

New supersymmetry classification of nuclear levels in ^{195}Pt

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The Coulomb excitation of ^{195}Pt by 125 MeV ^{32}S projectiles has been studied using γ ray spectroscopic techniques. On the basis of supersymmetry considerations, the observation of new levels, $B(E2)$ ratios, and $B(E2)$ values, a new assignment of negative-parity states within the $U(6/12)$ multi- j supersymmetry scheme of the interacting-boson-fermion model is proposed for the $\langle\sigma_1, \sigma_2, \sigma_3\rangle - (\tau_1, \tau_2) = \langle 7, 0, 0 \rangle - (2, 0)$ and $\langle 6, 1, 0 \rangle - (2, 0)$ quadruplets. With this classification the simultaneous description of the low lying ^{195}Pt and ^{194}Pt levels within the framework of the supersymmetry scheme is greatly improved. The predicted $E2$ branching ratios for the decay of the $(\tau_1, \tau_2) - L = (2, 0) - 4$ levels in ^{195}Pt are well reproduced, while for the decay of the $(2, 0) - 2$ levels discrepancies occur in both the new and the old classification.

Several attempts have been made to explain the structure of the nucleus ^{195}Pt in the framework of nuclear models. Recent developments of the group-theoretical interacting-boson-fermion model¹ (IBFM) and the $U(6/12)$ multi- j supersymmetry (SUSY) scheme,^{2,3} in which a neutron in a $J = \frac{1}{2}, \frac{3}{2},$ or $\frac{5}{2}$ orbit is coupled to an $O(6)$ boson core, were successful in describing the known level scheme of ^{195}Pt , at least qualitatively, up to an excitation energy of about 560 keV. Nevertheless, some discrepancies still remained between experiment and theory, e.g., all levels associated with the quantum numbers $\langle\sigma_1, \sigma_2, \sigma_3\rangle = \langle 6, 1, 0 \rangle$ of the SUSY scheme were predicted at much higher energies than observed experimentally. To take into account these deviations, a change in the chain of groups of the SUSY scheme was introduced by Hong-Zhou Sun *et al.*,⁴ by which the $\langle 6, 1, 0 \rangle$ centroid energy could be well reproduced. For the levels at higher energies, however, the agreement between theory and experiment was still not satisfactory. Moreover, when attempting to fit ^{194}Pt and ^{195}Pt simultaneously using the same set of parameters, it was found that this was not possible unless a somewhat *ad hoc* higher-order interaction was introduced.⁵

In all these investigations the classification of the observed levels in the framework of the SUSY scheme was mainly based on a comparison of experimental to theoretical energy-spin sequences. $B(E2)$ values have only been taken into account for five transitions between the lowest-lying levels.³ The values of the experimental $E2$ transition probabilities could only be explained by assuming a small symmetry breaking. Taking this into account, Hong-Zhou Sun *et al.*⁶ calculated an extended set of $B(E2)$ values. As a consequence of the smallness of the

symmetry breaking, the $B(E2)$ values for the higher-lying levels are also governed by rather sharp selection rules, which should enable one to verify the proposed assignments by measuring transition probabilities.

In order to determine the $B(E2)$ values for transitions between higher-lying levels, we have performed a multiple Coulomb-excitation experiment on the nucleus ^{195}Pt using 125 MeV ^{32}S projectiles from the Munich tandem Van de Graaff accelerator. Particle- γ coincidences were measured with a setup which included three Ge(Li) detectors positioned at $(\theta_\gamma, \Phi_\gamma) = (45^\circ, 0^\circ), (90^\circ, 0^\circ),$ and $(118^\circ, 0^\circ)$ with respect to the beam direction, and a position-sensitive parallel-plate gas-avalanche counter which covered an angular range $30^\circ \leq \theta \leq 150^\circ$ ($\Phi = 180^\circ \pm 36^\circ$) (Ref. 7). An additional Si annular counter ($162^\circ \leq \theta \leq 172^\circ$) served to detect backscattered projectiles. In a separate experiment γ - γ coincidences were measured in close geometry with three Ge(Li) detectors. The targets consisted of highly enriched (97.28% ^{195}Pt) self-supporting foils of 1.45 mg/cm² thickness. In the case of the γ - γ -coincidence experiment the Pt foil was pressed on a thick lead backing to stop the recoiling nuclei. The Ge(Li)-detector efficiency was determined by placing a ^{152}Eu source at the position of the target.

