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Efimov effect in 2-neutron halo nuclei

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Abstract. This paper presents an overview of our theoretical investigations in search of Efimov states in light 2-neutron halo nuclei. The calculations have been carried out within a three-body formalism, assuming a compact core and two valence neutrons forming the halo. The calculations provide strong evidence for the occurrence of at least two Efimov states in ^{20}C nucleus. These excited states move into the continuum as the two-body (core-neutron) binding energy is increased and show up as asymmetric resonances in the elastic scattering cross-section of the n-^{19}C system. The Fano mechanism is invoked to explain the asymmetry. The calculations have been extended to ^{38}Mg, ^{32}Ne and a hypothetical case of a very heavy core ($A = 100$) with two valence neutrons. In all these cases the Efimov states show up as resonances as the two-body energy is increased. However, in sharp contrast, the Efimov states, for a system of three equal masses, show up as virtual states beyond a certain value of the two-body interaction.

Keywords. Efimov states; 2-n halo nuclei; separable potential.

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1. Introduction

The advancement in the production of energetic radioactive ion beams (RIB) have opened up new vistas in contemporary nuclear physics. On the one hand it provides the means to explore the structural properties and reaction dynamics of nuclei near the drip lines. On the other hand some of the light, neutron-rich nuclei with their 2-neutron halo structure, characterized by large spatial extension due to the very low separation energy of the neutrons, have emerged as ideal candidates to search for exotic quantum mechanical effects like the Efimov effect [1]. In a landmark paper, over three decades ago, Efimov showed that a three-body system can support an infinite number of bound states near the three-body breakup threshold when the strength of the short-range potential (λ) for the binary subsystems reach a critical value (λ_c) to just bind (zero energy) the binary subsystems [2]. Increasing the two-body coupling strength beyond λ_c results in the rapid disappearance of the infinite number of the three-body bound states. This phenomenon is independent of the details of the two-body force and has been recognized as a universal property of a three-body quantum mechanical system in the low-energy regime [3]. Efimov states have been predicted in atomic and molecular systems, namely, helium and sodium trimers [4]. The central role of Efimov effect in Bose–Einstein condensation and other phenomena in ultracold dilute atomic gases is a topic of current interest. Inspite of an impressive body of theoretical work on Efimov effect the clear experimental observation of Efimov states has remained an elusive goal. Only recently a very strong indication of experimental observation of Efimov states has been reported in cold atom experiments [5,6].

2. Efimov Effect in ^{14}Be, ^{19}B and ^{20}C

The discovery of 2-neutron halo nuclei that can be realistically modelled as a three-body system with a compact core and two valence neutrons have rejuvenated the search for Efimov effect in atomic nuclei. The conditions for the occurrence of Efimov states in 2-neutron halos have been investigated employing the Faddeev equations in coordinate space [7,8]. It has been pointed out that the obvious place to look for the Efimov states is among the halo nuclei with the outer neutrons in the *sd* shells [7,8]. In a series of papers we have studied the structural properties of 2-neutron halo nuclei, such as, ^{14}Be [9], ^{19}B, ^{22}C and ^{20}C [10] in light of the Efimov effect. We have shown through numerical analysis and also from analytical considerations that Borromean-type halo nuclei like ^{19}B and ^{22}C, where n–n and n–core are both unbound, are much less vulnerable to respond to the existence of the Efimov effect [10]. On the contrary, those nuclei, like ^{20}C in which the halo neutron is supposed to be in the intruder low-lying bound state with the core, appear to be promising candidates for the occurrence of Efimov states at energies below the n–(nc) breakup threshold [10]. Our formalism is based upon a three-body model of the 2-n halo nucleus comprising a compact core and two valence neutrons. We assume s-wave separable potentials for the binary subsystems [11]. By solving the three-body Schrödinger equation in momentum space, we obtain two coupled integral equations for the spectator functions $F(p)$ and $G(p)$. These equations are recast involving only dimensionless quantities for studying the sensitive computational details of the Efimov effect. In this process the two-body strength and range parameters for the n–n and n–core systems are made dimensionless. The details are provided in [9] and will not be presented here. The first 2-n halo nucleus studied using this formalism, ^{14}Be, was considered to be a three-body system of a ^{12}Be core and two loosely bound valence neutrons [9]. Keeping the n–core range parameter fixed, the strength parameter was varied corresponding to n-^{12}Be virtual states from 50 keV to 0.01 keV. For a 50 keV virtual state, the three-body system is found to have binding energy close to the experimental value, but no excited state is predicted. As the virtual state energy of n-^{12}Be is decreased, we not only get the ground state energy, but also the excited state energy for the ^{14}Be system. In fact, the first excited state appears for n-^{12}Be virtual state of about 4 keV followed by the emergence of the second excited state at n-core virtual state of 2 keV. This methodology was followed to search for Efimov states in ^{19}B, ^{22}C and ^{20}C [10]. As mentioned in the beginning of this section, the analysis showed that Borromean-type halo nuclei like ^{19}B and ^{22}C are much less vulnerable to respond to the existence of the Efimov effect, whereas, the occurrence of Efimov states seems much more favourable in non-Borromean nuclei, like ^{20}C.

