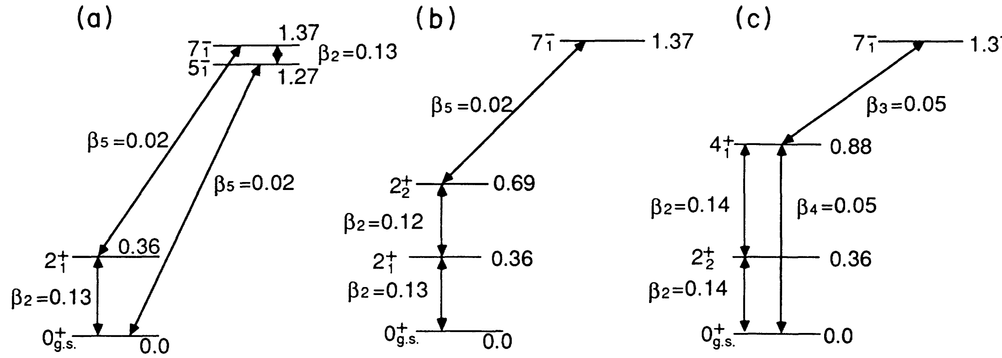

FIG. 1. Coupling schemes used in the coupled channels calculations described in the text. Panels (a), (b), and (c) correspond to 7_1^- state configurations of $5_1^-\otimes 2_1^+$, $5_1^-\otimes 2_2^+$, and $3_1^-\otimes 4_1^+$, respectively. Strength parameters β_L were determined as described in the text.

ture of this region, we would expect that these shell-model states would correspond to the $2qp$ configurations most important in the direct excitation of the 7_1^- states via $2qp$-core ground-state components.

A. Investigation of core-excited configurations

The excitation of core-excited components of the 7_1^- state via multistep processes was investigated using coupled channels calculations with collective form factors assuming pure coupled-state configurations for the 7_1^- state. The configurations considered here are $5_1^-\otimes 2_1^+$, $5_1^-\otimes 2_2^+$, and $4_1^+\otimes 3_1^-$. These couplings are all those of the form $J_1^\pi\otimes J_2^\pi$ among known states J_1^π and J_2^π for which the excitation energies $E(J^\pi)$ obey[6]

$$E(J_1^\pi)+E(J_2^\pi)<2.4 \text{ MeV} .$$

This would seem to be a reasonable constraint since $E(7_1^-)=1.37$ MeV. In addition, these are representative of some of the core-excited components in the wave function of Toki *et al.*[1] Coupled channels calculations of cross sections for two-step excitations of the 7_1^- state assuming each of the three-coupled configurations were performed with the computer code CHUCK,[20] the Becchetti-Greenlees optical potential[21] and coupling strengths extracted from data on direct excitations.

The three coupling schemes are illustrated in Fig. 1; the strength parameters β_L for the $E2$, $E3$, $E4$, and $E5$ excitations are listed in this figure as well. The β values, which are defined for the usual collective transition potential $\beta_L\ \partial U_{\text{opt}}/\partial r$, were taken from fits to the data of Deason *et al.*[19] excluding the coupling to the 7_1^- state.

As illustrated in Fig. 2, the calculation corresponding to the $4_1^+\otimes 3_1^-$ configuration seriously underpredicts the 7_1^- state cross section. Therefore, it can be inferred that the 7_1^- state of ^{196}Pt does not arise from coupling of the 3_1^- state. This finding lends direct experimental support to the theoretical conclusions reached by Toki *et al.*[1] as well those of Engel,[22] who examined negative parity states in several Pt isotopes in the context of an interacting-boson-approximation–(IBA) based model using an f boson to represent an octupole phonon. Engel concluded that while the observed behavior of $J\leq 4$ negative parity states in ^{190,192,194,196}Pt could be well reproduced with the f boson model, states of higher spin seemed not to be of the octupole type.

Figure 2 also reveals that the calculation based on the $5_1^-\otimes 2_1^+$ coupling does not reproduce the observed cross sections, although it does demonstrate that such core-excited components cannot be neglected. The second 2^+ state is seen to play no role in excitation of the 7_1^- state. None of these specific configurations can reproduce the experimental data, indicating the need for additional components in the wave function, as expected from Ref. 1.

