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Subshell effects in the A=100 region

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The A=100 region shows two unusual features only a few nucleons apart: a rapid onset of deformation at N=60 and the existence of an almost doubly-magic nucleus of ^{96}Zr (at N=56) characterized by an almost complete closure of the $d_{5/2}$ neutron and $p_{1/2}$ proton orbits. The purity of the ^{96}Zr g.s. is confirmed by one of the fastest $0^- \rightarrow 0^+$ β-transitions ($\nu s_{1/2} \rightarrow \pi p_{1/2}$) observed[1] in the decay of ^{96}Y→^{96}Zr. Federman and Pittel[2] interpreted a rapid onset of deformation at N=60 as due to a strong attractive neutron-proton interaction between particles in large-j orbits. When neutrons enter the $\nu g_{7/2}$ orbit near N=60 the n-p interaction lowers the spin-partner $\pi g_{9/2}$ orbit which effectively annihilates the Z=40 subshell gap between $p_{1/2}$ and $g_{9/2}$ orbits. There is an opposite effect in ^{96}Zr where far from magic shell closures at N,Z =28 or 50, there is a reappearance of an almost magic shell closures at Z=40 and N=56. The mechanism which overcomes the deformation driving forces in ^{96}Zr results from a mutual re-inforcement of otherwise weak proton and neutron shell closures.

^{16}O, ^{96}Zr, and ^{208}Pb have similar properties[1] with the valence $\pi p_{1/2}$ orbit filled and the valence neutron space influenced by the $\nu s_{1/2}$ orbit. The importance of a simultaneous occupation of low-j orbits by neutron and protons for a mutual reinforcement of subshell closures in ^{96}Zr has been pointed out by Molnár.[3] Thus when large-j neutron orbit crosses a large-j proton orbit there is an onset of deformation while at the crossing of low-j orbits occurs an island of sphericity. Alternatively, doubly magic ^{96}Zr and deformed ^{100}Zr are results of the same n-p mechanism involving a simultaneous occupation by neutrons and protons of specific orbits. Properties of the N_pN_n systematics discussed next will be used to search for other subshell effects in the A~100 region.

The N_pN_n parametrization[4] of collective variables underscores the correlation between the collectivity and the product of the number of interacting valence nucleons of opposite type. In particular, a detailed investigation of a large $132 \leq A \leq 208$ mass region has revealed[5] that, its three subregions, A~150, 160, and 190, which followed different systematics attributed[4] to different relative positions of highly overlapping proton and neutron orbits, can be in fact unified into a single systematics that depends exclusively on the product number of valence nucleons. This was obtained[5] by an inclusion of Z=76 subshell effect into the counting scheme. The resultant uniform systematics of this large region has been explained[5] in terms of two components of the n-p interaction: the monopole part[6,7] responsible for the movement of the single-particle orbits in the spherical limit which defines the crucial valence space by creation and destruction of subshell gaps,[5,8] and the quadrupole-quadrupole term which induces the configuration mixing necessary for deformation. A full separation of these effects demonstrated[5] for the $132 \leq A \leq 208$ region implies that the maxima in the collectivity defined, for example, by the lowest energy of the first excited 2_1^+ state or the highest energy ratio, $E_{4_1^+}/E_{2_1^+}$, for a given isotopic (or isotonic) sequence of nuclei define a mid point of an active neutron (or proton) space which may include up to a few degenerate orbits. Moreover, sharp minima in the collectivity indicate subshell gaps. These properties are used to search for subshell effects in the A~100 nuclei.

A systematics of collective variables in the A=100 region (from Ref. 9) indicate that for isotonic sequences for $N \leq 58$ there are local collective maxima at Z=44/46 consistent with the known subshell gaps at Z=40 and Z=50. At $N \geq 58$ the Z=40 gap is annihilated[2] and the proton space is vastly enlarged.[2,4] The systematics of the isotopic sequences for Zr nuclei indicate (see Fig. 1) collective maximum at N=52/54, which is located at approximately half way between the shell closures at 50 and 56, and a sharp collective minimum at N=56 consistent with a subshell gap at N=56. In Cd (and Sn) nuclei there are two collective maxima at 56/58 and ~70 (~74) and a minimum at about N=64 consistent with the subshell gap at N=64 with the $d_{5/2}$ and $g_{7/2}$ below and the $s_{1/2}$, $h_{11/2}$, and $d_{3/2}$ orbits above the gap. This can be explained if there is a rearrangement of orbits between spherical Zr and Sn nuclei. The lowering of the $\nu g_{7/2}$ and raising of the $\nu s_{1/2}$ relative to other orbits is mass dependent since no valence n-p interaction can be attributed to the closed shell (Z=40 or N=50) $^{90-96}$Zr or Sn nuclei, which raises the question to what extent the movement of orbits between shell closures depends on forces other than a direct n-p interaction of valence nucleons ?

Although weak, a new subshell effect at N=64 suggests that the movement of the $\nu h_{11/2}$ orbit was smaller than for the $\nu g_{7/2}$ orbit. Nevertheless, the $\nu h_{11/2}$ orbit strongly participates in the buildup of collectivity in the A~100 region yet only after the deformation process was started with the occupation of the $\nu g_{7/2}$ orbit. This is implied from a characteristic discontinuity of collective properties at N$\sim$58 for the isotopic sequences of Mo and Pd nuclei. The systematics at N$\leq$58 is due to occupation of $\nu d_{5/2}$ and $\nu g_{7/2}$ orbits. The second phase at N$\geq$58 with a minimum at N$\sim$64 for Mo (and also N$\sim$68 for Pd) nuclei indicates an occupation of the $h_{11/2}$ orbit and its full involvement in the deformation process for A=100 nuclei even below N=66.