The particle- γ -angular correlation data were analyzed for nine angle windows ($79^\circ \leq \theta_{c.m.} \leq 173^\circ$) on the particle spectra by comparison with the results of Coulomb-excitation calculations based on the Winther-de Boer program.⁸ In these calculations an extended set of electromagnetic matrix elements, relevant for the excitation of the states under consideration, was input and iteratively varied until the best agreement between the measured and theoretically calculated γ yields, including their impact-

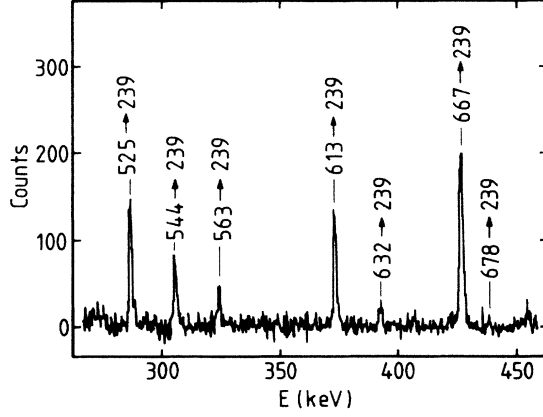


FIG. 1. Section of a coincidence spectrum of ^{195}Pt accumulated by requiring coincidences with the $239 \rightarrow 0$ keV transition.

parameter dependence, was obtained. From the γ -angular correlations it was possible to determine or to give limits on the spins for several excited states up to an energy of about 1200 keV, as well as to deduce $E2/M1$ multipole-mixing ratios. $B(E2)$ values were determined from the magnitude and impact-parameter dependence of the excitation probabilities.

Four new levels have been observed with energies (spins): 632.1 keV ($\frac{5}{2}^-, \frac{7}{2}^-$), 667.1 keV ($\frac{9}{2}^-$), 1091.8 keV ($\frac{5}{2}^-, \dots, \frac{13}{2}^-$), and 1155.8 keV ($\frac{5}{2}^-$). Typical uncertainties in the energies are about 0.5 keV. Each of the new levels was established by at least three transitions observed in γ - γ -coincidence spectra, except for the 1091.8 keV level, which decays exclusively to the 563 keV state. In Fig. 1 part of a coincidence spectrum is shown which was accumulated by requiring coincidences with the $239 \rightarrow 0$ keV transition. The γ lines shown serve to establish the 632 and 667 keV states.

Although the evaluation of the experimental data is not fully completed, several $B(E2)$ ratios and $B(E2)$ values, which are important for the SUSY classification presented here, have been determined.

$B(E2)$ ratios for the decay of states with spins $\frac{7}{2}^-$ and $\frac{9}{2}^-$ via $\Delta I=2$ transitions are compared with theoretical values in Fig. 2. If the states at 508 and 563 keV are associated with the doublet

$$\langle \sigma_1, \sigma_2, \sigma_3 \rangle - (\tau_1, \tau_2) - L - J = \langle 7, 0, 0 \rangle - (2, 0) - 4 - \frac{7}{2} \text{ and } \frac{9}{2}$$

[Fig. 2(a)], as assumed so far, then the observed $B(E2)$ ratios differ significantly from the predictions of the IBFM. This suggests that either the model in the present form is inadequate for predicting the electromagnetic properties of ^{195}Pt , or that the levels have been erroneously interpreted with respect to the SUSY quantum numbers. We have investigated the latter possibility and discovered that the states at 525, 544, 613, and 667 keV can be considered as forming a quadruplet, where the 613 and 667 keV states exhibit the decay behavior predicted for the $\langle 7, 0, 0 \rangle - (2, 0) - 4$ doublet [Fig. 2(b)]. If these states are now assigned to the $\langle 7, 0, 0 \rangle - (2, 0)$ quadruplet, a new assignment has to be found for the states originally associ-