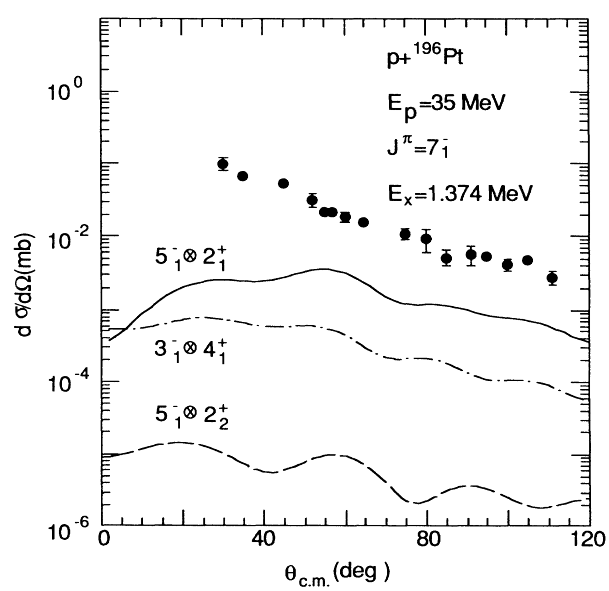

FIG. 2. Coupled channels calculations for proton inelastic scattering from ^{196}Pt at $E_p=35$ MeV compared to data for the $E_x=1.374$ MeV 7^- state from Ref. 19. The solid, dashed, and dash-dot curves correspond to the configurations shown in panels (a)–(c) of Fig. 1, respectively.

B. Investigation of core ground-state configurations

Direct population of the 7_1^- state can occur via the excitation of $2qp$-core ground-state contributions. This possibility was investigated for ^{196}Pt in the distorted wave approximation (DWA) using distorting potentials generated from the Bechetti-Greenlees optical model (BGOM) parameters.[21] The transition amplitudes were all calculated using harmonic oscillator wave functions with an oscillator constant $\alpha=0.414$; it might be better to use Woods-Saxon wave functions consistent with other scattering data if we were concerned with checking more than the order of magnitude of these effects. The calculations treat projectile-target antisymmetrization in the zero-range exchange approximation (ZREA) using the asymptotic wave number.[16,23] A density-dependent effective interaction[24] is used in the local density approximation (LDA) applied at the projectile position.[25] The calculations made use of the programs ALLWRLD (Ref. 26) and TAMURA.[27]

In this model, the contributions to the differential cross section for natural parity transitions of $0^+ \to J^\pi$ can be conveniently summarized with the schematic plane wave born approximation (PWBA) formula

$$\frac{d\sigma}{d\Omega}=4\pi\left[\frac{\mu}{2\pi\hbar^2}\right]^2(2J+1)(\,|t_m\rho_J^m|^2+|t_{ls}\rho_J^{ls}|^2+I_{m,ls}+|t_{s\perp}\rho_j^s|^2+|t_l\rho_J^{l\perp}|^2+I_{s,l\perp}) \tag{1}$$

given in Ref. 28, where μ is the relativistic reduced mass, the ρ_J^α are nuclear transition densities obtained from the matrix element of tensor operators of character α and rank J between initial and final target wave functions (schematically $\langle \text{e.s.}\|\mathcal{T}_J^\alpha\|\text{g.s.}\rangle$ where e.s. is the excited state and g.s. is the ground state), the t_α are combinations (defined in Table 1 of Ref. 28) of the usual central, tensor, and spin-orbit components of the effective nucleon-nucleon interaction and factors from the PWBA distortion functions that couple solely to a particular ρ^α, and the $I_{\alpha\beta}$ are interference terms. The sums over charge indices and dependence on momentum transfer are suppressed for convenience. The "t_ρ" form of this equation is representative of the folding model used here, although distortion and the LDA destroy this simple relationship in realistic calculations. It also demonstrates what is involved in any attempt to determine a transition density from experimental data, making evident the fact that, even in the simplest cases, no single probe can be used to fully characterize any part of the nuclear wave function.[28] The discussion in the introduction can be put in this language by noting that the $B(E2)$ transition rates give information on $\langle 5^-\|\mathcal{T}_2^m\|7^-\rangle$, while scattering gives information on $\langle 7^-\|\mathcal{T}_7^m\|0^+\rangle$. Scattering also gives information on $\langle 7^-\|\mathcal{T}_2^m\|5^-\rangle$ and $\langle 5^-\|\mathcal{T}_5^m\|0^+\rangle$, etc., when coupled channels are included as in the previous section.

These exploratory calculations examine only the one-step process using two typical configurations, pure $\nu(i_{13/2}^{-1}p_{1/2})$ and pure $\pi(h_{11/2}^{-1}d_{3/2})$, for comparison. Results are shown in Fig. 3. Both give fair agreement with the data except at forward angles, which is typical at this energy. Some possible deficiencies in our results are that important nonlocalities are neglected whose effects can be large, especially for higher multipoles,[29] and our wave functions are crude, probably overestimating the resulting cross section.

