Fragmentation of octupole strength in even-A Pt isotopes

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It is proposed that certain states of undetermined spin and parity observed in previously reported ^{198}Pt$(p,p'\gamma)$ and ^{194,196,198}Pt(p,p') experiments are 3^- states and contain a significant amount of octupole strength. These results show that the octupole strength is fragmented in the Pt isotopes. The predictions of Engel for the distribution of octupole strength in Pt isotopes are compared to the strengths obtained from (p,p'). Furthermore, an explanation for the anomalous behavior of 3_1^- states in the Pt-Hg region is proposed.

I. INTRODUCTION

The properties of many low energy octupole states throughout the Periodic Table have been successfully analyzed[1,2] with the use of models such as the random phase approximation (RPA). In particular, the RPA approach has yielded an understanding of 3_1^- states in spherical nuclei such as ^{208}Pb and can account for the fragmentation of octupole strength in well deformed nuclei, such as those found in the rare-earth region. More recently, other approaches, such as the interacting boson approximation (IBA), have been applied[3–8] to the analysis of octupole states.

One challenge encountered in such analyses is to describe the transition from a situation in which octupole strength is concentrated in a single state (as in spherical nuclei) to the fragmented strength picture associated with deformed nuclei. In order to characterize the transition occurring between the spherical region near ^{208}Pb and the deformed region more completely, it is quite useful to analyze the situation in the $A\approx 196$ Pt isotopes, which clearly have a quadrupole collective character, but are not rigid rotors.[9] Furthermore, the systematic behavior of 3_1^- states in the Pt isotopes appears[10–12] to be quite anomalous when compared to behavior in other regions of the Periodic Table: there is a 1 MeV difference between the excitation energies of the 3_1^- states of Pt and those of Hg. The recent observation[13] of a possible 3^- state in ^{198}Pt 1 MeV higher than the 3_1^- state via a $(p,p'\gamma)$ experiment suggests that significant fragmentation of octupole strength may indeed occur in the transitional Pt isotopes. If such fragmentation indeed occurs, it would have significant implications for the understanding of octupole states in transitional nuclei, and might provide clues to questions regarding the unique behavior of 3_1^- states in this region.

In the present work, we analyze previously reported[14] proton inelastic scattering data for evidence that significant octupole strength is located in states other than the single 3^- states presently known in each of the isotopes ^{194,196,198}Pt. In Sec. II, we present the experimental evidence that other 3^- states exist in these nuclei, and discuss our findings in the context of the IBA calculations for octupole states in Pt performed by Engel[6] and the semidecoupled model of Toki, Neergard, Vogel and Faessler.[15] The question of the anomalous behavior of 3_1^- states in Pt isotopes is addressed in Sec. III, and Sec. IV contains a summary of this work.

II. ANALYSIS OF DATA AND COMPARISON TO THEORY

In this section, we use the 35 MeV (p,p') data of Deason *et al.*[14] for evidence of octupole strength fragmentation in ^{194,196,198}Pt. Deason *et al.*[14] concentrated their analysis on the positive parity states in order to test IBA predictions for these states. However, they also populated a number of other states for which no spin assignments were made and classified these states according to the shapes of their angular distributions. One such class of states was characterized by minima at 40 degrees and maxima at 50 degrees.

Quite recently, Yates *et al.*[13] studied ^{198}Pt via the $(p,p'\gamma)$ reaction at a beam energy of 12 MeV. They established the existence of a state at 2603 keV that γ decayed exclusively to the 1680 keV 3_1^- state by means of the observation of a 923 keV γ ray in coincidence with protons of the appropriate energy to populate such a state. Because of the prompt nature of the γ ray, the possible spins of the newly observed state are $J=0-5$. Furthermore, it was noted by Yates *et al.*[13] that this state seems to correspond to one of the most strongly populated states (assigned a energy of 2611 keV) in the 35 MeV (p,p') experiment of Deason *et al.* (For the remainder of this article, we shall identify this state as the 2603 keV state.) This observation suggests that the state is populated directly by means of a collective mechanism, such as a quadrupole, octupole, or hexadecapole excitation. Yates *et al.*[13] suggested that all of this evidence is consistent with a 3^- assignment.