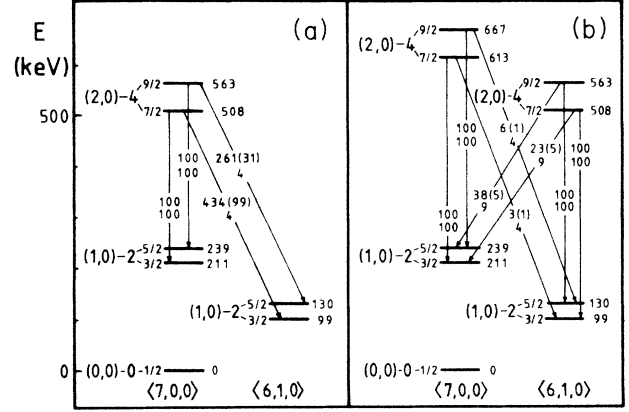


FIG. 2. Comparison of measured and calculated relative $B(E2)$ values in ^{195}Pt . The upper (lower) values at the transition arrows are the measured [SUSY predicted (Ref. 6)] relative $B(E2)$ values. The level energies (in keV) are printed to the right of the levels, while the quantum numbers $(\tau_1, \tau_2) - L - J$ are printed to the left. $\langle \sigma_1, \sigma_2, \sigma_3 \rangle$ are listed below each band. Only the $\Delta I=2$ transitions between $J = \frac{7}{2}, \frac{9}{2}$ and $J = \frac{3}{2}, \frac{5}{2}$ levels are shown. (a) Previous classification of the levels as given in Refs. 2–6 and 9. (b) Proposed new classification of the levels as described in the text.

ated with this quadruplet. From energy considerations it seems likely that the states at 420, 455, 508, and 563 keV belong to the $\langle 6, 1, 0 \rangle - (2, 0)$ group. Furthermore, the decay pattern of the 508 and 563 keV states exhibit the behavior expected on the basis of the selection rules for this group.

In addition to these $B(E2)$ ratios, we have obtained $B(E2)$ values for the $\Delta I=2$ transitions just discussed. These values were determined from the measured γ yields and are normalized to the $239 \rightarrow 0$ keV transition. The observed strengths, of these transitions [$B(E2; 508 \rightarrow 99 \text{ keV}) = 0.24(5) e^2 b^2$, $B(E2; 563 \rightarrow 130 \text{ keV}) = 0.24(4) e^2 b^2$, $B(E2; 613 \rightarrow 211 \text{ keV}) = 0.17(7) e^2 b^2$, and $B(E2; 667 \rightarrow 239 \text{ keV}) = 0.20(4) e^2 b^2$] are in agreement with the theoretical expectations for allowed transitions. Together with the $B(E2)$ ratios they therefore support the new classification of the $\frac{7}{2}^-$ and $\frac{9}{2}^-$ levels proposed here.

In contrast to the electromagnetic properties of the $\frac{7}{2}^-$ and $\frac{9}{2}^-$ levels, the decay of the $(\tau_1, \tau_2) - L - J = (2, 0) - 2 - \frac{3}{2}$ states cannot be understood within the framework of the IBFM. Although all these transitions are dominated by $M1$ contributions, which make the determination of their $E2$ strength rather difficult, several $B(E2)$ values have been obtained from both the present study and a recent Coulomb-excitation experiment with α particles.⁹ Our results as well as those of Ref. 9 are at variance with the theoretical expectations from both the new and the old classification schemes. These results will be discussed in more detail below after a comparison of experimental and theoretical energy-spin sequences has been made.

The new classification of levels proposed here leads to an improved agreement between experimental excitation energies and the multiplet structure predicted by the IBFM, as can be seen in Fig. 3. The theoretical level energies were calculated using the formula given in Ref. 4,

$$E(h_1 h_2; \sigma_1 \sigma_2; \tau_1 \tau_2; L; J) = A[h_1(h_1 + 5) + h_2(h_2 + 3)] - A''/4[\sigma_1(\sigma_1 + 4) + \sigma_2(\sigma_2 + 2)] \\ + B/6[\tau_1(\tau_1 + 3) + \tau_2(\tau_2 + 1)] + CL(L + 1) + C''J(J + 1), \quad (1)$$

with the parameters A , $A''/4$, $B/6$, C , and C'' obtained by fitting the excitation energies

$$E_{\text{exc}} = E(h_1, h_2; \sigma_1, \sigma_2; \tau_1, \tau_2; L; J) \\ - E_{\text{g.s.}}(7, 0; 7, 0; 0, 0; 0; \frac{1}{2})$$

