PARTICLE-HOLE STATES IN O^{16}†

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The coexistence of "deformed" and "spherical" states in the same nucleus has lately been established. The oxygen isotopes, in particular, were treated successfully[1-4] with this approach. In O^{16}, the major incentive for the inclusion of the deformed states was the experimental observation of excited rotational bands, of both parities. Those states, as also pointed out by others,[5] were mostly 4p-4h (four-particle, four-hole) states, in the spherical shell-model representation. The negative-parity deformed states, 3p-3h mostly, interacted quite appreciably with the spherical 1p-1h states, to bring about the experimentally observed spectrum.

Two dilemmas remain to be solved: (a) If the two families of states have indeed different underlying inert cores, is it at all conceivable that they will interact strongly with one another? (b) In the same framework, where would the spherical 2p-2h and 1p-1h, of positive parity, lie?

We have done a complete calculation of the particle-hole states resulting from promoting two $p^{1/2}$ nucleons to the s-d shell, in conjunction with a total decoupling of the deformed states from the spherical states. The effect of including states where one $p^{1/2}$ nucleon is promoted to the p-f shell was found to be small. In anticipation of the results reported herein, we wish to make the following points:

Having separated the spherical and deformed states, and including the positive-parity spherical particle-hole states in the calculation, it is impossible to achieve consistency with the data, using any acceptable force. Extending the collective analysis of Ref. 2 will yield far too low 2p-2h states; the analysis of Ref. 7, far too high 4p-4h states; the analysis of Ref. 5, far too low 1p-1h states.

These inconsistencies stem from the fact that we have been using the same two-body interaction, and the same spherical one-body splittings,[6] for both spherical and deformed states. But there is no strong reason why, in principle, one should at all insist on making that common choice. The interaction one uses is an effective interaction, and does in no way reflect directly any basic feature of the free nucleon-nucleon force. It also reflects the effect of higher configurations, which should have been included in the calculation, otherwise. The spherical one-body splittings are of even less independent significance, as they reflect an average interaction with an inert core. In fact, if for two sets of states, the corresponding cores are radically different (as we believe our case is), one would rather expect different single-particle splittings to be applicable to the two sets. In particular, we expect the appearance of an energy gap between occupied and unoccupied Hartree-Fock states. For the spherical states, the $p^{1/2}$ level is occupied and should, therefore, be well separated from higher levels. For the deformed states, it is essentially unoccupied and should not be appreciably separated for them. This is, precisely, what we propose should be done: retain a common effective two-body interaction, but allow for the more sensible choice of the one-body splittings for the deformed and spherical sets of states.

Thus, for the deformed states we essentially quote the results of Ref. 2. For the spherical states we use [normalized to $e(p^{1/2})=0$]

$$e(d^{5/2})=11.5;\quad e(s^{1/2})=12.4;\quad e(d^{3/2})=16.6.$$

The p-f shell energies are read off C^{13}, with the assumption that only the $p^{1/2}$-$d^{5/2}$ splitting is affected in going over to the oxygen region. The two-body interaction used is the Elliott-Flowers[7] force, with the Rosenfeld[8] mixture,

$$V=V_0\frac{\tau_1\cdot\tau_2}{3}(0.7+0.3\sigma_1\cdot\sigma_2)\frac{e^{-r/a}}{r/a},$$

with $a=1.37\times10^{-13}$ cm, $V_0=42.5$ MeV, and the harmonic oscillator parameter $b=1.65\times10^{-13}$ cm. The results are summarized in Fig. 1, where the generally consistent interpretation

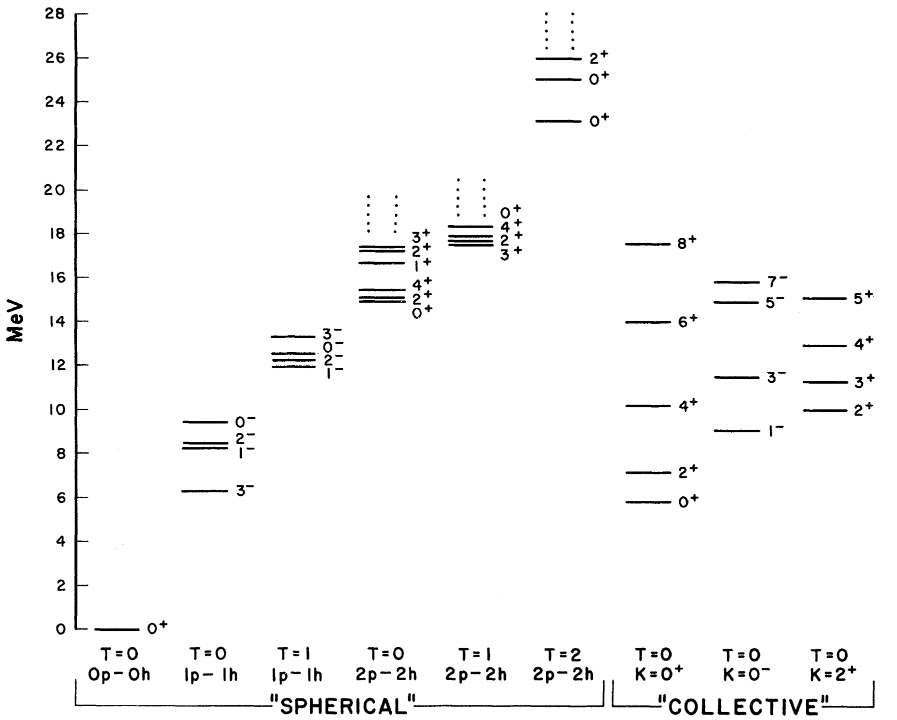

FIG. 1. The various particle-hole states in O^{16}, resulting from promoting particles out of the $p^{1/2}$ shell. The states are divided into "spherical" and "deformed." For the 2p-2h states, only the lowest ones in each group are indicated.