The proposed 3^- assignment for the 2603 keV state can be checked with distorted-wave Born approximation (DWBA) calculations if one assumes a one step excitation mechanism. The lack of a decay to the ground state, 2_1^+ or 2_2^+ states makes the 0^+ and 1^- assignments highly unlikely; consequently, only $L=2$, 3, 4, and 5 DWBA calculations were performed. The results of the calculations, for which the computer code CHUCK[16] was used, are compared to the experimental angular distribution in Fig. 1. The $L=2$ and 4 curves are clearly out of phase with the experimental angular distribution. Furthermore, the $L=3$ curve matches the features at 40 to 50 degrees considerably better than the $L=5$ curve. Finally, the size of the cross section is consistent with collective octupole nature. We therefore confirm the $J^{\pi}=3^-$ tentative assignment of Yates *et al.* for the 2603 keV state of ^{198}Pt.

It can be seen from inspection of the data of Deason *et al.* that the angular distributions of states at 2154, 2246, and 2543 keV in ^{194}Pt, 2431, 2608, 2638, and 2707 keV in ^{196}Pt, and 2441, 2514, 2796, and 2826 keV in ^{198}Pt all bear strong resemblances to that of the state under discussion here. Therefore, it is reasonable to assign $J^{\pi}=3^-$ to this entire class of states. DWBA calculations assuming $L=3$ for these states are shown in Figs. 2–4.

Extracted values for β_3 and $B(E3;0^+_{\rm g.s.}\to 3^-_1)$ are listed in Table I and demonstrate significant fragmentation of the octupole strength. In fact, the 2603 keV state of ^{198}Pt is populated more strongly than the 3^-_1 state in that nucleus.

In discussing the origins of the apparent octupole fragmentation in the Pt isotopes, it is quite important to notice that the distribution of strength into states corresponding to different K values cannot by itself account for the observed fragmentation. Only four K values are available to an octupole phonon; however, there are five states having a significant amount of octupole strength in ^{196}Pt and six such states in ^{198}Pt. This additional fragmentation probably arises from the mixing with 3^- states having the structure of two quasiparticles coupled to rotational excitations of the nucleus. Such states are treated in the "semidecoupled" model of Toki *et al.*[15] Although Ref. 15 does not explicitly discuss the distribution of octupole strength, it does illustrate how "semidecoupled" two-quasiparticle rotational states can mix with low-lying octupole states.

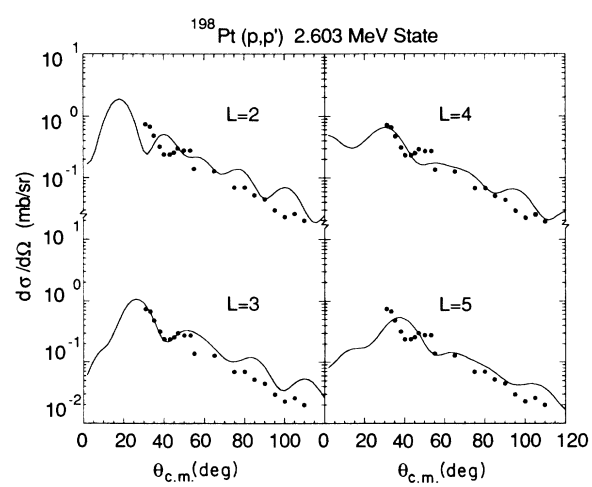

FIG. 1. A comparison of angular distributions calculated with the DWBA for $L=2$, 3, 4, and 5 with the data of Deason *et al.* (Ref. 14) for the 2.603 MeV state of ^{198}Pt.

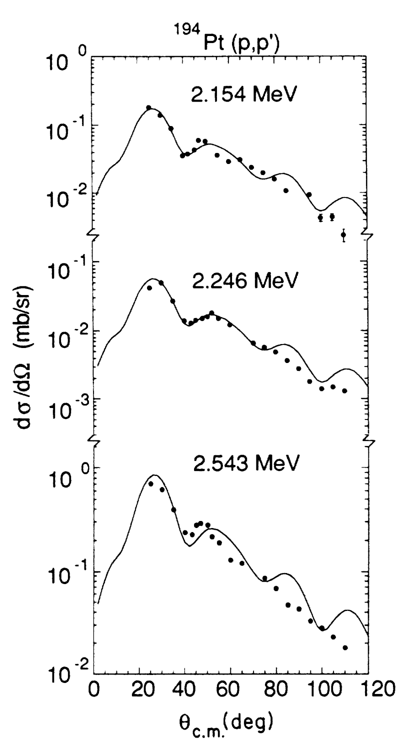

FIG. 2. The data of Deason *et al.* (Ref. 14) for proposed 3^- states of ^{194}Pt, and calculated DWBA curves for $L=3$.