Two other observations should also be made. The neutron configuration is strong because proton probes are particularly sensitive to neutrons at low bombarding energies.[30] Other neutron configurations give comparable strengths so even small admixtures could be important if they come in coherently. Second, only 30% of the strength associated with the proton configuration is due to its matter density. The remainder comes from the diagonal spin (ρ^s) term in Eq. (1). This means that it would be incorrect to model this proton configuration by simply adding a direct $E7$ collective model piece within a standard coupled channels code, since such calculations only include the matter (ρ^m) contribution. (It could be reasonable for the neutron configuration, which lacks the strong spin component, provided the coupling correctly represents the proton-neutron interaction strength.) It also means that the transverse-electric form factor in electron scattering might show whether a $\pi(h_{11/2}^{-1}d_{3/2})$ component is present and, in addition, be used to adjust the magnitude of the spin density which enters the nucleon scattering calculation.

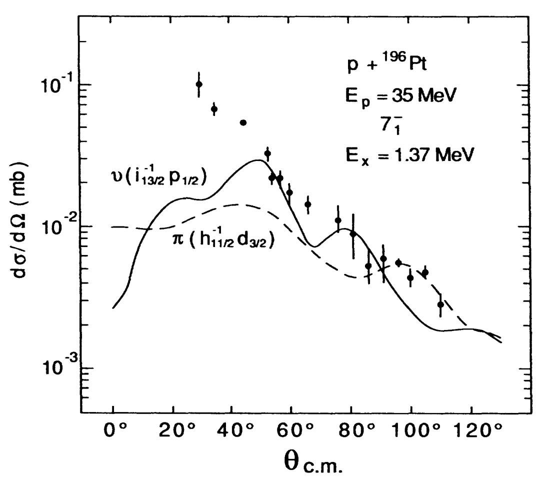

FIG. 3. Microscopic calculations for proton inelastic scattering from ^{196}Pt at $E_p=35$ MeV with pure proton $(h_{11/2}^{-1}2d_{3/2})$ and neutron $(i_{13/2}^{-1}3p_{1/2})$ configurations shown with dashed and solid curves, respectively. Data for the $E_x=1.374$ MeV 7^- state are from Ref. 19.

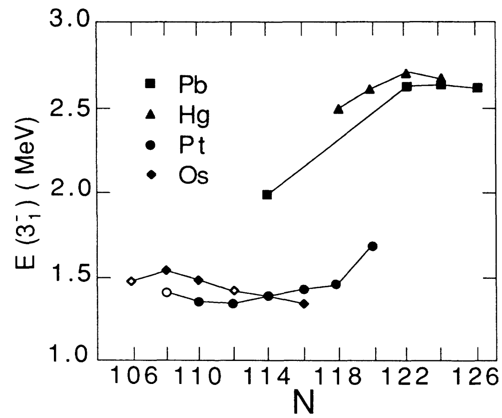

FIG. 4. Systematic behavior of 3_1^- states of Os, Pt, Hg, and Pb nuclei from Refs. 32 and 33.

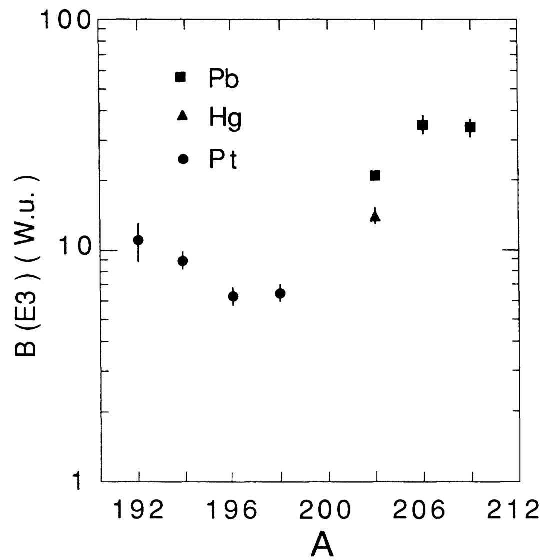

FIG. 5 Reduced matrix elements $B(E3;0^+_{\mathrm{g.s.}}\rightarrow 3_1^-)$ for Pt, Hg, and Pb from Refs. 39–42 and this work.

