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VALENCE PROTON-NEUTRON INTERACTION STRENGTHS FROM DOUBLE BINDING ENERGY DIFFERENCES

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Empirical p-n interaction strengths have been extracted from experimental mass data using double-difference binding energy equations. The especially strong interactions for self-conjugate nuclei will be discussed as well as microstructure found for deformed and in doubly magic regions. Valence correlation schemes provide a basis to comment on the stability of medium mass near-drip-line nuclei and superheavy elements.

1 Introduction

Even though it has been known for many years[1-6] that the T=0 component of the proton-neutron interaction is primarily responsible for configuration mixing and the onset of deformation in medium and heavy nuclei, there has been a resurgence of interest in interpreting a wide variety of nuclear phenomena in terms of this force. Recently, simple parameterizations such as N_pN_n, the valence nucleon product, and $P \equiv N_pN_n/(N_p+N_n)$, a measure of the competition between the deformation-driving quadrupole p-n interaction and the spherical-driving like-particle pairing interaction, have been successful in systematizing many observables.[7,8,9] While these valence correlation schemes account for the gross systematic behavior of nuclear properties in the regions between shell closures, it is clear that a more comprehensive analysis of the p-n interaction, including its orbit and isospin dependence, would lead to a richer understanding of its role in defining structure. Nevertheless, we will adopt a simple empirical approach in this paper.

2 Empirical p-n Interaction Strengths

Near closed shells, empirical methods have been used to extract both T=0 and T=1 interaction strengths and to develop phenomenological residual interactions.[2,10-12] The T=1 component, which is identical to the n-n and p-p residual interactions, assuming charge independence, is strongly attractive in the J=0 (pairing) state but becomes repulsive as J increases. In contrast, the T=0 interaction is nearly always attractive and is, on average, stronger than the T=1 force.

Here, we present empirical p-n interaction strengths, throughout the nuclidic chart, extracted using simple double difference equations. This method was introduced by Zhang *et al.*,[13] and for even-even nuclei is given by,

$$\delta V_{pn}(N,Z) \equiv \{[B(N,Z) - B(N-2,Z)] - [B(N,Z-2) - B(N-2,Z-2)]\}/4, \qquad (1)$$

where B(N,Z) is the (negative) binding energy of an even-even nucleus with N neutrons and Z protons. This simple procedure cancels the p-p and n-n mean field contributions thus isolating the average p-n interaction energy between the last proton and last neutron. Recently, this approach has been extended to odd-A and odd-odd nuclei[14,15] where the meaning of δV_{pn} is not quite the same due to the specific orbital occupancy of the odd particle or particles. We use here the equations for δV_{pn} for all types of nuclei as presented in Ref. 15.

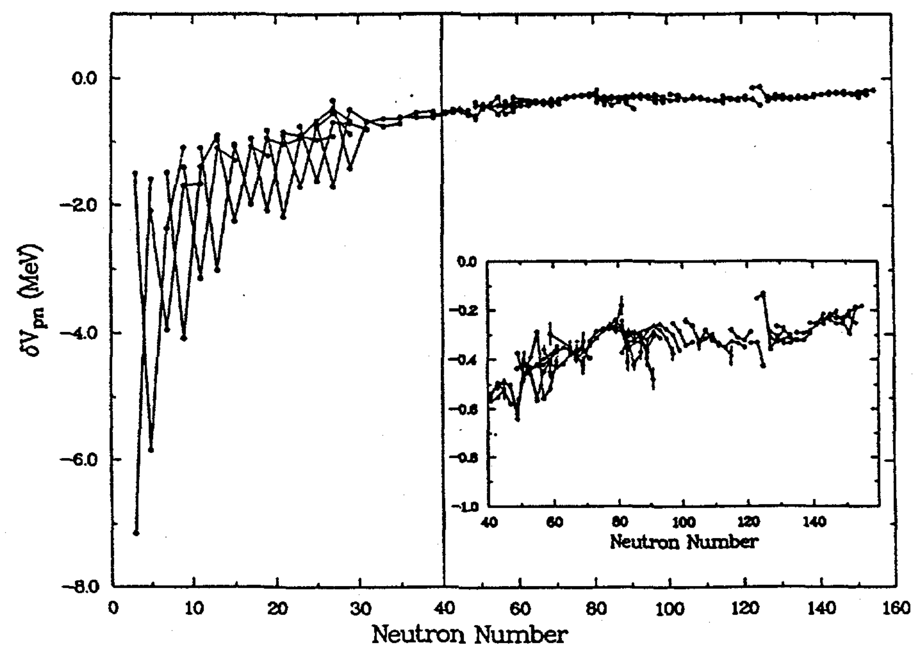

Figure 1: δV_{pn} values from experimental binding energies. (Note the change in horizontal scale at N=40.) The inset is an expanded view for N>40. The sharp downward spikes all occur at N=Z.