A weak subshell effect at N=64 in the Z$\sim$50 nuclei can be explained by a (relative) movement of the $\nu g_{7/2}$ orbit, which by lowering the energy difference with the $\nu d_{5/2}$ orbit annihilated the N=56 gap and at the same time created a gap at N=64. This is equivalent to a two-fold subshell effect in the 132$\leq$A$\leq$208 region[5], where a movement of $\pi h_{11/2}$ orbit annihilated the Z=64 gap and created a new one at Z=76. These phenomena support the interpretation of the deformation process proposed by Federman and Pittel[2]. Furthermore, the movement of the $\nu g_{7/2}$ orbit that annihilates the N=56 subshell gap takes place at the same time when the movement of its spin-partner $\pi g_{9/2}$ orbit annihilates the Z=40 gap. A relative movement of the $\nu s_{1/2}$ orbit appears opposite to that of the $\nu g_{7/2}$. It may suggest that lowering of the $\nu s_{1/2}$ orbit at N=56 is due to the interaction with protons in the $p_{1/2}$ or $p_{3/2}$ orbits and represents an important factor for the magicity of the ^{96}Zr as suggested before.[3]

Subshell effects suggested for the A=100 region imply a counting scheme of valence nucleons more complex than presently accepted.[4] Thus the N_p and N_n numbers are presently overestimated in IBA-type calculations, g-factor systematics and related problems. Furthermore, for nuclei where Z=40 or N=56 subshell gaps are weak or totally annihilated the previously closed inner orbits of $\nu d_{5/2}$, $\pi f_{5/2}$, $\pi p_{3/2}$ and $\pi p_{1/2}$ are active and thus, should be included explicitly in the shell model calculations.

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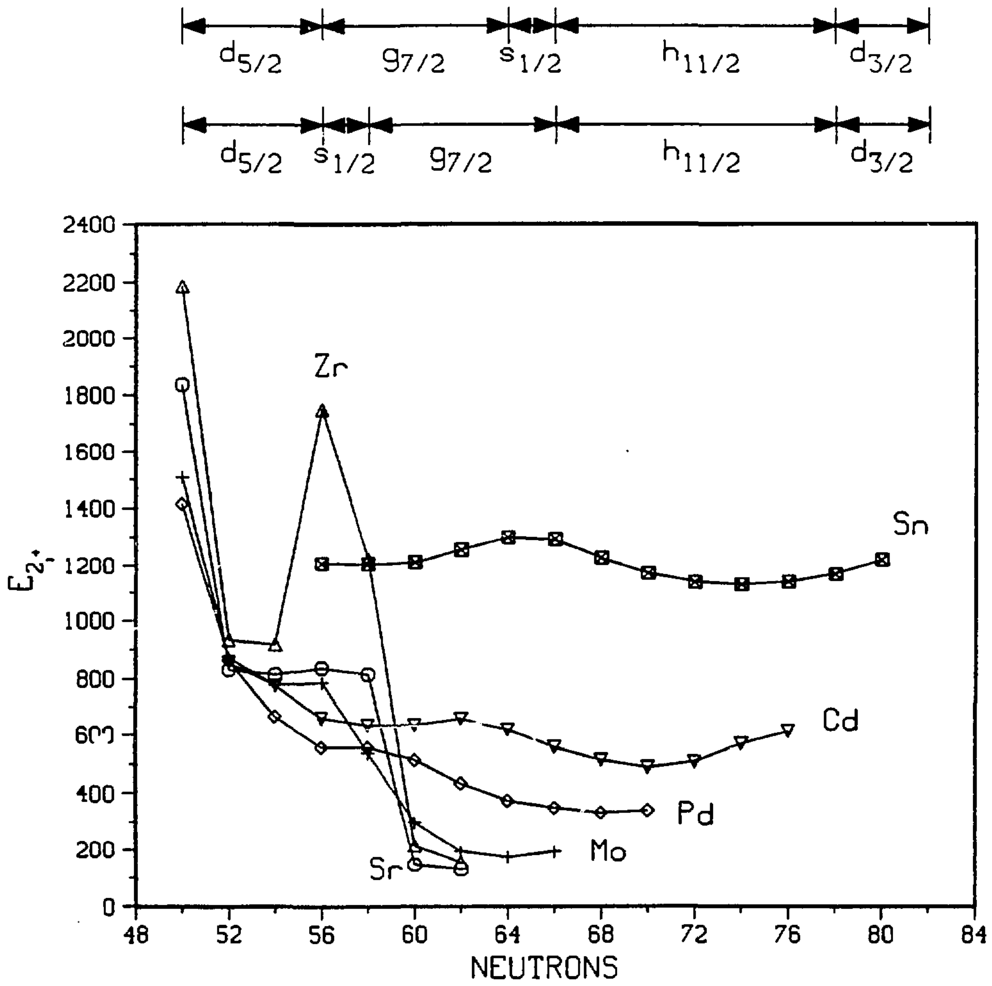

Fig. 1 Energies of the 2_1^+ states (from Ref. 9) plotted against the neutron number for selected isotopes in the A∼100 region. Sequences of shell model orbits suggested for ^{96}Zr (lower row) and Sn nuclei (upper row) are illustrated in the top.