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Exploring Efimov States in light 2n halo nuclei.

Vandana Arora[1]
[1](*Department of Physics, Keshav Mahavidyalaya , University of Delhi ,India*)

Abstract: *Efimov effect is the onset of infinite bound states in three body system provided two- body barely bind the binary subsystem. In the year 1970 Efimov discovered this remarkable phenomena in the three particle system. Due to its universal nature it can manifest in any quantum mechanical three body system provided the necessary conditions for its occurrence are achieved. In the present article we propose the three body approach to study Efimov states in light 2n halo nuclei.*
Key Word*:* *EFIMOV STATES,HALO NUCLEI,SCATTERING LENGTH*

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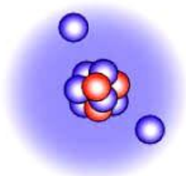
I. Introduction

The Efimov states are observed in ultracold Caesium atom [1], and this has rejuvenated the Efimov Physics . It has given new dimensions and horizons to dwell further experimental search of these unseen states. Initially Efimov states has mostly been searched in atomic system. The helium trimer [2] used to be the happy hunting ground for the occurrence of Efimov states. The obvious reason to search for these states in helium is due to the fact there exist weak binding in He-He binary system which results in large scattering length thereby fulfilling the Efimov criteria. The extensive theoretical studied were made to search Efimov states in helium trimer but not a single experiment confirmed the existences of these states. The advent of radioactive ion beam has led to major advancement in the field of Nuclear Physics. There is an expansion in nuclear chart with the discovery of new nuclei. The matured techniques have resulted in creation of new nuclei with extreme ratio of N/Z. The most spectacular is the discovery of exotic nuclei called "Halo Nuclei" [3]. The unique and striking properties of these nuclei requires new theories to understand their structures. . Further experimental measurement of quadrupole moment of ^{9}Li and ^{11}Li ruled out any deformation of ^{11}Li [4]. The narrow momentum distribution of fragments of halo nuclei indicated large spatial extent. The formation of halo i.e. low density cloud around the core (ordinary nuclei) is well accepted now. The figure (1) shows ^{11}Li halo nuclei with 2 neutrons loosely bound orbiting around core.



II. Favorable conditions for the manifestation of Efimov Effect.

The quantum mechanical three particle system can have infinite bound states if the two body barely bind the binary subsystem is Efimov phenomenon. Efimov [5] showed that in case of three identical bosons bound by very weak two body short ranged force can bear infinite number of bound states. The cause of this effect is emergence of attractive three body long range attraction and this attraction may give rise to large number of three body bound states. The prerequisite for the Efimov effect to manifest in a three body system is the presence of resonating force between the two body binary subsystems. The two body forces must be short ranged r_0 with large scattering length a_{sc} .

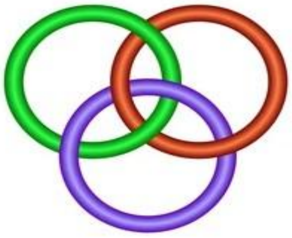
$$a_{sc} \gg r_0$$

Another condition to be fulfilled is the low energy requirement i.e. two body as well as three body energy of the system must be small . The conditions may look severe initially but can be realized in few systems. For instance the case of helium trimer the $a_{sc} = 104A^0$ and $r_0 = 9\ A^0$. In nuclear system the separation energies are of the order of 6 to 8 MeV. Clearly the ordinary nucleus does not fulfill the condition for Efimov states. But in case of exotic nuclei we can hope to find these states. The halo nuclei are well suited to search for these states. The very weak binding of valence neutrons and large spatial extent make them eligible candidates for Efimov states. The two neutron halo nuclei can be visualized as loosely bound three body systems with large spatial extent. The experimental data available for two neutron separation energy for known halo nuclei is listed below in table 1.

S no.	Nuclei	Separation Energy (MeV)
1.	^{6}He	0.971
2.	^{11}Li	0.300
4.	^{14}Be	1.260
5.	^{19}B	0.550
6.	^{22}C	0.420

Table 1: Two- neutron (S_{2n}) separation energies of halo nuclei candidates.

III. Borromean in 2n Halo nuclei.



BORROMEAN RING

The discovery of 2n halo nuclei provided ideal three body system to look for Efimov states. The low separation energy of valence neutrons which results in large spatial extents help to fulfil the necessary conditions to manifest Efimov effect. . There are two types of halo nuclei: Borromean and Non Borromean. The Borromean nuclei are the one where no bound states are there in any two body subsystem but the three body system forms a bound system. ^{6}He,^{11}Li,^{14}Be and ^{22}C are few Borromean type of halo nuclei, whereas ^{20}C is Non Borromean.

The name Borromean has been picked from the famous Borromean rings. The three rings are joined in such a manner that removal of any one results in separation of other two.

IV. Three body Model

Nuclei like ^{19}B, ^{20}C can be considered as three body system with a core and two neutrons forming low density cloud around the core. Let two neutrons and core have momenta p_1 , p_2, p_3 respectively. We assume the core to be a structure less and spinless object . The Schrodinger equation for the three body nuclear system is :

$$(\boldsymbol{K}-\boldsymbol{E})\boldsymbol{\psi} = -(\boldsymbol{U_{12}}+\boldsymbol{U_{23}}+\boldsymbol{U_{31}})\boldsymbol{\psi} = \mathbf{0} \qquad \textbf{(1)}$$

Where $\boldsymbol{K}$ and $\boldsymbol{E}$ are Kinectic energy and total energy respectively and $\boldsymbol{U_{12}}$, $\boldsymbol{U_{23}}$ and $\boldsymbol{U_{31}}$ are the respective Potential energies.Further we take nonlocal separable potentials for neutron-neutron and neutron-core subsystems details are given in article[5] , we numerically solve the three body equation to seek solution for two neutron separation energies in the ground and excited states of halo nuclei. We obtained the ground state energies for ^{19}B, ^{22}C and ^{20}C from our three body model. The values of ground state energies are in good agreement with the experimental data available. On the basis of our numerical analysis we observed that Borromean nuclei ^{19}B and ^{22}C are less prone to respond to existence of Efimov states. In contrast ^{20}C which is Non Borromean type of nucleus seems to be better candidate to search for Efimov States. Further we observed that when we increase the two-body interaction (which results in decrease in scattering length), the Efimov States in ^{20}C start disappearing in accordance to Efimov theory[5] as number of Efimov states is governed by

$$N = \frac{1}{\pi}\ln\left(\frac{|a_{sc}|}{r_0}\right)$$

Our analysis shows that ^{20}C is ideal candidate for the occurrence of Efimov effect and experimental probes in this direction is suggested.

V. Conclusion

As a result of advancement in experimental techniques, Efimov states in ultra-cold ^{133}Cs are observed [1]. This gave impetus to search for these states in other systems as well. By controlling the scattering length with the help magnetic field in ultra-cold atoms Efimov conditions are realised and these states are seen experimentally. This effect is remarkable due to its universality. As effect can manifest itself in any three body quantum system provided necessary conditions for its occurrence are met. The conditions for three particle system to interact via two body resonance forces and low energy condition is difficult to realise. Due to this reason Efimov states are observed experimentally after 36 years of its theoretical prediction. The advancement in the field of radioactive ion beam has resulted in new era of Nuclear Science. The halo nuclei provides ideal scenario to search Efimov states. With the help of matured techniques, experimental observation of these states in light halo nuclei is desired.

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