δV_{pn} values with precision better than 50 keV are shown in Fig. 1. Three features are immediately evident; a smooth systematic decrease (excepting N=Z

nuclei) in $|\delta V_{pn}|$ with increasing A, a large enhancement in $|\delta V_{pn}|$ for N=Z nuclei, and small, yet significant, fine structures more evident in deformed regions and near shell closures.

2.1 A-Dependence of δV_{pn}

In Fig. 1 we see that δV_{pn} exhibits a generally smooth decrease in magnitude (from ~700 keV for light nuclei to ~200 keV in the actinides) as A increases, excepting the special case of N=Z nuclides. Qualitatively the behavior is understood in terms of the radii of the proton and neutron orbits. As Z and N increase successive oscillator shells fill and the orbit radii of valence particles increase. Since the range of the residual interaction is short and roughly constant, as the average distance between the last proton and neutron increases, the interaction strength decreases, even for particles in equivalent orbits. For medium mass and heavy nuclei, where protons and neutrons are filling different shells, this effect is exacerbated.

2.2 N=Z Enhancements

Perhaps the most remarkable feature of Fig. 1 is the occurrence of especially large interaction strengths for N=Z nuclei. For these nuclei δV_{pn} increases by a factor of 2 or more relative to N≠Z neighbors and ranges in value from ~1.5 to more than 6 MeV, pointing to special p-n interaction effects in such nuclei. This feature, which is implicitly incorporated in successful mass equations by introducing an asymmetry term, has been investigated using both schematic and realistic shell model calculations and shown to be a consequence of the T=0 p-n interaction.[16]

Very recently Van Isacker *et al.*,[15] revisited this phenomenon and concluded that the N=Z enhancements of $|\delta V_{pn}|$ are an inevitable consequence of Wigner's SU(4) symmetry. Furthermore, they were able to demonstrate that the degree of enhancement provided a sensitive test of the quality of the symmetry itself. As mass increases, the SU(4) symmetry is increasingly broken, as indicated by the fall-off in $|\delta V_{pn}|$ with N in Fig. 1. While the systematics of δV_{pn} suggest that such N=Z enhancements will disappear in heavier nuclei due to two effects which conspire to disrupt the SU(4) symmetry, the spin-orbit term in the nuclear field potential and the Coulomb repulsion, there is speculation that a *pseudo*-SU(4) symmetry could restore the strength of the interaction for N=Z nuclei beyond ^{56}Ni.[15] The measurement of masses and determination of δV_{pn} along the N≈Z line from ^{56}Ni to ^{100}Sn, a stated goal for radioactive beam facilities, should provide a sensitive test for the existence of a *pseudo*-SU(4) symmetry in these nuclei.

2.3 *Microstructure and Orbital Occupancy*

It is also instructive to examine the orbit sensitivity of the p-n interaction as manifested by the fine structure visible in Fig. 1 and expanded in Fig. 2. Fig. 2a shows the region around doubly magic ^{208}Pb where rather sharp jumps in δV_{pn} occur as both N and Z pass through the shell closures at N=126 and Z=82. Qualitatively, this behavior reflects the spatial overlap of valence orbitals. When valence protons and neutrons are *both* filling either low-*j* orbits at the end of a major shell or high-*j* orbits at the beginning of the following one, a strong p-n interaction results from the high degree of spatial overlap. In contrast, when one type of nucleon is at the end of its shell and the other at the beginning of a shell the interactions should be much weaker because of the very different inclinations of the orbits. For Z=81, N<126 the last proton occupies a low *j* (e.g., $s_{1/2}$) orbital at the top of the 50-82 shell while the neutron hole is also in a low *j* orbital (e.g., $p_{1/2}$) near the top of the 82-126 shell. These orbitals have good spatial overlap resulting in a strong p-n interaction. Just above Z=82, in contrast, the valence protons are in high-*j* orbits (e.g., $h_{9/2}$, $f_{7/2}$) which overlap poorly with the $p_{1/2}$ neutrons yielding a weak p-n interaction. However, once the neutron shell is filled (N>126) the $g_{9/2}$ orbital is occupied and we expect a strong p-n interaction with the valence protons. This is indeed what is seen in Fig. 2a for even-even nuclei. These qualitative arguments have been substantiated by *both* shell model and Nilsson model calculations where excellent agreement was obtained with experiment.[17] A similar effect has been reported for odd-Z, even-N nuclei in this region by Zhao *et al.*[14]

