TRITON CLUSTERING IN NEUTRON RICH NUCLEI

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Abstract

Recently, it has been reported that as one goes from oxygen to fluorine, just the addition of one more proton, provides extraordinary stability to fluorine which can bind six more neutrons beyond what oxygen can. It is shown here that this surprising stability can be understood if neutron rich nuclei, $^{24}O$ and $^{27}F$ are treated as bound states of eight and nine-tritons respectively. Also the recently discovered $^{42}Si$ is predicted to have a bound state structure of fourteen tritons.
It has been found that the doubly magic nucleus $^{28}O$ is unbound and in fact the heaviest isotope of oxygen is $^{24}O$ [1,2]. On the other hand adding just one more proton to oxygen leads to a very neutron rich bound state of $^{31}F$ [1,2]. Both these results are puzzling. As stated by Sakurai [2], "It is remarkable that six additional neutrons can be bound by moving from oxygen to fluorine, where $Z$ differs by one. The sudden change in stability from oxygen to fluorine indicates an extra push of stability for the very neutron-rich fluorine isotope". The reason for this "extra push" is not understood. As stated in [2], a consistent description of all these effects, in the same theoretical framework, is sadly lacking.

Continuing in the same vein, it turns out that $N=28$ though remains magic for $^{42}Si$. But it requires that $Z=14$ become magic too to provide a spherically stable $^{42}Si$ [3]. Thus sudden loss of magicity for $N=20$ but its retention for $N=28$ (though requiring a new proton magic number at $Z=14$) is quite puzzling. However note that the state $^{24}O$ is bound. In the above perspective one is trying to seek common feature between $^{28}O$ and $^{42}Si$. However, actually there is not much common between them, as one is unbound and the other bound.

Let us change our perspective and seek commonality between $^{24}O$ and $^{42}Si$. Both of these are bound - and that is an important common feature to be accounted for. The other common feature is that both of these can be considered as bound states of clusters of tritons - $^{24}O$ of 8-tritons and $^{42}Si$ of 14-tritons.

Just as even-even and $N=Z$ nuclei can be treated as clusters of $N/2$ number of alphas, can it be that we can treat nuclei $^{3Z}_{Z}X_{2Z}$ as a bound state of $Z$ number of tritons?

Indeed, this is exactly what has been suggested and shown to hold empirically [4,5]. This picture clearly seems to hold true even for a very neutron-rich nucleus as heavy as $^{42}Si$.

Let us use this triton clustering picture to understand the above puzzle of as to why as one goes from oxygen to fluorine, just the addition of one extra proton, induces extraordinary stability, thereby allowing for the addition of
as many as six extra neutrons on top of what oxygen can do.

Treating all \( ^{\frac{3Z}{2}} X_{2Z} \) nuclei as being a bound state of \( Z \)-number of tritons \( (\frac{3}{1}H_2) \). So \(^{12}\text{Be}\) is 4-t, \(^{27}\text{F}\) is 9-t etc. Viewed in this manner, the relevant degree of freedom is tritons treated as "elementary" entities. Let us pick out and knock out a single triton from this unique bound state of tritons. This is clearly a single-triton separation energy defined as

\[
S_t = \text{BE}(Z,N) - \text{BE}(Z-1,N-2) - \text{BE}(t)
\]

Let us plot \( S_t \) as a function of the number of tritons in Fig1. The experimental data is from [6]. Here, for example, triton number 8 would correspond to the nucleus \(^{24}\text{O}\) and triton number 5 to \(^{15}\text{B}\) etc. Some remarkable features emerge in this figure. One clear feature is even-odd effect in triton numbers. Whenever triton number is even, the triton separation energy is significantly higher than the adjoining odd triton numbers. This feature is similar to the odd-even effects seen in one neutron and one proton separation energies plotted with respect to the neutron and proton numbers respectively. Therein this is seen as evidence for identical particle n-n and p-p pairing in nuclei.

