Neutron-Proton Interaction between States of Same l in Nuclear Shell Model*

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Talmi has suggested that the movement of the $g_{7/2}$ neutron state from the top to the bottom of its major shell between $_{40}$Zr and $_{50}$Sn is due to a strong attractive interaction between $g_{7/2}$ neutrons and $g_{9/2}$ protons which fill in this region, arising from the fact that both are g states. Other evidence for this interaction is cited; e.g., the $h_{9/2}$ neutron state moves down several MeV in the region where the $h_{11/2}$ proton level fills ($Z=60$–80), and the $f_{5/2}$ neutron level moves down considerably in the region where the $f_{7/2}$ proton state fills ($Z=20$–28). Other evidence in support of this effect is presented; there is no apparent counter-evidence from nuclear level schemes.

It has recently been shown experimentally[1] that the $1g_{7/2}$ neutron single-particle level moves down in energy relative to the other single-particle states in the same major shell between the zirconium and tin regions. This is shown in Fig. 1(a) where the experimentally determined single-particle states in the two regions are shown. The shift is very large, from near the top of the shell to the bottom. It does not appear to be a size effect since the mass difference between the heaviest zirconium and lightest tin isotopes studied is only 20 amu.

Talmi[2] pointed out that the principal difference between Zr and Sn is that the $g_{9/2}$ proton shell is empty in the former and full in the latter. He therefore suggested that the data may indicate a strong attractive force between $g_{9/2}$ protons and $g_{7/2}$ neutrons arising from the fact that they have the same principal and orbital angular momentum quantum numbers.[2a] It is the purpose of this paper to point out that there is much additional experimental evidence for this interpretation.

The principal evidence derives from cases completely analogous to the Zr-Sn situation in other shells. That is, we present evidence that the $j=l-\frac{1}{2}$ neutron level comes down in energy relative to the other single-particle states as the $j=l+\frac{1}{2}$ proton level fills. The clearest situations of this type arise for (1) the $h_{9/2}$ neutron state while the $h_{11/2}$ proton subshell is filling (between $Z\sim 64$–76), and (2) the $f_{5/2}$ neutron level while the $f_{7/2}$ proton state is filling between $Z=20$ and 28. Less definite situations of this type might be expected for (3) the $d_{3/2}$ neutron states while the $d_{5/2}$ proton states are filling in the regions $Z=8$–14 and $Z=50$–56.

The experimental evidence for case (1) is shown in Fig. 1(b). In $_{58}$Ce^{141}, the $h_{9/2}$ neutron level lies about 2 MeV above the $f_{7/2}$ and $\sim$1 Mev above the $p_{3/2}$ level[3] (the fact that $h_{9/2}$ is at least above $f_{7/2}$ is demonstrated by ground state spins, and stripping on Ba, Pr, and Nd isotopes[3]). On the other hand, in $_{82}$Pb^{207}, for which the $h_{11/2}$ proton level is full, the recently identified $h_{9/2}$ hole level[4] lies 1.1 MeV above the $f_{7/2}$ hole level, indicating that the $h_{9/2}$ single-particle level is at least that much lower than the $f_{7/2}$ state and more than 2.5 MeV below the $p_{3/2}$ state.

The experimental evidence for case (2) is shown in Fig. 1(c); the data are from (d,p) reactions.[5] In Ti^{49}, where the $f_{7/2}$ proton level is only one-quarter full, the $f_{5/2}$ level is about 3.5 MeV above the $p_{3/2}$ level, and even well above the $p_{1/2}$ level. However, in the nickel isotopes where the $f_{7/2}$ proton level is full, the $f_{5/2}$ is rather close to the $p_{3/2}$, and well below the $p_{1/2}$ state.

The situation in case (3) is less certain, but is surely not contradictory. In O^{17}, where $d_{5/2}$ is empty, the $d_{3/2}$ neutron state[6] is more than 4 MeV above the $s_{1/2}$, whereas in Si^{29}, for which the $d_{5/2}$ proton state is filled, the $d_{3/2}$–$s_{1/2}$ separation is only a little more than 1 MeV.[7]

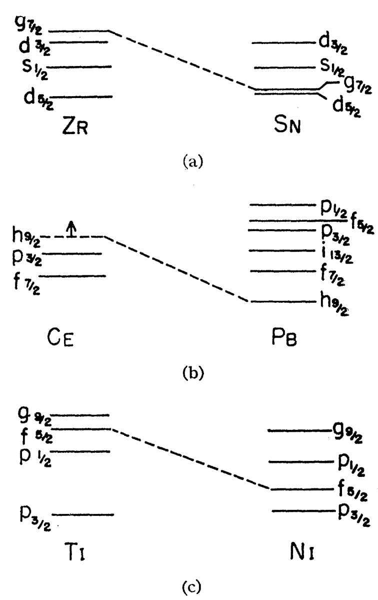

Fig. 1. Shell-model levels in various regions of the periodic table. See discussion in text.

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[1] B. L. Cohen, Phys. Rev. **125**, 1358 (1962).

[2] I. Talmi (private communication).

[2a] *Note added in proof.* Similar suggestions have been proposed by A. M. Lane.

[3] R. H. Fulmer, A. L. McCarthy, and B. L. Cohen (to be published).

[4] P. Mukherjee and B. L. Cohen, Phys. Rev. (to be published).

[5] B. L. Cohen, R. H. Fulmer, and A. L. McCarthy, Phys. Rev. **126**, 698 (1962).

[6] E. L. Keller, Phys. Rev. **121**, 820 (1961); other references are listed therein.

[7] A. G. Blair and K. S. Quisenberry, Phys. Rev. **122**, 869 (1961).

This evidence should probably not be taken too seriously since the fractional mass change is large, and the $s_{1/2}$ state may not be completely empty in Si^{28}. In the region between masses 50–56, the situation is even less clear since the $d_{5/2}$ proton state may not be filling appreciably. However, the surprisingly small separation between the $d_{3/2}$ and $s_{1/2}$ single hole states in the 81-neutron isotope Ba^{137} (0.28 MeV vs 1 MeV for the corresponding particle states at the beginning of the shell) is consistent with the effect we are studying. *Note added in proof.* The $d_{3/2}$–$s_{1/2}$ separation has been found[3] to decrease from Ba^{137} to Ce^{139} to Nd^{141} as expected from this effect.

It is important to point out that the cases considered here were not selected; they represent the only cases where a $j=l+\frac{1}{2}$ neutron state can be studied experimentally in a region where a $j=l-\frac{1}{2}$ proton state is filling. All other cases are in regions too far from the stability curve to be studied experimentally.

A secondary line of evidence for our thesis may be derived from differences between single-particle level orders for neutrons and protons. The attraction between neutrons and protons in the same l state is in some ways an isotopic spin analog to the pairing force. The latter increases in strength with increasing l, so that a similar behavior might be expected for the latter.

In heavy nuclei, when a given proton state is filling, the corresponding neutron state is already full, but the opposite is not true. Thus, the effect we are considering should lower all proton states. However, if the effect is stronger for higher l, those states should be lowered more. Thus, the high-l states should lie lower relative to the lower-l states for protons than for neutrons. Such an effect has been well known for sometime; it was ascribed by Klinkenberg[8] to Coulomb effects, but perhaps the effect considered here may also be important.

The author is greatly indebted to I. Talmi for first suggesting this explanation of the Zr data, and to P. Mukherjee for various helpful discussions.

[8] P. F. A. Klinkenberg, Revs. Modern Phys. **24**, 63 (1952).