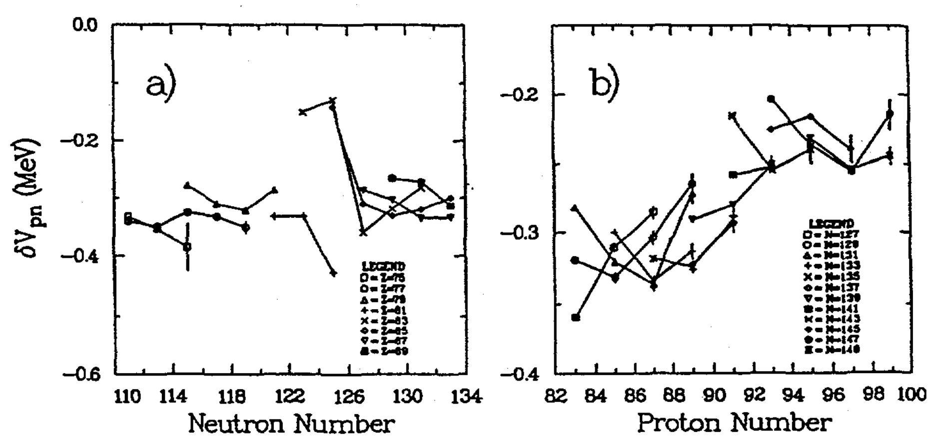

Figure 2: All experimental δV_{pn} for even-even nuclei in (a) the ^{208}Pb region and (b) the actinides. See Ref. 16 for details.

Additional insight into the orbital dependency is gained by considering the behavior of δV_{pn} in a deformed region, such as the actinides (Fig. 2b). Here we see a clear trend toward smaller $|\delta V_{pn}|$ as Z increases toward mid-shell. This trend can be understood in a Nilsson model context where all shells exhibit a characteristic structure. At first nucleons enter steeply downsloping equatorial orbits and then, as the shell fills, the orbit inclinations gradually increase, ending with the filling of polar orbits. Very approximately, then, as any given shell is being filled, the fractional occupancy of the shell serves as indicator of valence orbital slope. For example, in the actinide region near Z=84 the δV_{pn} values result from neutrons near the beginning of the neutron shell so that both protons and neutrons occupy orbits of similar *j* values. As a result $|\delta V_{pn}|$ is high. Near Z=94, N≈145, in contrast, the valence proton orbits are significantly more downsloping than those for the valence neutrons and $|\delta V_{pn}|$ is considerably reduced.

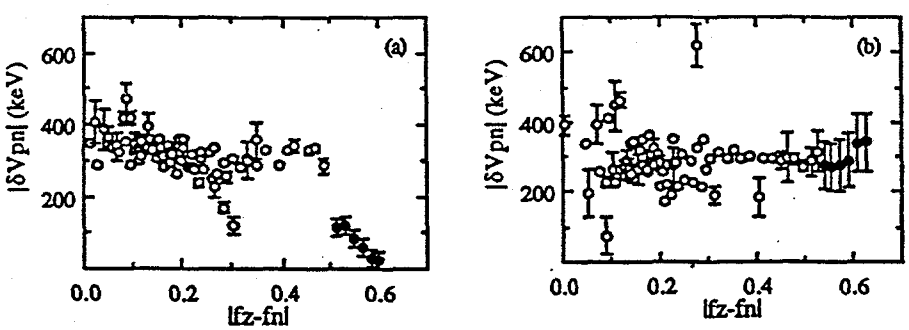

Figure 3: Average attractive p-n interaction strengths for (a) even-even nuclei and (b) for even-Z, odd-N nuclei in the Z=50-82, N=82-126 region. See text for details.

