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Evidence for a coexisting four-particle, four-hole band in doubly closed subshell ^{96}Zr

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The occurrence of a coexisting four-particle, four-hole band built on the first excited 0^+ state in the doubly closed subshell nucleus ^{96}Zr is established from $(n,n'\gamma)$ reaction experiments and previous multiparticle transfer studies.

Shape coexistence arguments were originally invoked[1] to explain the rotational band associated with the first excited 0^+ state in doubly closed shell ^{16}O. Since that time, the common occurrence of coexisting deformed states near closed shells resulting from particle-hole pair excitations has been established[2] both in even-even and odd-mass nuclei. Although there is some evidence[2,3] for intruder state mechanisms applying to subshells, this phenomenon has not been thoroughly investigated in closed subshell regions. Here we present evidence for the existence of a band built on the well-known first excited 0^+ state in doubly closed subshell ^{96}Zr.

Near closed major shells, such as $N=50$, nuclear shapes are spherical. A gradual transition from spherical to deformed shape is expected to take place as neutron number increases, with maximum deformation at midshell, as observed in both even-even[4] and odd-mass[5] nuclei near $A\sim100$. However, the $Z=40$ proton subshell closure in this region leads to the appearance of intruder configurations which coexist with the ground-state configuration. The influence of configuration mixing on the level structure of transitional $_{42}Mo$ nuclei has been explored[6] in recent proton-neutron interacting boson model (IBM-2) calculations which took into account explicitly the two-particle, two-hole proton excitations across the $Z=40$ subshell.

A special situation occurs at ^{96}Zr $(Z=40)$ where the $N=56$ neutron subshell closure gives this nucleus a double subshell closure. Thus, particle-hole pair excitations across both subshell gaps are possible. This could produce situations much like those in doubly closed shell ^{16}O, in which the lowest-lying intruder deformed band has been shown[7] to arise from such excitations.

The first excited state of ^{96}Zr is a 0^+ state, as in doubly closed shell ^{16}O. Support for the identification of the 0_2^+ state in ^{96}Zr as an intruder state comes primarily from particle-transfer data. Figure 1(a) summarizes the results of two-proton,[8] two-neutron,[9,10] and alpha-particle[11] transfer reaction studies. In addition, the compositions of the ground-state wave functions of the Mo nuclei, which are the target nuclei in cases involving proton transfer, are shown in Fig. 1(b). They come from the aforementioned IBM-2 calculations with configuration mixing.[6]

In Fig. 1(a) the most striking feature is the unusually high alpha-pickup strength[11] to the 0_2^+ state of ^{96}Zr. Although strict correlation of the two-neutron and the two-proton transfer data with the alpha-transfer results is not expected, as different target nuclei are involved, there are apparent similarities. In particular, two-neutron stripping strength to the 0_2^+ state and two-proton pickup strength to the ground state change with neutron number in the same way as does the corresponding alpha-pickup strength. It is easy to see that the high value of the cross section ratio in favor of the 0_2^+ in ^{96}Zr is a common feature. We suggest that this is due to its character as a four-particle, four-hole deformed state, like the 0_2^+ state[1,7] of doubly closed shell ^{16}O.

Because of inconsistencies in the interpretation of previous experiments[12–14] and a paucity of experimental data, we have undertaken an independent study of the level structure of ^{96}Zr by several techniques.[15–17] Our particular emphasis has been on elucidating the nature of the 0^+ excitations and searching for associated levels.

We have performed $(n,n'\gamma)$ reaction studies using two facilities. First, gamma-ray singles measurements were carried out at the reactor neutron beam facility of the Institute of Isotopes in Budapest. These measurements[15] led to the identification of several hitherto unknown transitions from previously unplaced levels. Excitation function measurements performed at the University of Kentucky pulsed neutron beam facility have shown that a transition of 644.18