in terms of various particle-hole states is demonstrated. The eventual inclusion of the $1p^{3/2}$ level is not expected to change the picture greatly, as can be evidenced by analyzing more detailed works on the subject.[9-11]

One may argue that the single-particle energies used for the 2p-2h states calculation —following the general argumentation of this Letter—should not be identical to those used for the 1p-1h states. Rather, they should have a value intermediate between them and the ones used for the deformed states. We did not do this, lacking specifically a quantitative sound choice of these energies. But we note that the effect of such a modification would be to lower the bulk of 2p-2h states, bringing them to closer agreement with experiment.

The lowest positive-parity states in O^{16}, not belonging to the $\kappa = 0$ band, still seem to lie well below the bulk of the calculated 2p-2h spherical states. It is with this in mind that we call attention to the striking similarity between the spectrum of Mg^{24} (up to about 7.5 MeV) and that of O^{16} (positive-parity states in the region 6-12 MeV) in Fig. 2. It seems plausible to suggest that the 2^+ level at 9.83 MeV, the 3^+ level at 11.20 MeV, and perhaps the level at 12.02 MeV are also "deformed" in nature, and form, in fact, a $\kappa = 2^+$ rotational band.

This being so, it seems that all the "deformed" states in O^{16} are projectable from one single

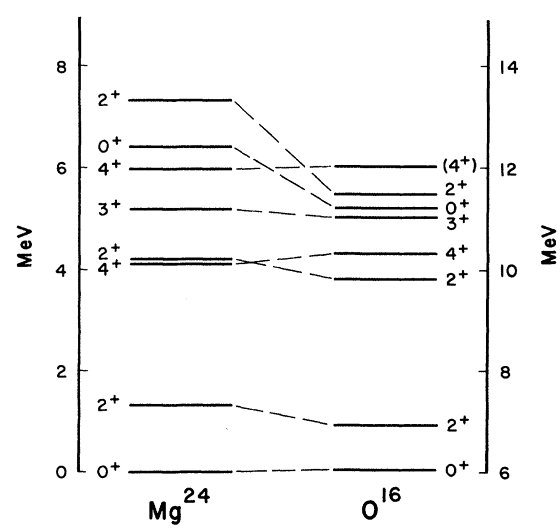

FIG. 2. Energy levels of Mg^{24}, and of O^{16} (positive parity), displaying the similarity of the spectra.

intrinsic Hartree-Fock state, which is not only pear-shaped,[2] but also axially asymmetric.

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EXPERIMENTAL EXPLORATION OF THE LIMITS OF THE NILSSON MODEL; VIBRATIONAL STATES IN Hf^{177} AND Hf^{181} †

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Lack of specific Nilsson states with low K value for assignment of rotational bands observed in Hf^{177} and Hf^{181} between 1 and 2 MeV, together with cross-section measurements, suggest fragmentation of bands into a large number of vibrational components. It is suggested that the previously unobserved pairing vibrations, the β vibrations, and the more common $K-2$ gamma vibrations may be responsible.

Nuclear reaction studies of the levels in Hf^{177} and Hf^{181} utilizing both (d,p) and (d,t) reactions when possible have yielded large numbers of excited states in the energy region from the ground state to ~2 MeV. The use of angular distribution measurements in the (d,p) reactions has made possible, essentially for the first time, the comprehensive analysis and assignment of almost all of the states into rotational bands. The detailed spectroscopic analysis of these data will be published separately. However, the theoretical questions raised by the analysis of the experimental data in the energy region from 1 to 2 MeV seem to require marked deviations from the Nilsson model. In particular, the large numbers of low-K rotational bands observed in this experiment cannot be easily explained. We believe these bands, observed in the (d,p) reaction through single-particle components in their wave functions, to be partially vibrational in character; this fragmentation of single-particle strength is quantitatively suggested in the total (d,p) cross section observed in the energy region below ~2.0 MeV. In Hf^{181} the large number of low-spin states appears to require, in addition to γ-vibrational bands, bands such as the β and/or pairing vibrations. This is the first experimental suggestion of pairing vibrational bands.

The deformed odd-A nuclei Hf^{181}, Hf^{179}, and Hf^{177} have been studied by analysis of the emergent particles from the reactions $Hf^{180}(d,p)Hf^{181}$, $Hf^{180}(d,t)Hf^{179}$, $Hf^{178}(d,p)Hf^{179}$, $Hf^{178}(d,t)Hf^{177}$, and $Hf^{176}(d,p)Hf^{177}$. The incident deuterons of 10-12 MeV were obtained from a tandem Van de Graaff accelerator,[1] and the emergent protons or tritons were analyzed in a broad-range magnetic spectrograph.[2]

Angular distributions have been measured for the levels up to 2 MeV observed in the reactions $Hf^{180}(d,p)Hf^{181}$ and $Hf^{176}(d,p)Hf^{177}$. The high level density in these nuclei has forced the routine use of a least-squares fitting program in order to resolve the states, even though the experimental resolution is approximately 15-keV full width at half-maximum. The comparison of the experimental angular distributions with those predicted by the distorted-wave Born approximation (DWBA) code T-SALLY[3] has allowed the assignment of l values to approximately two-thirds of the levels observed between 1 and 2 MeV. The collective model predicts that the spectra should consist of rotational bands based on intrinsic states, the mem-