The concept of fractional filling can explored further. Fig. 3a shows a plot of δV_{pn} for even-even nuclei as a function of the quantity $|f_Z-f_N|$ for the Z=50-82, N=82-126 region. Here f_Z and f_N are the fractional filling of the proton and neutron shells, respectively. Thus a small value of $|f_Z-f_N|$ corresponds to those instances where protons and neutrons are filling their respective shells to the same degree and a large value, the opposite. The significance of $|f_Z-f_N|$ is that the attractive p-n interaction should be strongest among protons and neutrons in nearly coplanar orbits, i.e., ones with small values of $|f_Z-f_N|$ and weakest when $|f_Z-f_N|$ is large. Although this parameter greatly oversimplifies the actual situation, the correlation seen in Fig. 3a is intriguing in that there is a gradual decrease, on average, for δV_{pn} up to $|f_Z-f_N|$~0.3, a plateau from 0.3 to 0.5, followed by a steep drop. What is especially interesting is that all the data beyond $|f_Z-f_N|$=0.5 (shown as filled circles in Fig. 3a) belong to the T_Z=8 chain of nuclei which are linked by α decays extending from ^{172}Pt near the proton drip line to ^{148}Dy. This "arm" of δV_{pn} data is isolated from the main body of data for this region.

To explore this issue further we recently measured the mass of ^{151}Er which serves as the termination point for a known α decay chain beginning at ^{167}Os, in the vicinity of the proton drip line. This measurement determined the masses of six other members of this T_Z=7/2 chain which lies adjacent to the T_Z=8 one. Using the appropriate formula from Ref. 15 we have calculated δV_{pn} for the T_Z=7/2 chain (shown as filled circles in Fig. 3b.) Clearly a very different and somewhat puzzling behavior is seen for the two types of nuclei. Two possible explanations come to mind. There could be some problem with the T_Z=8 chain mass data or the different systematics could arise from different manifestations of an orbital occupancy effect since in even-even nuclei the last two protons are paired and scatter over a number of single particle orbits while in the odd-Z, even-N nuclei the proton occupies a single orbit. Additional mass measurements in this region should provide the means to resolve this issue.

3 Superheavy Elements

We have seen that the p-n interaction plays a critical role in determining structure and stability in nuclei. It is therefore interesting to speculate about the heaviest elements, ones beyond the terminus of Fig. 1. Since the masses are unknown in this region we cannot extract p-n interaction strengths but we can use a valence nucleon correlation parameter, the P factor, which embodies the competition between like-particle pairing and the p-n interaction, as a basis for projection. The definition of P (see Sec. 1) is based on counting the number of valence protons and neutrons from their nearest shell closures, respectively. It has been shown for all major shells in medium and heavy nuclei that P~4-5 is a necessary condition for nuclear deformation to occur.[8] This means that a minimum of 4-5 valence particles of *each type* are required for permanent deformation.

In a recent article[18] a remarkable correlation between the experimental ratio ε/Δ and the empirical P factor was presented for the region beyond A=200. ε/Δ is the ratio of the quadrupole deformation to the pairing gap: the former can be derived from B(E2) values and the latter from mass data. The efficacy for using P and ε/Δ to map the evolution from spherical, closed shell structures to stable deformed shapes has been previously demonstrated for other regions of the mass surface.[19,20] Beyond Z=82, N=126, shell closures are not established and assumptions must be made about their location. Numerous theoretical studies have suggested that the next proton shell may occur at Z=114 and the next neutron shell at N=178 or 184 depending on the details of the potential.[21] It is interesting to see if we can use the correlation of P with ε/Δ to test these shell assumptions.