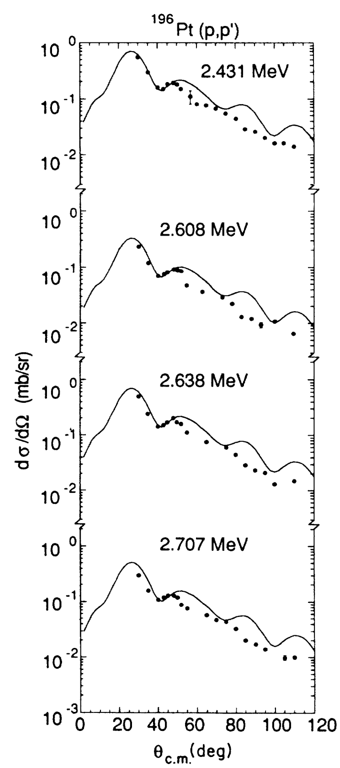

FIG. 3. Data of Deason *et al.* (Ref. 14) for proposed 3^- states of ^{196}Pt, and calculated DWBA curves for $L=3$.

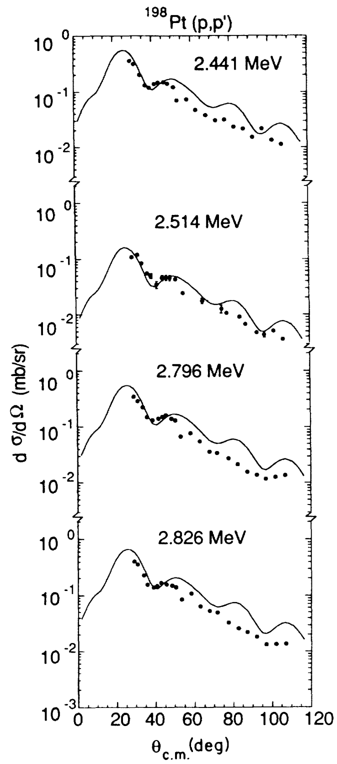

FIG. 4. Data of Deason *et al.* (Ref. 14) for proposed 3^- states of ^{198}Pt, and calculated DWBA curves for $L=3$.

Engel[6] described the negative parity states of ^{190,192,194,196}Pt with an IBA-based model in which an f boson is coupled to the usual s and d bosons in the 0(6) analytic limit of the IBA, which is the limit that represents a γ unstable or triaxial nucleus. Despite the fact that his model did not account for the presence of states of the "semidecoupled" type, Engel did predict significant octupole fragmentation. A comparison of Engel's predictions for the distribution of octupole strength to the experimental data is shown in Fig. 5. It is important to note that this model is specifically tailored to the transitional nature of the Pt nuclei, and that the fragmentation result does not rely upon the assumption of a well deformed shape. Therefore, we may conclude that significant fragmentation of the low-energy octupole strength can occur in a transitional nucleus, and that such a phenomenon can be understood in the context of present models.

TABLE I. Results for ^{194,196,198}Pt (p,p') to 3^- states. Results for 3_1^- states are taken from Ref. 21.

Nucleus	E (MeV)[a]	β_3[b]	$B(E3)$[c] (W.u.)
^{194}Pt	1.432	0.059	8.7
	2.154	0.021	1.1
	2.246	0.012	0.4
	2.543	0.047	5.5
^{196}Pt	1.447	0.050	6.2
	2.431	0.042	4.4
	2.608	0.029	2.1
	2.638	0.042	4.4
	2.707	0.036	3.2
^{198}Pt	1.682	0.050	6.2
	2.441	0.037	3.4
	2.514	0.020	1.0
	2.611	0.052	6.7
	2.796	0.037	3.4
	2.826	0.041	4.2

[a] Energies correspond to those assigned in Ref. 14.
[b] Errors of 10% are assumed.
[c] Calculated via method I of Ref. 17. Errors are ±20%.