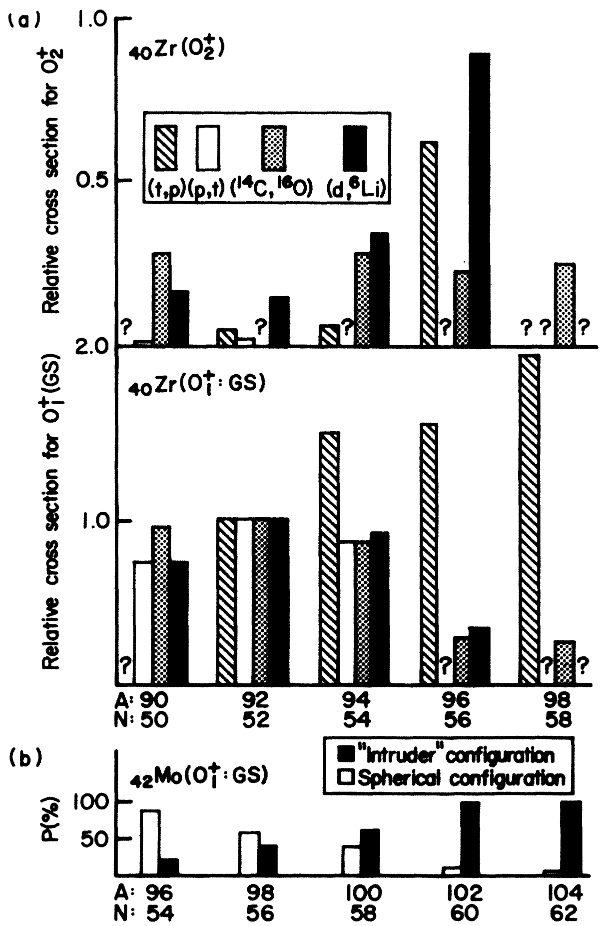

FIG. 1. (a) Relative cross sections for transfer reactions populating the first two 0^+ states of $_{40}$Zr nuclei. All cross sections are normalized to the ground-state cross section of ^{92}Zr. (b) Percentage composition of the ground states of the target $_{42}$Mo nuclei. Unshaded bars: configuration with one proton boson; shaded bars: intruder configuration with three proton bosons.

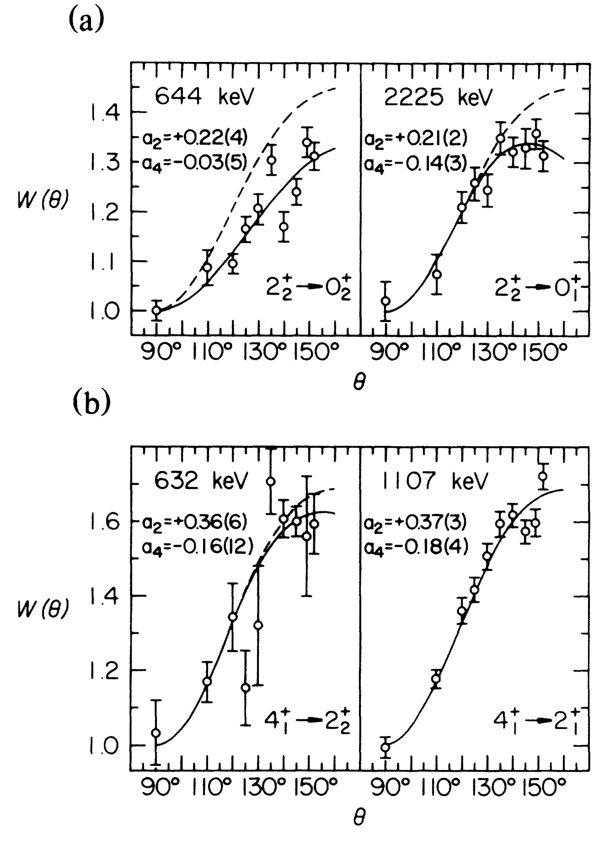

FIG. 2. Angular distributions of gamma rays from the (n,n$'\gamma$) reaction on ^{96}Zr obtained at (a) 2.85- and (b) 3.4-MeV neutron energy. Solid lines are Legendre polynomial fits to the data, with coefficients indicated; dashed lines denote Hauser-Feshbach angular distributions for pure $E2$ transitions when distinguishable from the experimental fits. (a) Transitions deexciting the 2225-keV 2^+ state. (b) Transitions deexciting the 2857-keV 4^+ state.

± 0.06-keV energy, also identified in the Budapest experiments, populates the 0_2^+ state. Our parallel beta decay experiments[16] and similar studies[18] indicate that the correct energy of this state is 1581.4 ± 0.5 keV, contrary to the previously determined value[19] of 1594 ± 1 keV. Hence the 644-keV transition can be placed as deexciting the known 2225-keV level. This placement has been confirmed by recent beta decay[16] and in-beam (t,p$\gamma\gamma$) coincidence measurements.[17] The angular distributions of the 2225-keV and 644-keV gamma rays deexciting this level to the first and second 0^+ states, respectively, have been measured at the Kentucky facility. As Fig. 2(a) shows, both of them give a 2^+ spin-parity assignment, in contrast with the previously suggested[14,20] value of 3^-, which would require more than twice as large an angular distribution anisotropy.

We associate the 2225-keV 2^+ state with the second largest inelastic peak observed in the (d,^{6}Li) reaction study by van den Berg *et al.*[11] Although these authors prefer a 5^- assignment, their angular distribution data are equally consistent with spin 2^+. This gives about 60% alpha-pickup strength with respect to the ground-state strength.[11] We have searched for a possible doublet at this energy with the (n,n$'\gamma$) reaction which should lead to significant population of a 5^- state, but have found no evidence for a second state. Hence, the (d,^{6}Li) reaction leads to strong population of the 2^+ state as well. The $B(E2;2^+ \to 0_2^+)/B(E2;2^+ \to 0_1^+)$ ratio of 100 demonstrates a strong preferential decay to the 0_2^+ state. We use these two facts to establish the 2225-keV state as the 2^+ member of an intruder band built on the 0^+ first excited state in ^{96}Zr.