C. Discussion of 7_1^- states

The results that we have presented are generally consistent with the conclusions of Toki *et al.*[1] that significant contributions from 2*qp*-core ground-state configurations are found in the calculated wave functions of the 7_1^- states of ^{190}Pt and ^{192}Hg. The proton scattering data might present rigorous tests for the detailed content of the wave functions, but it will be necessary to formulate a fully microscopic coupled channels code that includes the effects of exchange to properly investigate the full content of the "semidecoupled" wave function proposed in Ref. 1. These tests are complementary to those presented by gamma-ray data, particularly measurements of $B(E2)$ values connecting the 7_1^- states with nearby 5^- and 9^- states. Taken together, these "probes" suggest that both excited and nonexcited core states might play significant roles. More careful theoretical study, and possibly electron scattering and intermediate energy proton scattering data, seem warranted.

III. 3_1^- STATES OF ^{194,196,198}Pt

The most apparent failure of the semidecoupled model is its severe underprediction of the excitation energies of the 3_1^- states of ^{198,200}Hg. Several single-particle orbitals had to be included by Toki *et al.*[1] in their study of the Pt and Hg isotopes specifically to reproduce the octupole vibrational character of 3_1^- states in even-A Pt isotopes. When the octupole states of ^{198,200}Hg were observed several years later,[31] they were found almost 1 MeV higher than both the corresponding states in the Pt isotones and the energies predicted by Toki *et al.* The energies[32,33] of presently known octupole states in Pt and Hg, as well as those of Os and Pb, are shown in Fig. 4.

TABLE I. β_3 and $B(E3;0^+_{\mathrm{g.s.}}\rightarrow 3_1^-)$ values for ^{194,196,198}Pt.

	β_3[a]	$B(E3;0^+_{\mathrm{g.s.}}\rightarrow 3_1^-)$ (W.u.)
^{194}Pt	0.059	8.7±0.6
^{196}Pt	0.050	6.2±0.6
^{198}Pt	0.050	6.2±0.6

[a]Values have errors of ±0.002.

The systematic behavior which is displayed in Fig. 4 is, in fact, unique: the discontinuity which occurs between $Z=78$ and 80 cannot be seen in any other region of the periodic table[34–36] above $Z=20$. Khan and Yates[37] assert that this discontinuity supports a nonoctupole interpretation for the 3_1^- state of ^{198}Pt. However, our analysis of the data of Deason *et al.*[19] seems to support a collective octupole picture for the 3_1^- states of ^{194,196,198}Pt. Fits of the Deason data using the DWBA and Becchetti-Greenlees optical model[21] yield the values for β_3 listed in Table I. The values for $B(E3;0^+_{\mathrm{g.s.}}\rightarrow 3_1^-)$ listed in Table I are derived from the prescription of Ref. 38. Results of these calculations are shown in Fig. 5 along with results[39–41] on ^{204,206,208}Pb, ^{204}Hg and the Coulomb excitation result for ^{192}Pt from Ronningen *et al.*[42] In the latter study, a value for ^{194}Pt was also extracted; their result, 8±2 W.u., is in agreement with ours. These Pt $B(E3)$ values are not far below the 14 W.u. matrix element[39] measured for ^{204}Hg (no other values have been extracted for Hg isotopes).

The anomalous behavior of 3_1^- state excitation energies may be indicative of large differences in shell structure between the Pt and Hg isotopes. It has been observed that the excitation energies of the particle-hole (or 2*qp*) configurations which compose octupole states depend on the spacing of the single-particle levels involved. Therefore, the energy of the 3_1^- state itself would depend on these spacings. If they changed strongly with a variation of Z, a discontinuity in $E(3_1^-)$ could result.

As mentioned earlier, Engel[22] was able to reproduce the behavior of $J\leq 4$ negative parity states of ^{190,192,194,196}Pt using an IBA-based model with an f boson, which represents an octupole phonon. His work demonstrates that the Pt 3_1^- states can be understood within an octupole framework.

IV. CONCLUSIONS

In this work, we have studied the origin of 7_1^- and 3_1^- states of ^{194,196,198}Pt via the analysis of the 35 MeV (p,p') data of Deason *et al.*[19] The data suggest that $2qp$-core ground-state configurations might play an important role in the 7_1^- states of Pt isotopes, as proposed by Toki *et al.*[1] Furthermore, the data support an octupole phonon interpretation for 3_1^- states of ^{194,196,198}Pt. The anomalous behavior of 3_1^- states in the Pt-Hg region may, therefore, indicate a significant change in shell structure between the Pt and Hg isotopes.

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