3. Evolution of Efimov states in ^{20}C to resonances

In light of the uncertainties in the experimental data, we have studied the effect on the behaviour of Efimov states in ^{20}C by scanning a wide region of the n-core binding energy from 60 to 500 keV. It has been noticed that as the two-body binding energy reaches around 140 keV, the second Efimov state has its energy less than that of the two-body binding energy leading to an unstable state. Similarly, the first Efimov state also becomes unstable for the two-body binding energy around 240 keV. This is in conformity with what was originally predicted by Amado and Noble about the movement of Efimov states into the unphysical sheet associated with the two-body unitarity cut on increasing the strength of the binary interaction [12]. This particular behaviour was investigated by extending the study in the scattering sector. We studied the elastic scattering amplitude for n-^{19}C system as a function of incident neutron energy by computing the integral equations for the amplitude at energies below the three-body break-up threshold [13]. It was found that for binding energies greater than or equal to 250 keV for the n-^{18}C system the disappearance of the first Efimov state gives rise to a resonance at the neutron energy of 1.6 keV with a full width of around 0.25 keV. The same trend was also observed for binding energies of 200 and 350 keV with the resonances appearing at the same position with similar widths of around 0.25 keV. The second excited state was also found to disappear above the n+^{18}C threshold of about 140 keV with the appearance of a resonance showing the generality of this behaviour.

4. Fano resonances of Efimov states in ^{20}C

A very intriguing feature of the resonances described in the previous section is their asymmetric profiles. This is unlike the symmetric Breit–Wigner or Lorentzian shapes encountered more often in nuclear physics. We have interpreted the asymmetric shapes of the resonances as Fano resonances widely observed and studied in atomic and molecular systems. The Fano resonances originate due to the presence of two alternative pathways to the final state, viz. one directly into the continuum and the other through the embedded discrete state, interfere both constructively and destructively to give the asymmetric resonance. In ^{20}C, the very weak binding and large spatial spread of the Efimov states lead to a strong overlap with the continuum states leading to comparable amplitudes of the two pathways and the very asymmetric profile. We have fitted the resonances by Fano profiles and have extracted the best-fit Fano indices for the resonances [14]. The fits to the resonances at 250 and 150 keV n-^{18}C binding energies yield the same Fano index (q), displaying their origin as members of the same family of Efimov states. In very recent calculations we have revisited the problem of the movement of Efimov states into resonances with increasing strength of the n-core binary system.

5. Mass dependence of the movement of Efimov states

In the previous section we have discussed the appearance of the asymmetric resonances from the Efimov states in terms of the Fano mechanism. In addition we