of the 16 lowest lying $(\tau_1, \tau_2) = (0, 0), (1, 0)$, and $(2, 0)$ levels to the corresponding experimental values. All calculated level energies with the quantum numbers $(\tau_1, \tau_2) = (0, 0), (1, 0)$, and $(2, 0)$ agree with the experimental values within 16 keV. Even the position of the doublet 199 keV $(\frac{3}{2}^-)$ and 222 keV $(\frac{1}{2}^-, \frac{3}{2}^-)$, associated with $\langle 6, 1, 0 \rangle - (1, 1) - 1 - \frac{3}{2}$ and $\frac{1}{2}$, is well reproduced. Larger deviations occur only for the higher-lying levels associated with the quantum numbers $\langle 6, 1, 0 \rangle - (1, 1)$ and $(2, 1)$. From the similar excitation strengths, and from energy considerations, there is evidence that the states at 591 keV $(\frac{3}{2}^-)$ and 630 keV $(\frac{1}{2}^-, \frac{3}{2}^-)$ correspond to the levels $\langle 6, 1, 0 \rangle - (2, 1) - 1 - \frac{3}{2}$ and $\frac{1}{2}$ rather than to the levels $\langle 5, 0, 0 \rangle - (0, 0) - 0 - \frac{1}{2}$ and $\langle 7, 0, 0 \rangle - (3, 0) - 0 - \frac{1}{2}$, respectively, as was originally suggested in Refs. 2 and 3. We propose that the three lowest lying levels of the $\langle 5, 0, 0 \rangle$ band are the states at 927 keV

$(\frac{1}{2}^-, \frac{3}{2}^-)$, 1132 keV $(\frac{1}{2}^-, \frac{3}{2}^-)$, and 1156 keV $(\frac{5}{2}^-)$.

So far, levels other than those shown in Fig. 3 have not been classified in ^{195}Pt because the energy differences between predicted and experimentally observed levels and the increase in level density make unique assignments difficult. However, since there is a nearly one-to-one correspondence, not only for the number of states, but also for the spin values up to about 1200 keV, it may be possible to extend this classification to several of the higher-lying levels.

We have also investigated the consequences of the new level classification for the simultaneous description of ^{194}Pt and ^{195}Pt in the framework of the SUSY scheme. Level energies calculated for ^{194}Pt using the set of model parameters obtained for ^{195}Pt are compared with the corresponding experimental values in Fig. 3. Although deviations are evident, the overall agreement is considerably improved due to the larger level spacings obtained with the new classification.

We now return to the electromagnetic properties of the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states of the proposed configurations $\langle 7, 0, 0 \rangle - (2, 0) - 2$ (525 and 544 keV) and $\langle 6, 1, 0 \rangle - (2, 0) - 2$ (420

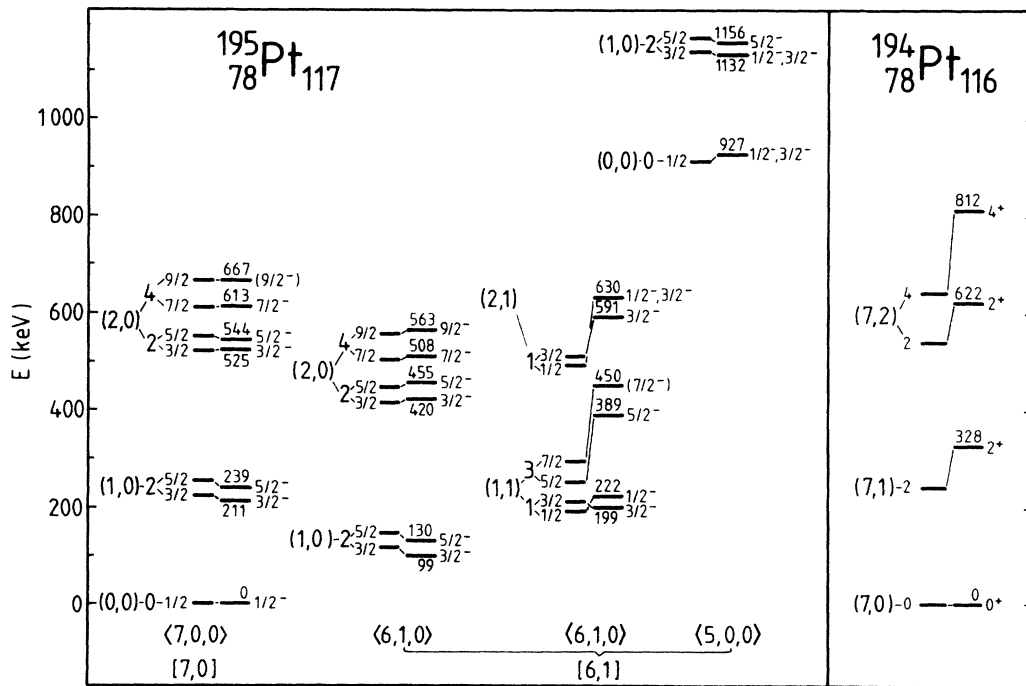


FIG. 3. Comparison of the experimental levels of ^{195}Pt (left part of the figure) and ^{194}Pt (right part of the figure) to theoretical levels based on the new SUSY classification of levels in ^{195}Pt . Predicted levels are shown on the left and the corresponding experimental levels with energies in keV on the right. The values of the parameters used in Eq. (1) are $A=64.43$ keV, $A''/4=56.69$ keV, $B/6=49.78$ keV, $C=1.16$ keV, and $C''=5.96$ keV. The labels in the left part of the figure have the same meaning as in Fig. 2. In addition, the IBFM parameters (h_1, h_2) are given below the bands. In the right part of the figure the IBM quantum numbers (σ, τ) are printed to the left of the levels.

