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Nuclear Physics A 790 (2007) 257c–261c

Efimov effect in $2n-$core halo nuclei and appearance of resonant states in $n-{}^{19}$C scattering

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A brief overview of the attempts carried out by us in recent years to study the structural properties of 2n-rich halo nuclei such as ^{14}Be, ^{19}B, ^{22}C, and ^{20}C in the light of Efimov effect is presented. In particular, the effect of occurrence of Efimov state in ^{20}C is analysed to show how it causes a resonance in $n-{}^{19}$C scattering near scattering threshold. The observed asymmetric structure has been identified to have a close resemblance to Fano resonance widely known to occur in atomic and molecular phenomena.

1. INTRODUCTION

Efimov's treatment[1] of three body quantum mechanical systems with resonating pair-wise interactions resulting in an effective attractive inverse quadratic potential as a function of three body radial variable (hyper radius. R) leading thereby to an infinite number of weakly bound states, has proved to be a landmark result in few body quantum physics. It opened new vistas in research and attracted great interest in many areas of physics. Indeed the observation of Efimov quantum states has remained an elusive goal for many years. Recognizing the central role of 'Efimov physics' in Bose-Einstein condensation and other ultra cold phenomena in dilute atomic gases, the first experimental observation of Efimov states has only recently been reported [2] in ultra cold cesium trimers.

We believe that our study of 2n-rich halo nuclei has complementary aspects and holds the hope of observing this phenomenon in nuclear systems. Before describing the central theme of the present work, let me give you a flavour of some of the attempts we made in recent years to study the Efimov effect in some of the neutron-rich halo nuclei.

2. EFIMOV EFFECT IN ^{14}Be, ^{19}B, ^{22}C, AND ^{20}C

The first attempt[3] in this direction was to investigate Efimov effect in the nucleus ^{14}Be - considered as n-n-^{12}Be three body system. Assuming a possibility of the existence of low lying s-orbital state for the halo neutrons with ^{12}Be as core, the idea was to explore the consequences of considering such an intruder state in the context of studying the structure of ^{14}Be as a three body system and looking, in particular, for its effect on the occurrence of Efimov states. We thus assumed s-state interactions for the n-n and n- ^{12}Be pairs and using separable potentials solved the 3-body Schrodinger equation in momentum space to

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doi:10.1016/j.nuclphysa.2007.03.041

obtain the two coupled integral equations for the spectator functions F(p) and G(p)[4]. For the purpose of studying the sensitive computational details of the Efimov effec, we recast these equations involving only dimensionless quantities by redefining the terms:

$$\tau_n^{-1} = \mu_n^{-1} - \left[\beta_r\left(\beta_r + \sqrt{\frac{p^2}{2a} + \epsilon_3}\right)\right]^{-1} , \tau_c^{-1} = \mu_c^{-1} - 2a\left[1 + \sqrt{2a(\frac{p^2}{4c} + \epsilon_3)}\right]^{-2} \quad (1)$$

These are the factors appearing on the left hand side of the spectator functions F(p) and G(p) respectively. In the above equations,$\mu_n = \frac{\pi^2\lambda_n}{\beta_1^3}$, $\mu_c = \frac{\pi^2\lambda_c}{\beta_1^3}$ are the dimensionless strength parameters; β andβ_1 are the range parameters in the n-n and n-c potentials and $\beta_r = \frac{\beta}{\beta_1}$ and $\frac{-mE}{\beta^2} \equiv \epsilon_3$ is the dimensionless three body (n-n-c) binding energy. For other details see refs. [3,4]. By defining $\tau_n^{-1}F(p) \equiv \phi(p)$ and $\tau_c^{-1}G(p) \equiv \chi(p)$, the two coupled integral equations in $\phi(p)$ and $\chi(p)$ can actually be reduced to one integral equation for $\chi(p)$ (see eq. 6 in ref.[3]). It can then be computed as an eigen value problem after performing the angular integration. By feeding the parameters of n-n and n-c potentials in the kernels, we seek the solution for the three body energy parameter when the eigen value approaches to one, accurate to at least three significant figures. It should be noted that the factors τ_n and τ_c defined above are quite sensitive particularly when the scattering lengths of the binary subsystems attain infinitely large values. In fact, these factors blow up as the variable $p \rightarrow 0$and ϵ_3 approaches extremely small values.

Keeping the range parameter $\beta_1 = 5\alpha$ as fixed, we vary the strength parameterλ_1 to produce virtual n-^{12}Be state at energies varying from 50 keV to 0.01 keV corresponding to scattering length ranging from -21.0 fm to -1491 fm. At 50 KeV virtual state, three body system is found to have binding energy close to the experimental value, but no excited state is predicted. However, for virtual state starting from scattering length -60 fm, the Efimov region begin to develop to produce Efimov states as the scattering length ,a, approaches the value less than -100 fm.

As far the impact of this study, it would be interesting to recall that about a couple of years later, the first experimental evidence of a low lying intruder neutron unbound to ^{12}Be was reported by Thoennessen et.al,[5] from the fragmentation of ^{18}O suggesting a virtual state with scattering length a < -10 fm.

The above methodology was then extended to carry out the analysis of the occurrence of Efimov states in 2n-rich nuclei like ^{19}B, ^{22}C, and ^{20}C [6]. The important point to note here is that in the case of Borromean type nuclei like ^{19}B and ^{22}C, where $n-n$ and $n-$core are both unbound, the Efimov region begins to develop only when the $n-$core corresponds to a virtual state with a scattering length of the order of a few hundred fermis. On the other hand, in the case of non-Borromean ^{20}C, for $n-^{18}$C binding around 60 keV or less corresponding to the scattering length ≥ 20 fm, the signatures of the occurrence of Efimov states begin to appear. This can be easily explained from analytical considerations as follows:The point to realize here is that the Efimov region resulting from the universal character, independent of the detailed nature of the two body interactions, is essentially governed by eqn.1 given above. Expressed in terms of the two body scattering length, the above equation for the n-core system, for instance, can be rewritten as

$$\tau_c^{-1} = 2a\left[1 - \frac{2}{\alpha_{nc}\beta_1} - \frac{1}{1 + \sqrt{2a(\frac{p^2}{4c} + \epsilon_3)^2}}\right] \quad (2)$$