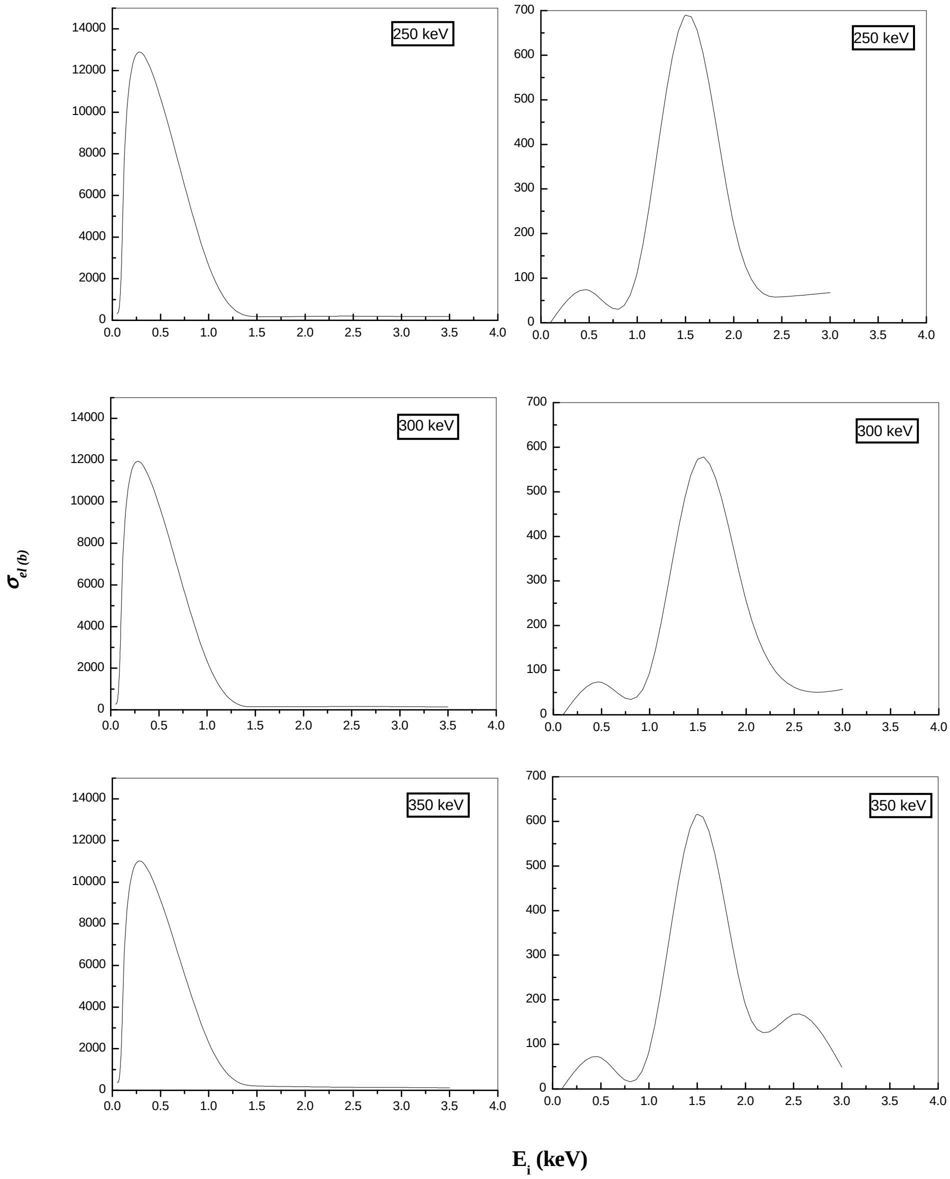

Figure 1. The peak structures in the scattering cross-sections for (right) one very heavy core and two valence neutrons and (left) three equal masses.

have also noticed a clear dependence of the formation of the resonances on the mass ratios of the core and the valence neutrons. We have extended the calculations for a hypothetical case of a very heavy core (∼100) with two valence neutrons and also for a system of three equal mass particles. For the heavy mass ($A = 100$) case we reproduce the same behaviour as seen in ^{20}C. The results further establish the finding of the movement of Efimov states into resonances beyond a certain strength of the n-core bound system. The right panel of figure 1 shows the asymmetric resonance structures in the elastic scattering cross-sections (for a very heavy core) for three different n-core binding energies. We have also checked the scattering length of the n–(n+core) system for the incident energy tending to zero to be positive and large, thereby, supporting a bound state. This helps in establishing the results obtained on a firmer foundation and over a large mass range. The left panel shows the peak position of the elastic cross-sections for a system of three equal masses for three different n-core binding energies. In this case the peak position has shifted towards the origin with very large cross-sections hinting at virtual states. It would be really interesting to search for the same effect of movement of Efimov states to resonances in lighter 2-n halo nuclei with the halo neutron and the core forming a bound system. While ^{20}C is by far the most promising case for an experimental campaign we may suggest few more nuclei, like, ^{38}Mg and ^{32}Ne. For both these nuclei the 2-n separation energies are comparable to that of ^{20}C (2570 and 1970 keV respectively) with the n-core systems of ^{37}Mg and ^{31}Ne nominally bound by 250 and 330 keV. Our 3-body calculations for both of these nuclei reproduce the same trend of movement of the Efimov states into asymmetric resonances with increase in the 2-body interaction strength.

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