Positive-Parity States in Pt and Hg Isotopes and the Coriolis Antipairing Effect in the Deformed-Rotor Model

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(Received 24 June 1977)

Anomalies in the experimental spectra for the positive-parity states of the Pt and Hg isotopes are explained in the γ-deformed-rotor model which takes into account the coupling of the two quasiparticle excitations with the ground band. It is found that the 0–2-quasiparticle coupling is very important. Moreover, it is recognized that the linear increase in the moment of inertia with the square of the angular velocity can be described by this coupling.

A variety of spectra for low-lying high-spin states in the transitional even-even nuclei $^{186-196}$Pt and $^{190-200}$Hg by (HI, xn) and (α,xn) reactions has been obtained[1-5] during the last few years. The positive-parity ground-state bands (gsb) in these nuclei show some interesting anomalies which are presumably explained[1-5] in terms of two-quasiparticle (qp) excitations (rotation-alignment picture[6]). In this Letter we report the results of our detailed investigation of the gsb carried out using two different descriptions for the energy of the core which is taken to be γ deformed.

(i) In the first description, which is developed in this contribution, we extend the asymmetric rotor model of Davydov to include the coupling between 0- and 2-qp states. In the following we shall refer to it as AROT02. As a reference we shall give also the results of the simple asymmetric rotor (AROT) model of Davydov.

(ii) We compare the results of AROT02 with a calculation where we neglect the interaction between the 0- and 2-qp states. Instead we allow for an increase of the moment of inertia of the asymmetric rotor with growing angular momentum as described by the variable moment of inertia (VMI) model[7] extended previously to include γ deformations[8] (AVMI2), and include also 2-qp excitations.

The main result we want to emphasize is that the two descriptions mentioned above (AROT02 and AVMI2) provide very similar results. This indicates an underlying relationship between the VMI model and the 0–2-qp coupling. Moreover, this leads us to believe that the Coriolis antipairing (CAP) effect which is supposed to be responsible for the increase in the moment of inertia with the square of the angular velocity [as seen, for example, in cranked–Hartree-Fock-Bogoliubov (HFB) calculations[9]] can be described in the simple deformed-rotor model in terms of the coupling of the 0-qp and 2-qp bands.

For the description of the 0- and 2-qp excitations the Hamiltonian of the system is written as[10]

$$H = H_{\text{sp}} + H_{\text{rot}} + H_{\text{res}}, \tag{1}$$

in which H_{sp} is the Hamiltonian of the independent quasiparticle and H_{rot} describes the rotational motion of the γ-deformed core. The residual interaction H_{res} is taken to be the modified surface γ interaction[10] of Green and Moszkowski. The total wave function of the system with the core and the 2 qp is expressed in the basis[10]

$$|(j_1 j_2 J)R\alpha; IM\rangle = (1+\delta_{j_1 j_2})^{-1/2} \sum_{M_J M_R} (JM_J RM_R|IM)|(j_1 j_2)JM_J\rangle |R\alpha M_R\rangle, \tag{2}$$

in which $|(j_1 j_2)JM_J\rangle$ is the wave function of the 2 qp and $|R\alpha M_R\rangle$ represents the core eigenfunctions. The 0-qp component is described by the asymmetric rotor multiplied by the BCS vacuum. The symbols used in the above expressions are self-explanatory. The essential theoretical formulation relevant to the present calculations is similar to that given in Ref. 10.

The moment-of-inertia parameter of the asymmetric rotor model is fitted to the 2_1^+ energy. The deformations ($\gamma = 60°$ for Hg and $\gamma = 30°$ for Pt isotopes) are taken from our work[10] on the negative-parity states in these nuclei. The stiffness parameter of the AVMI2 model is adjusted by the 4_1^+ energy. For the single-particle configuration we have considered only the $\pi h_{11/2}$ and $\nu i_{13/2}$ spherical subshells. The other parameters λ and Δ which are very important to decide the band head energies of the proton or the neutron 2-qp states have been indicated in the figure captions and are obtained in the following manner. An extensive study of the parameter dependence of the level spectra in the Hg and Pt nuclei has been made, and our results show that in the case of the $(\pi h_{11/2})^{-2}$ configuration the 10^+ and 8^+ states are almost degenerate whereas for the $(\nu i_{13/2})^{-2}$ configuration the 12^+, 10^+, and 8^+ are very close to each other. These distinct features of the level spectra for the proton and the neutron 2-qp excitations are independent of the values (within reasonable limits) of the parameters λ and Δ. Thus a comparison of the experimental spectrum with the theoretical results allows us to know the nature of the excitation (proton or neutron) and in most of the cases this answer is unambiguous. After the nature of the 2-qp excitation is decided we take the appropriate values of the parameters λ and Δ to obtain the energy of the band head.