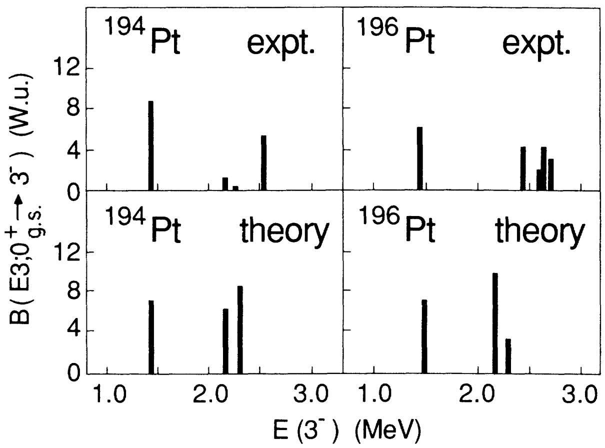

FIG. 5. Comparison of distributions of octupole strength in ^{194,196}Pt to those predicted by Engel (Ref. 6).

III. SYSTEMATIC BEHAVIOR OF 3^- STATES FOR $Z=78-82$

It has been noted elsewhere[10–12] that the systematic behavior of 3_1^- states in the $Z=78-82$ region is anomalous. The energies of these states [which we write as $E(3_1^-)$] are nearly constant at about 2.6 MeV as a function of N and Z in the $N>118$ Hg and $N>122$ Pb isotopes. However, the 3_1^- states in the stable Pt isotopes ($N=112-120$) are located in the range 1.4–1.6 MeV, 1 MeV below the corresponding states in Hg. Such a discontinuity cannot be observed[12,18–21] in any other region of the Periodic Table with $A>16$. One explanation advanced for this anomaly[13] is that the 3_1^- states of the Pt isotopes are not octupole states, but are instead composed entirely of two-quasiparticle states coupled to rotational excitations of the nuclei. However, such an explanation cannot account for the large $B(E3;\,0^+_{\rm g.s.}\rightarrow 3_1^-)$ values observed.[21]

One possible resolution to this problem is suggested by the apparent concentration[22] of octupole strength at energies of 2.6 MeV in both Pb and Hg nuclei. Since the octupole strength is fragmented in Pt it may be more appropriate to consider the "center of gravity" of the octupole strength when examining the experimental data for smooth trends which may be interpreted in a simple way. The concept of center of gravity has long been used for the location of single-particle orbitals via single nucleon transfer reactions.[23] In such studies, a number of states containing components of a particular single particle orbit are identified by the angular distributions of their corresponding ejectiles. The "amount" of a single particle orbit j located in a state i is given by the spectroscopic factor S_{ij}, which is determined from the cross section for the transfer reaction. The energy of a single-particle orbit is then given by the "center of gravity" of the component states by the expression

$$c_g = \frac{\sum_i E_i S_{ij}}{\sum_i S_{ij}} ,$$

where E_i is the energy of state i. In order to draw an analogy with the stripping picture, we replace the spectroscopic factor by the $B(E3;\ 0^+_{\text{g.s.}} \to 3^-)$ value. Therefore, for calculating the center of gravity of the octupole states in Pt, we have

$$c_g = \frac{\sum_i E_i B(E3;\ 0^+_{\text{g.s.}} \to 3^-_i)}{\sum_i B(E3;\ 0^+_{\text{g.s.}} \to 3^-_i)} .$$

For the three Pt isotopes under discussion here, we obtain the centers of gravity of 2.41±0.04 MeV for ^{198}Pt, 2.24±0.04 MeV for ^{196}Pt, and 1.89±0.07 MeV for ^{194}Pt.