We have located a higher-spin band member as well. Figure 2(b) shows the angular distribution of the 1107-keV gamma ray deexciting the 2857-keV level. It has pure $E2$ character and is consistent *only* with a $4^+ \to 2^+$ decay. The 2857-keV state decays preferentially, although only slightly so, to the 2225-keV state by the 632-keV transition of similar character, as shown in Fig. 2(b). This level can be associated with the 2.87-MeV peak in the (d,^{6}Li) spectrum of Ref. 11, even though their particle angular distribution has been fitted with $L=3$, in contrast with our 4^+ assignment. These facts combined enable us to identify the 2857-keV state as the 4^+ intruder band member. In Fig. 3 we summarize our results, emphasizing the proposed band structure. While $E2$ transition rates for the 632- and 644-keV transitions would certainly prove instructive, they could not be obtained from our measurements and must remain the topic of future studies.

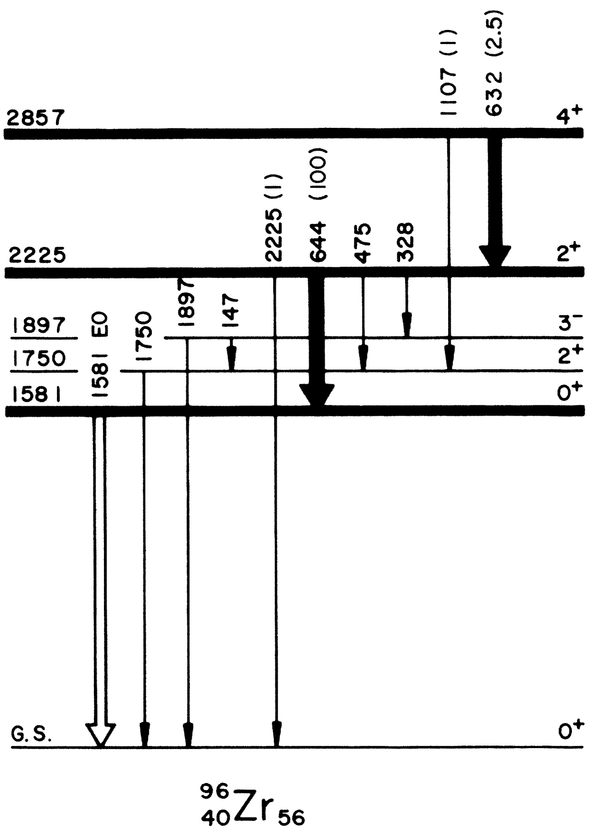

FIG. 3. Partial level scheme for doubly closed subshell ^{96}Zr showing the $4p$-$4h$ intruder band. Numbers in parentheses are the relative $B(E2)$ branching ratios for the J to J-2 transitions.

It is important to understand what gives rise to this coexisting intruder band in doubly closed subshell ^{96}Zr. The slight predominance of the intruder deformed configuration in the ground-state wave function of ^{100}Mo shown in Fig. 1(b) cannot explain the large difference between the alpha-pickup strengths to the two 0^+ states of ^{96}Zr which is clearly demonstrated in Fig. 1(a). This is not unexpected, since the simultaneous occurrence of proton *and* neutron subshell closures should produce a marked difference with respect to other nuclei near the middle of the 50–82 neutron shell where two-proton, two-hole excitations can account entirely for the observed shape coexistence phenomena. Here, instead, the picture of cross-subshell excitations of proton *and* neutron pairs should be invoked, which produces four-particle, four-hole excitations[1,7] just as in ^{16}O. The driving mechanism is the proton-neutron interaction described by Federman and Pittel[21] which is particularly strong when protons and neutrons are in the highly overlapping $\pi g_{9/2}$ and $\nu g_{7/2}$ orbitals.

Recently, Iachello and co-workers[22,23] have developed the nuclear vibron model which introduces bosonic degrees of freedom with $J^\pi = 0^+$ and 1^- to describe dipole deformation due to clustering. This model can account for several features of nuclei[23] such as the low-lying negative-parity states with small alpha-decay hindrance factors in ^{222}Ra and the unusually large population of groups of excited states in the actinides by the (d,^{6}Li) alpha-pickup reaction. The latter feature is also exhibited by ^{96}Zr. Thus, the observed intruder band could arise from alpha-clustering configurations. As the vibrons are associated[23] with particle-hole pairs, this assumption does not contradict the microscopic picture of four-particle, four-hole excitations. However, without firm evidence for the requisite negative-parity states, alpha clustering cannot be offered as an unambiguous explanation.

In summary, we have given evidence for the 2^+ and the 4^+ member of a coexisting four-particle, four-hole intruder band built on the 1581-keV 0_2^+ state in the doubly closed subshell nucleus ^{96}Zr. We suggest that an alternative explanation in terms of alpha clustering may be possible. Parallel experiments are in progress using symbiotic experimental techniques in order to search for other band members and to establish the degree of collectivity of the states involved.

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