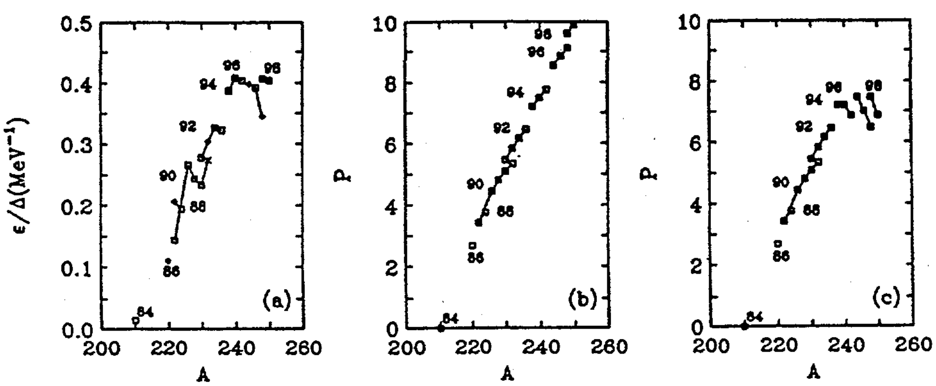

Figure 4: (a) ε/Δ for the A≥200 region; (b) P vs A for the same nuclei as in panel (a); (c) P vs A for this region where P is calculated assuming a subshell closure at N=164.

Fig. 4 is a comparison between the ε/Δ systematics and those of P for the region beyond A=200. Comparing parts (a) and (b) shows that the values for ε/Δ peak near A~240 whereas the values of P, calculated assuming the classical shell assumptions of Z=82, 126 and N=126, 184, continue to rise. This discrepancy between the ε/Δ and P systematics can be resolved simply by invoking a significant *spherical* neutron shell gap at some value of N less than 184. In fact, such a gap is a persistent feature of model calculations at N=164, lying above the $g_{9/2}$, $i_{11/2}$, and $j_{15/2}$ neutron single particle levels.[22-24] If we assume a closure at N=164 then we get the P plot shown in Fig. 4c. Clearly a closure at N=164 significantly improves the agreement between the two systematics. It should be noted that no effect from a proposed proton shell closure at Z=114 should appear until data for higher-Z nuclides are available, since Z=98 (Cf) would be midshell. Therefore, it is reasonable to propose that the ε/Δ systematics are indicative of a *spherical* neutron shell or subshell closure at N=164. It should be emphasized that the P formalism is based on *spherical* shell gaps; *deformed* gaps, such as the one predicted for N=162, do not appear to play a significant role.[9]

It is quite intriguing that elements with Z≥106 and N approaching 162 have enhanced stability against α decay and spontaneous fission compared to predictions of models which do not take into account any stabilizing effect near N~164. Lazarev *et al.*[25] attribute this stabilization to the effect of a *deformed* subshell at

N=162 citing as evidence the enhancement in stability going from $^{260}106$ to $^{266}106$: stability increases by factors of $\geq 3x10^3$ for spontaneous fission decay and $\sim 3x10^3$ for alpha decay. Using the P formalism one can suggest an alternate explanation. Suppose the next shell closures are, in fact, Z=114 and N=164. Then P is 4.44 for $^{260}106$, suggesting a deformed shape, and 2.67 for $^{266}106$, characteristic of a spherical or transitional nucleus.[8] Even if there is no shell at Z=114 and the next proton shell is at Z=126 then P changes from 6.67 to 3.33 which also suggests a deformed to spherical shape transition going from $^{260}106$ to $^{266}106$. Thus it is possible to conjecture that the extra stability that sets in between $^{260}106$ and $^{266}106$ results from a deformed to spherical shape change traceable to a *spherical* shell or subshell at N=164 rather than from a *deformed* one at N=162, independent of the existence of a Z=114 shell.

If, on the other hand, we assume that a shell closure at Z=114 is valid then certain conclusions follow from P considerations. For example, one expects that all even-even nuclei with Z=112-116 will be spherical *even if there is no subshell at N=164*. This is because a minimum of 4-5 valence particles of *each type* are a necessary condition for deformation, as has been found for all other shell regions in medium and heavy nuclei.[8] Of course, there is no conclusive evidence, to date, for the existence of either a Z=114 shell or N=164 shell gap and the source of enhanced stability beyond Z=106 remains an open question at this juncture.

Conclusion

The p-n interaction is a crucial and pervasive determinant of nuclear structure throughout the nuclidic chart. It will be exciting to see how it influences structure at the extremes of nuclear stability; near the proton drip line where new self-conjugate N=Z nuclei will be investigated, near the neutron drip line where new collective modes may exist, and in the superheavy region. Experimental studies of these regions will in many cases require radioactive ion beam facilities.

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