and 455 keV). In addition to the data of our experiment, information is available for the states at 420 keV ($\frac{3}{2}^-$), 525 keV ($\frac{3}{2}^-$), and 455 keV ($\frac{5}{2}^-$) from a recent (α, α') Coulomb-excitation experiment of Bruce *et al.*,⁹ which is complemented by conversion-electron data of Casten *et al.*¹⁰

For the 420 keV level a very small $E2$ -decay strength to the 99 keV level [$B(E2)=0.005(4) e^2 b^2$] has been reported.⁹ This small value is in accordance with the old classification, in which this transition is forbidden. However, it is at variance with the new classification in which this transition is allowed with a predicted $E2$ strength of $B(E2)=0.175 e^2 b^2$. The experimental information presently available for the transitions to the 211 and 239 keV levels, which are allowed in the old scheme, does not suffice to support either classification. These transitions were not seen by Bruce *et al.*⁹ Although we do observe the 420→211 and 420→239 keV transitions in our coincidence spectra, we were unable to determine their multipole-mixing ratios due to their low intensities in the particle- γ -coincidence spectra. Therefore, values for their $E2$ strengths cannot be determined. From the magnitude and impact-parameter dependence of the excitation, there is evidence for a two-step contribution to the 420 keV state. From the measured excitation strength alone, however, we cannot decide whether this excitation proceeds via the 211/239 or the 130 keV states.

For the 525 keV level the excitation strength and its impact-parameter dependence observed in our experiment can be explained by a predominant one-step excitation from the ground state with a $B(E2)$ value of $0.015 e^2 b^2$. This is in good agreement with the value of $0.017 e^2 b^2$ reported in Ref. 9. Our results for the $B(E2)$ values for the decay of the 525 keV level to other excited states, derived from branching ratios and multipole-mixing ratios, agree with the finding of Ref. 9 that the $E2$ strength is very small for the decay to the 99 and 130 keV levels, and to the 239 keV level as well. These low values contradict both the old and new classifications, as at least one of the two decay branches is expected to have transitions of appreciable $E2$ strength in either scheme.

For the 455 keV ($\frac{5}{2}^-$) and 544 keV ($\frac{5}{2}^-$) levels no specific information on their configurations was obtained

from our data because the multipole-mixing ratios of their decay transitions could not be determined with sufficient accuracy. Some qualitative conclusions can be drawn from the observed excitation strengths, however. The impact-parameter dependence of the excitation of the 455 keV level supports the result of Ref. 9 that the $E2$ strength to the ground state is very small. It shows the characteristic function of a two-step excitation with collective strength. For the 544 keV level, which was not observed by Bruce *et al.*, the decay to the ground state, the 99, 130, 211, and 239 keV states is observed in our experiment. The dependence of the excitation strength on the scattering angle is consistent with a dominant direct excitation from the ground state with $B(E2; 544 \rightarrow 0 \text{ keV})=0.008(4) e^2 b^2$.

In summary, a new interpretation of levels in ¹⁹⁵Pt in terms of U(6/12) quantum numbers is proposed which leads to a substantially improved agreement between experimental and theoretical energy-spin sequences. Using the same set of model parameters the experimental levels of ¹⁹⁴Pt are also rather well described in the supersymmetry scheme. Although the observed $E2$ -decay properties of the (τ_1, τ_2) - $L=(2,0)$ -4 states in ¹⁹⁵Pt agree well with the predictions of the SUSY scheme when the new classification is used, discrepancies occur for the decay of the (τ_1, τ_2) - L - $J=(2,0)$ -4- $\frac{3}{2}$ levels. The experimental $E2$ strength of the 420→99 keV transition contradicts the new scheme, while transitions originating from the 525 keV ($\frac{3}{2}^-$) level are at variance with both the old and new classifications. Further experimental and theoretical work appears to be necessary to explain the remaining deviations.

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