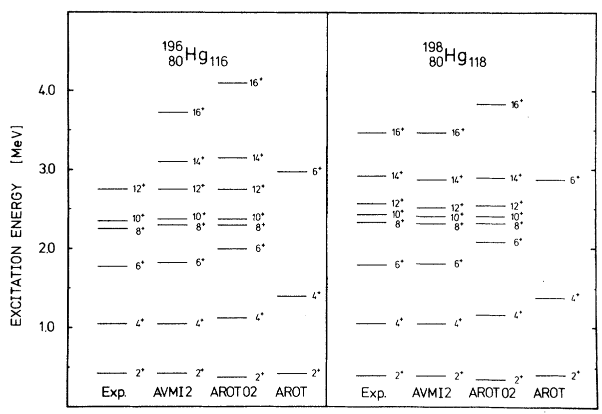

FIG. 1. Experimental and calculated results for the positive-parity states in $^{196,198}Hg$. Experimental data (on the left) are compared with the asymmetric rotor model (AROT) in column 4, the results of the asymmetric rotor model with the 2-qp mixing wherein the increase of the moment of inertia with growing angular momentum is described by the extended VMI model (AVMI2) in column 2. The parameters used in the calculations are $\beta = 0.116$, $\gamma = 60°$, $\lambda_p = 42.20$ MeV, $\lambda_n = 48.05$ MeV, $\Delta_p = 0.90$ MeV, and $\Delta_n = 1.24$ MeV for ^{196}Hg, and $\beta = 0.099$, $\gamma = 60°$, $\lambda_p = 42.04$ MeV, $\lambda_n = 48.18$ MeV, $\Delta_p = 0.90$ MeV, and $\Delta_n = 1.12$ MeV for ^{198}Hg.

The values of λ and Δ thus obtained here are a little different from those used in Ref. 10. This modification of the Fermi surface could also be described by a shift of the $i_{13/2}$ neutron and $h_{11/2}$ proton levels. The spurious components in the description of the 2-qp states arising due to the nonconservation of the number of particles have been removed by Schmid orthogonalization method.

Figures 1 and 2 show the results for the $^{196,198}Hg$ and ^{190}Pt isotopes as the representative examples. It is evident that the two descriptions (AROT02 and AVMI2) give similar results and both are in good agreement with the experimental data. However, it should be pointed out that the difference between the results of the two models for higher spins (14^+, 16^+, etc.) is only the indication of the fact that one has to take into account the admixture of the 4-qp states to the 2qp states and this is quite expected. Figures 1 and 2 also show on the right-hand side the core energy of the simple asymmetric rotor without including the 0–2-qp coupling (AROT). A comparison with the results which include this coupling (AROT02) shows a remarkable lowering of the core energy (0-qp energy) providing a nice agreement with the data. Such an appreciable influence due to the admixture of the 0-qp and 2-qp states is contrary to the existing notion[11] which is derived from the fact that the different 10^+ states, which are supposed

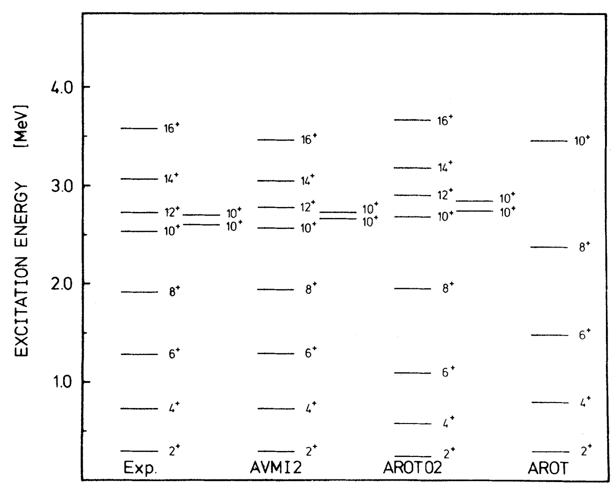

FIG. 2. Experimental and calculated results for the positive-parity states in ^{190}Pt. For the details see Fig. 1. Here the second and third 10^+ states have been shown beside the yrast band in each case. The parameters employed in the calculations are $\beta = 0.155$, $\gamma = 30°$, $\lambda_p = 43.30$ MeV, $\lambda_n = 48.76$ MeV, $\Delta_p = 0.80$ MeV, and $\Delta_n = 1.10$ MeV.