However the odd-even effect seen in Fig 1. cannot be attributed to identical nucleon n-n or p-p pairing. Here we can clearly and unambiguously attribute it to two triton pairing i.e. a t-t pairing effect in these triton constituent nuclei.

Note that the pairing n-n and p-p, necessarily arises from a shell structure, wherein n-n and p-p are most strongly paired if they are in the same shell. This analogy can be carried over to the bound states of triton in our example here as well. Two tritons in the same shell seem to be strongly paired, thereby leading to a stronger binding with respect to a single unpaired triton.

The next most prominent feature in Fig1. is the highest peak in the separation energy for \( N_t=8 \) i.e. for \(^{24}\text{O}\) and an equally sharp dip for \( N_t=9 \) i.e. for \(^{27}\text{F}\).
We know that such drops in one-neutron and one-proton separation energies when going from one $Z/N$ number to the next one is a signal of magicity character of a particular $Z/N$ number. In the context of our discussion here, magicity means a much stronger binding for a particular number of tritons as compared to the adjoining number of tritons. Hence clearly here $N_t=8$ is a magic number with respect to different bound states of tritons. So clearly there exists a shell structure of the bound states of tritons and wherein there is a large extra stability for $N_t=8$ and indicating magicity for this nucleus.

Let us treat this triton binding potential to be of Harmonic Oscillator (HO) kind. In HO potential the magic numbers are 2, 8, 20, 40 etc. For our bound state of tritons $N_t=2$ is where the system starts and hence may be justifiably treated as magic number. Next $N_t=8$, as indicated above, is indeed a magic number. Unfortunately the data does not go upto $N_t=20$. But clearly as per our model here we predict that $^{60}Ca$, as a bound state of twenty tritons, would be a magic nucleus.

For the case of magicity in one neutron/proton separation energies, to avoid the jumps due to the odd-even effect, one resorts to the smoother plot of two neutron/proton separation energies and wherein magicity is indicated by kinks in the plot at appropriate neutron/proton numbers. So here too we also plot two triton separation energies $S_{2t}$ as a function of the number of tritons in Fig 1. The kink at $N_t=8$ is most prominent, thereby justifying the magic character of $N_t=8$.

We notice that the behaviour of $S_{2t}$ for the region of number of tritons equal to 12-17 appears to be erratic. Note that for triton numbers 12, 14, 15, 16, 17 the masses are actually "estimated" and are not experimental [6]. Infact, the uniform behaviour of the triton separation energies for the region of triton numbers 2-11 in Fig 1 gives us confidence to state that the estimated masses in [6] for the relevant nuclei here, have to be corrected and changed.

To understand the reason that in going from oxygen to fluorine (i.e. an increase of only one proton ) as many as six extra neutrons can be bound to fluorine, let us look at $^4He$. It is an exceptionally bound nucleus and its binding energy is already saturated. Because of its extraordinary stability and also as its binding is saturated, it does not allow extra nucleons to be bound to it. In fact the next bound even-even nucleus after $^4He$ is actually
$^{12}\text{C}$. So extra-stability and saturation translates into lack of interest in interacting with other nucleons to form bound structures. As per Fig 1., $^{24}\text{O}$ is such a strongly bound system of eight tritons. Also the fact that $^{27}\text{F}$ is so weakly bound system of tritons, in comparison, that we can treat $^{24}\text{O}$ as a saturated system of bound tritons. As such (just like $^{4}\text{He}$) it has no interest in binding extra neutrons. Hence $^{24}\text{O}$ is the highest bound isotope of oxygen and also as to why the putative doubly magic nucleus $^{28}\text{O}$ is found to be unbound. In contrast $^{27}\text{F}$ is a much more weakly bound system of 9 tritons. As such it could be willing to add extra neutrons, in fact six as per the detection of the bound state $^{31}\text{F}$. Hence it appears that this feature of oxygen and fluorine is a result of the reality of triton clustering in the neutron-rich isotopes of these nuclei.
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Figure 1: One and two triton separation energies as a function of triton number