Only one octupole state is known in each of the isotopes ^{200,202,204}Hg and ^{204}Pb. Two nearly degenerate 3^- states are known in ^{198}Hg. Consequently, if we wish to study systematic trends we must compare the centers of gravity for Pt to the known 3^-_1 states of Hg and Pb. There are two pieces of experimental information that give us confidence that such a comparison is meaningful. First, the center of gravity of $E3$ strength of 3^- states in ^{208}Pb, where fourteen 3^- states have been observed in the (p,p') experiments of Finck *et al.*,[24] is at 3.1 MeV, only 450 keV above the 3^-_1 state of that nucleus, and the strength is heavily concentrated in the 3^-_1 state at 2.64 MeV. Second, in the study of octupole states in Pb and Hg of Baxter *et al.*,[22] the investigators did not observe any evidence for significant splitting in ^{200,202,202}Hg and ^{204}Pb. (Two states of ^{198}Hg seem to share the octupole strength; however, they are located within 50 keV of one another.) We can conclude, therefore, that the octupole strength is substantially concentrated at the 3^-_1 state in all of the stable Pb and Hg isotopes (with the exception of ^{196}Hg, in which the 3^-_1 state has not been observed), and that a comparison of centers of gravity of Pt with 3^-_1 states of Pb and Hg is reasonable.

A graph of the 3^-_1 states of Pt, Hg, and Pb ($N<126$) isotopes as well as the centers of gravity calculated for ^{194,196,198}Pt and ^{206}Pb is shown in Fig. 6. It is clear that the systematic trends are considerably smoother using the centers of gravity rather than the 3^-_1 states of Pt. The least consistent result is that for ^{194}Pt; however, the fewest 3^- states have been located for this nucleus, and it is reasonable to conclude that significant octupole strength has been missed in the (p,p') experiment, so that this result is the least reliable of those presented.

The trends observed with the use of the centers of gravity can be interpreted in a straightforward way. In regions where significant octupole fragmentation does not

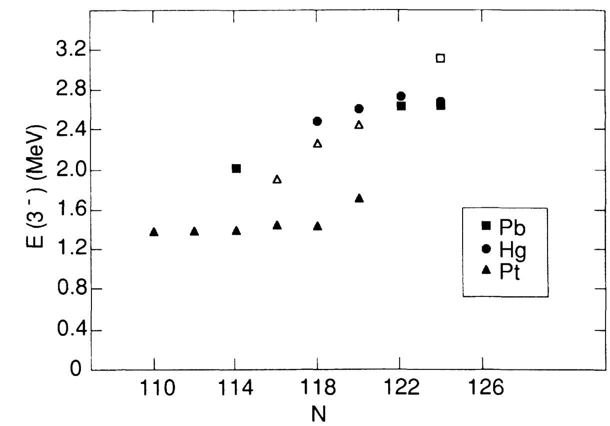

FIG. 6. Energies of 3^-_1 states (full shapes) and octupole centers of gravity (open shapes) for $N=110-124$ isotopes of Pt, Hg, and Pb.

take place, the systematic behavior of 3^-_1 states is affected most strongly by the interactions of a particular pair of neutron orbits and a corresponding pair of proton orbits.[18] One member of each of these pairs is the unique parity orbit of the valence shell. For the neutron shell discussed here, the unique parity orbit is $i_{13/2}$, and for the proton shell, $h_{11/2}$. The second member of a pair is the normal parity orbit for which both the orbital angular momentum l and the total angular momentum j are $3\hbar$ less than that of the unique parity orbit. Consequently, the neutron pair of interest (dubbed the $\Delta l=3$ pair elsewhere[18]) is $f_{7/2}-i_{13/2}$; the $\Delta l=3$ pair for protons in Pt is $d_{5/2}-h_{11/2}$. The importance of these pairs for octupole behavior in Pt and Hg is also discussed briefly in Ref. 15. Generally, the systematic behavior of 3^-_1 states in nuclei in which significant fragmentation does not take place can be described in the following way.[18,19] As the lower-energy orbit of the $\Delta l=3$ pair (the normal parity member in all known cases) is filled, $E(3^-_1)$ decreases. When the lower-energy orbit is full and the higher-energy orbit begins to fill, $E(3^-_1)$ increases. In the case of the $N>114$ Pt, Hg, and Pb isotopes, the Fermi levels for both protons and neutrons lie above the unique parity orbits. Therefore, in the absence of significant fragmentation we would expect $E(3^-_1)$ to vary relatively slowly with N and Z. The behavior we actually observe in the 3^-_1 states of Hg and Pb and the centers of gravity of Pt seems to reflect this expectation.