to be 0- and 2-qp states, are close together indicating no appreciable mixing. The important point is that yrast 2-qp states do not have any appreciable admixture with the 0-qp states. This is because the yrast 2-qp states are built by large J and small R values (J = total angular momentum of the two quasiparticles; R = angular momentum of the core), while the 0-qp state has $R = I$. Indeed, in this case the matrix element between 0- and 2-qp states is small. In contrast to the yrast 2-qp states, there are quite a few high-lying 2-qp states which are essentially made of small J and large R values. For the 2-qp states with such a configuration the Coriolis interaction can provide a large coupling to the 0-qp states. The consequence of this is that the yrast deformed-rotor states are pushed down as demonstrated in Fig. 1 for ^{196,198}Hg, and in Fig. 2 for ^{190}Pt (compare AROT and AROT02). Thus it has been shown that a linear increase in the moment of inertia with the square of the angular velocity is caused by the admixture of the 2-qp excitations which reduces in a smooth way the pairing correlations (CAP effect).

The experimental spectra of the Hg isotopes are similar in structure excepting the following irregularity: Up to $A = 196$ the 8^+ and 10^+ states are almost degenerate and the spacing between the 10^+ and 12^+ is roughly identical to the 0^+ and 2^+ energy difference. Beyond $A = 196$ the spacing between 10^+ and 12^+ states is substantially reduced and the difference between the 12^+ and 14^+ states corresponds to about the 2^+ energy (see Fig. 1). From our calculations wherein we have considered $(\pi h_{11/2})^{-2}$ and $(\nu i_{13/2})^{-2}$ configurations for the 2-qp excitations, we find that the change in the structure of the spectrum for $A = 198$ is due to the fact that beyond $A = 196$ the neutron 2-qp energies are lower than the proton ones. A similar conclusion has been reached by Günther *et al.*[1] in their experimental studies of the $B(E2)$ values in the Hg isotopes. The lowering of the $(\nu i_{13/2})^{-2}$ excitation energy in the case of ^{198}Hg is partly due to the movement of the neutron Fermi energy (λ_n) very close to the highest Nilsson levels and partly due to the decrease of the pairing gap energy (Δ_n). In fact, with increasing neutron number we fill for the oblate shape in the Hg isotopes the smaller Ω levels of the $i_{13/2}$ neutrons. This makes it easier to align two neutrons which further lowers the 8^+, 10^+, and 12^+ neutron 2-qp states. Our calculations show that for the Hg isotopes the states up to spin 6^+ are 0-qp states (with a small admixture of 2-qp states) whereas 8^+, 10^+, etc., are essentially 2-qp states of proton nature for $A \leq 196$ and of neutron nature for $A \geq 198$.

A similar study for the Pt isotopes (see Fig. 2) shows that the yrast states up to spin 8^+ belong to the 0-qp band. In ^{186}Pt the 10^+, 12^+, and 14^+ are also found to be 0-qp (with a small admixture of 2-qp) states. In the $^{188-194}$Pt isotopes the yrast 10^+ state is found to be throughout of $(\pi h_{11/2})^{-2}$ configuration. Further, our analysis shows that in $^{188-194}$Pt the 12^+ and 14^+ states are due to neutron excitations. The variation in the excitation energy of the 12^+ and 14^+ states is again due to the change in the neutron Fermi energy (λ_n) with increasing neutron number.

An interesting feature of the spectra in Pt is that there are three close-lying 10^+ states (see Fig. 2). Two of these states are supposed to be of $(\pi h_{11/2})^{-2}$ and $(\nu i_{13/2})^{-2}$ configurations whereas the other one is known to be a member of the gsb. Our calculations confirm these conclusions and we get the neutron 2-qp 10^+ state a little higher in energy relative to that of the proton 2-qp 10^+ state, the gsb 10^+ being the highest one. Because the three 10^+ states are quite close in energy it has been thought by others that 0–2-qp coupling is extremely weak.[11] This understanding, however, needs modification in the following sense. As indicated earlier the 0-qp 10^+ state has, in fact, appreciable coupling with other high-lying 2-qp states having small total single-particle angular momentum and is consequently pushed down.

