A double potential model for neutron halo nuclei

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Abstract

It is shown here that loosely bound halo structure of neutron rich nuclei and the ground state spin of single neutron halo nuclei are correlated and are consistently explained if one assumes a double potential shell model for these nuclei.
Halo nuclei offer unique challenges in nuclear physics. It seems that around a core of a few nucleons, there sit one or two nucleons very far away from the centre of the whole nucleus but still bound to it. As such their radii are much larger than what should be as per our understanding in standard nuclear physics [1]. Another feature is that for all the single neutron halo nuclei discovered so far the ground state spin has always been \( \frac{1}{2}^+ \). At present this is being interpreted as shifting and mixing of single particle levels in the shell model [1,2]. Here we make a novel suggestion of a double potential shell model which accounts for both the loose halo structure and its ground state spin. Hence it is shown that the two are correlated in a basic way in this new model.

As of now a few two neutron halo nuclei and a few single neutron halo nuclei have been discovered. However what is puzzling is the experimental fact that for all the single neutron halo nuclei [1-3] ( which are \( {}^{11}\text{Be} \), \( {}^{15}\text{C} \) and \( {}^{19}\text{C} \)) the ground state spin has always been \( \frac{1}{2}^+ \). At present this is being viewed as shifting and mixing of different levels in these diverse nuclei in ways which may justifiably be called ”mysterious and arbitrary”. The author feels that for such unique and global features as very loose structure of the valence neutron and the unique ground state spin of \( \frac{1}{2}^+ \) in all the cases known there has to be some common connection which should be basic and ”simple”.

What is it that these empirical features are hinting at. Let us use the fact that the core is almost decoupled from the valence neutrons. In simple shell model we know that the central potential follows rather closely the nuclear density distribution [4].

\[
V = -V_0 \int_0^\infty \rho(r) r^2 dr
\]  
(1)

Let us put the empirical fact that the total density in a halo nucleus may be written as made up of a core and a halo part

\[
\rho(r) = \rho_{\text{core}} + \rho_{\text{halo}}
\]  
(2)

And thus the total potential separates out as

\[
V = V_{\text{core}} + V_{\text{halo}}
\]  
(3)
Hence the author here makes a suggestion that these features are hinting at the existence of double potential for these nuclei. A schematic plot of such a double potential well is given in Figure 1. Let us take $^{11}_4Be_7$ as an example. Here as per empirical information $^{10}_4Be_6$ forms a core and a single neutron orbiting it in a loose halo around this core. We assume that the core $^{10}_4Be_6$ is built as per standard shell structure in the inner potential in Fig 1. The second potential structure assumes that it exists because there exists a primary inner potential. Now the last valence neutron fills the orbits in the second potential starting with the s-state. Hence its spin is $\frac{1}{2}^+$ which also is the spin of the whole nucleus $^{11}_4Be_7$. This is the situation in all the single neutron halo nuclei. The core is built upon the inner potential as per standard nuclear shell model and the last valence neutron sits in the lowest orbital to give total ground state spin to the nucleus. If there are two neutrons in the halo then its spin contribution would be zero. Quite clearly in this picture if one were to add any more protons to halo nucleus it will go to the inner shell for these neutron rich nuclei. Quite clearly this double potential is for valence neutrons only. So for $^{11}_3Li_8$ as the 2-valence neutrons which form the halo would sit in the second potential s-state and thus contribute spin zero. Thus the total spin of the nucleus would come from the protons as per these filling up the first potential shell.

This picture predicts that as the lowest orbital in the second potential can absorb only upto two neutrons so halos should most likely be observed for upto two neutrons. In all confirmed cases this is what the situation is, If one wants to add more neutron one has to send it to the higher p-state. This would still be permitted but would require higher excitation energy. So higher number of neutrons in the halo is not ruled out as per this model. However cases with more than 2-neutrons in the halo will be suppressed.

References

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Figure 1: Schematic double well potential to explain the properties of halo nuclei