The behavior of the centers of gravity of the Pt isotopes may also be discussed in the framework of a method formulated in Ref. 12 to describe the global behavior of octupole states. Although this method was intended to treat nuclei in which the octupole strength is concentrated in the 3^-_1 state, the simplification of the graph of Fig. 6 using centers of gravity for Pt suggests that the method may be appropriate for the description of the centers of gravity of Pt as well. The method is based on a highly schematic model for 3^-_1 states in which $E(3^-_1)$ is given by

$$E(3^-_1)_{\text{model}} = y_0 - D(n_p + n_n) , \quad (1)$$

where n_p and n_n are calculated values which reflect the occupancies of the $\Delta l = 3$ pairs, D is an interaction strength parameter set to 0.25 MeV for the entire Periodic Table, and y_0 is a parameter which is fitted for the region of interest. Nuclei in which $E(3_1^-)_{\mathrm{expt}}$ falls more than 350 keV from $E(3_1^-)_{\mathrm{model}}$ are then said to have anomalous octupole behavior. In the analyses of Ref. 12, the value for y_0 for a particular region was extracted from a straight line fit to the octupole states of that region. In the present case, data is available only for a small range of $n_p + n_n$ values; consequently, a straight line fit does not yield reasonable parameters. However, y_0 is intended to be the octupole energy when the proton and neutron shells are closed, so a value of 2.60 MeV seems to be reasonable for our purposes. Values for $E(3^-)$ [which are $E(3_1^-)$ for Hg and Pt and the centers of gravity for Pt] and the model values from Eq. (1) are listed in Table II, along with a listing of the differences of the two energies. Calculated numbers for $n_p + n_n$ are taken from Ref. 12. All but two of the $E(3^-)$ values now fall within the "normal" range. The first, ^{196}Pb, comes from a β-decay measurement made recently,[25] and may reflect several effects, one of which may be the narrowing[26] of the $Z = 82$ shell gap near $N = 114$. On the other hand, we have already stated that a significant amount of octupole strength in ^{194}Pt may not have been observed in the experiment of Ref. 14, and that the center of gravity value may, therefore, be somewhat unreliable.

To further test the simple picture for octupole behavior in the Pt region that we have described, more data must be collected. As discussed earlier, only rudimentary information on the distribution of octupole strength is available for ^{198,200,202,204}Hg and ^{204}Pb. The situation is similar for ^{190,192}Pt and the osmium ($Z = 76$) and tungsten ($Z = 74$) isotopes. Further experimental investigation would require detailed Coulomb excitation experiments with light projectiles or inelastic α-particle and proton scattering experiments. It should also be emphasized that the lack of data on the distribution of octupole strength in the deformed rare-earth region has prevented detailed testing of models for octupole behavior, such as those of Neergard and Vogel[1] and Barfield.[5]

TABLE II. Results for $E(3^-)_{\mathrm{expt}}$ and $E(3^-)_{\mathrm{model}}$. All energies are in MeV.

Nucleus	$E(3^-)_{\mathrm{expt}}$	$E(3^-)_{\mathrm{model}}$	$E(3^-)_{\mathrm{model}} - E(3^-)_{\mathrm{expt}}$
^{194}Pt	1.89	2.35	+0.46
^{196}Pt	2.24	2.39	+0.15
^{198}Pt	2.41	2.42	+0.01
^{198}Hg	2.48	2.42	−0.06
^{200}Hg	2.61	2.46	−0.15
^{202}Hg	2.71	2.48	−0.23
^{204}Hg	2.67	2.49	−0.18
^{196}Pb	1.99	2.41	+0.42
^{204}Pb	2.63	2.55	−0.08
^{206}Pb	2.65	2.56	−0.09

IV. SUMMARY

In the present work, we have presented experimental evidence for the fragmentation of strength of the octupole states of ^{194,196,198}Pt. This fragmentation confirms in a qualitative way the predictions of Engel[6] and demonstrates that such phenomena can occur in nuclei which are not rigid rotors. By using this experimental information to calculate the centers of gravity of the octupole strength of the Pt isotopes, we have been able to propose that fragmentation of octupole strength is responsible for the apparent anomalous behavior of 3_1^- states in the Pt-Hg region.

ACKNOWLEDGMENTS

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