Our results regarding the influence of 0–2-qp coupling studied in the Hg and Pt isotopes might be general. This can be argued in the following way. For small deformation β the Coriolis force ($\propto 1/\beta^2$) is large and hence the 0–2-qp coupling is strong. Indeed, for nuclei with small β the deviation from the simple asymmetric rotor spectrum (AROT) is large and we have shown that this deviation can be accounted for by the 0–2-qp coupling. For well-deformed nuclei the 0-2-qp coupling is expected to be weak and the deviation would be very small which is quite well known. However in such nuclei where the deviation is already small the influence of the coupling with β and γ bibrational bands may be comparable to the 0–2-qp coupling and both should be included.[12]

In the present calculations we have considered only the high-spin single-particle states ($\pi h_{11/2}$ and $\nu i_{13/2}$) for the two quasiparticles. It is expected that other single-particle states may contribute. This contribution would depend on the following factors: (i) Only if the quasiparticles are in high–angular-momentum (j) shells does the Coriolis interaction admix such 2-qp to 0-qp states appreciably. (ii) Only if the Fermi level is near to the level in question can it contribute strongly.

In our calculations of the Pt and Hg isotopes additional contributions have been calculated and are found to be small. This is obviously because in these nuclei the 2-qp states ($\nu i_{13/2}$ and $\pi h_{11/2}$) are the only high-j levels near the Fermi surface.

We thank Professor H. J. Mang, Professor V. Madsen, Dr. K. Goeke, Dr. K. W. Schmid, and Dr. K. Shimizu for numerous enlightening discussions. Our collaboration with Professor P. Vogel and Dr. K. Neergard in the study of negative-parity states of even-even mass nuclei has been of immense help in the present investigation.

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^{12}C$(e,e'\pi^+)$ Reaction Leading to Low-Lying States in ^{12}B

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(Received 21 July 1977)

Energy and angular distributions of photopions from ^{12}C, leading to low-lying residual states in ^{12}B, have been measured via the $(e,e'\pi^+)$ reaction at $E_e = 195$ MeV. The shape of the patterns agrees with the theoretical estimates deduced from other electron scattering data and also with shell-model calculations. A comparison of the absolute value shows the importance of correct estimation of the pion wave. The result demonstrates that photopion experiments can provide a promising method for studying spin-flip–type electromagnetic transitions in nuclei.

It is well known that the photopion production from a nucleon is caused mainly by a spin-flip-type transition, the leading term of the amplitude of this transition being proportional to $\vec{\sigma}\cdot\vec{\epsilon}$, where $\vec{\sigma}$ is the intrinsic spin operator of nucleon and $\vec{\epsilon}$ is the photon polarization vector.[1] When only the leading term is applied to express the photopion cross section of complex nuclei, the cross section is given in the impulse approximation by

$$\left(\frac{d\sigma}{d\Omega}\right)_{\gamma\pi} = \frac{p_\pi}{k m_\pi^2} e^2 f^2 \frac{1}{\hat{J}_i^2} \sum_{M_i M_f} \sum_{S_\gamma} |\vec{\epsilon}\cdot\vec{\mathfrak{M}}|^2, \qquad (1)$$

$$\vec{\mathfrak{M}} = \langle J_f M_f | \sum_{n=1}^{A} \vec{\sigma}_n \tau_n^{\pm} \exp(i\vec{q}\cdot\vec{r}_n) | J_i M_i \rangle, \qquad (2)$$

where k and p_π are the momenta of the incident photon and the outgoing pion, respectively, m_π is the pion rest mass, $e^2 = \frac{1}{137}$, $f^2 = 0.08$, $\hat{J} \equiv (2J+1)^{1/2}$, J and M are nuclear spin and magnetic quantum number with suffix i or f denoting the initial or final state, respectively, $\tau^{\pm}$ is the isospin raising and lowering operator, $\vec{q} = \vec{k} - \vec{p}_\pi$ is the nuclear recoil momentum, $\vec{r}_n$ is position vector of a component nucleon, $|J_i M_i\rangle$ and $|J_f M_f\rangle$ are the initial and final nuclear states, respectively, and $\sum_{S_\gamma}$ means summation over the photon polarization.[2,3]

As shown by Eqs. (1) and (2), photopion cross sections on complex nuclei are expressed in terms of the matrix element $\vec{\mathfrak{M}}$ of the nuclear spin-flip–type charge-exchange electromagnetic transition of a momentum transfer $\vec{q}$. On the ba-