

Multi-fermion systems with contact theories

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Abstract

We demonstrate numerically the instability of quantum few-body systems with zero-range resonant two-body interactions if an indistinguishable pair of particles enforces mixed spatial symmetry in the wave function.

The result is significant for the theoretical formulation of any physical system which falls into this universality class in which the two-body scattering length is much larger than the interaction range. We exemplify this with nuclear physics, where the feature is realized as the inability of a momentum-independent contact effective field theory, the EFT(π), to pre-/postdict the bound character of $A > 4$ nuclei. We find a finite interaction range necessary to stabilize an asymmetric A -body system, and we assess the dependence of the minimal value of this range which allows for a bound state on the proximity of a system to unitarity, on A , and on various realizations of discrete scale invariance.

Keywords: P-wave systems, universality, contact effective field theory, unitarity, renormalization, pionless, stochastic variational method, resonating group method.

1. Introduction

Quantum systems whose two-body interaction (range r_0) gives rise to a much larger two-body scale in form of, *e.g.*, a bound or resonant state (typically parametrised by a scattering length a_0), develop behaviour which is universal in the sense of being independent of the energy scale of the problem and the details of the inter-particle interaction. These universal or scale invariant features can thus be identified in hadronic, nuclear, and atomic physics (see, *e.g.*, Refs. [1, 2, 3, 4, 5, 6]) with very different degrees of freedom, masses, and interaction mechanisms because regardless of these differences, they give rise to $r_0/a_0 \rightarrow 0$. Prominent examples of such universal behaviour include the Thomas collapse [8] of the three-body system, the related accumulation of three-body bound states at threshold with a constant energy ratio [7], the correlation between three- and four-body bound states (Tjon line [5]) and between the three-body bound- and scattering-systems (Phillips line [4]), and the spectrum of the multi-boson system [9]. All these examples are expressed in states with total spatial symmetry and are accessible for distinguishable particles, only.

Very few instances of universal behaviour are known in comparison for systems which cannot reside in pure S -wave states. Notable in this regard is the inability of a zero-range theory to stabilize three mass-imbalanced two-component fermions if the mass ratio between the two species is smaller than $m_B/m_A \gtrsim 13$ [10]. A zero-range resonant two-body interaction was found to have similar consequences for the stability of an equal-mass four-body system, in which the universal ratio between the scattering lengths of two two-component dimers to the fermion-fermion scattering length implies the unbound nature of the four fermions [11, 12, 13].

Analyses for nuclei typically focus on larger systems because a single nucleon can access four different internal (iso)spin states, and up to four nucleons can realize Bose-like universality. Realizing the resonant interaction condition within a contact EFT framework, the ^{16}O nucleus was postdicted unstable with respect to a four- α decay [14]. Similarly, ^6He was found not to be stabilized by a momentum-independent short-range interaction [15], but stable if a P -wave attraction is included nonperturbatively. All four studies hint towards a general characteristic of interaction theories with $a_0/r_0 \rightarrow \infty$, namely, the universal prediction of unstable mixed-spatial-symmetry systems (P -wave systems, from here on).

In this paper, we analyze precisely this issue: whether unitary contact

theories in the zero-range limit exhibit unbound P -wave states in general and therefore must be augmented in order to include such stable states for systems which contain them. In our approach, we formulate the contact theory as the leading order (LO) of an effective field theory (EFT). First, we complement afore-cited studies of few-nucleon systems with 6-, 7-, and 8-body calculations. Subsequently, we attempt to find universal and stable P -wave states under the most favourable conditions. Motivated by Ref. [10] in which the binding of two non-interacting identical fermions is induced by a third massive particle for large enough mass ratios between the species, we devise a system of $A + 1$ particles, which includes a pair of identical fermions and $A - 1$ particles forming a massive spatially symmetric core which might induce binding – the number of particles in the core creating a mean field for the out-of-shell particle in which it moves with a larger mass. Increasing the number of particles in the core is by this analogy expected to realize similar conditions as the larger fermion-species mass ratio as in Ref. [10], which might eventually lead to a stable system. As we will show, there is no evidence of P -wave binding even in this ideal scenario independent of the specific realization of the discrete three-body scale symmetry. This leads us to conclude that unbound P -wave states are a consequence of universality and is featured in all the systems at unitarity with a contact S -wave interaction. This conjecture affects theoretical descriptions of all physical systems which can be put into the class of unitary systems, arguably most prominently in the EFT for nuclei, where the P -wave stability for $A > 4$, as of now, is unaccounted for and might demand the promotion of an additional scale.

Theory

The minimal EFT for non-relativistic point particles exhibiting two- and three-body shallow states has been studied extensively (*e.g.* Refs.[16, 17, 18, 19, 20, 21]). The theory is defined as a perturbative series and can be refined systematically to attain a desired accuracy. Its Hamiltonian formulation at leading order (LO) comprises zero-range two- and three-body vertices which depend on the renormalization parameter Λ :

$$H = - \sum_{i < j} \frac{\hbar^2}{2m} \nabla_{ij}^2 + C^\Lambda \sum_{i < j} \delta_\Lambda(\mathbf{r}_i - \mathbf{r}_j) + D^\Lambda \sum_{\substack{i < j < k \\ \text{cyc}}} \delta_\Lambda(\mathbf{r}_i - \mathbf{r}_j) \delta_\Lambda(\mathbf{r}_i - \mathbf{r}_k). \quad (1)$$

In the expansion of any resultant amplitude, the LO is represented by all Born terms depending solely on the coupling constants C^Λ and D^Λ . Parameters representing the aforementioned refinements enter perturbatively at the order given naïvely by their mass dimension. In this work, a Gaussian regulator $\delta_\Lambda(\mathbf{x}) \propto \Lambda^3 e^{-\frac{\Lambda^2}{4}\mathbf{x}^2}$ is used. The specific dependence of C^Λ and D^Λ on Λ thus induced, was calibrated to the energy of a single state in the two- ($B(2)$) and three-body ($B(3)$) system, respectively. Whether or not the Λ convergence of another amplitude depends on the specific choice for $B(2)$ and $B(3)$ classifies the corresponding observable as universal or emergent. The few-body problem is thereby specified at LO with four parameters: the particle's mass (here, $m = 938$ MeV), the number of particles and their statistics, and the dimer and trimer binding energies. The possibility of varying the cut-off and/or including sub-leading orders renders the contact EFT a useful framework for studies of the universal regime.

We use this structure to consider both the nuclear scenario and a class of $(A+1)$ -body equal-mass systems which contain only one pair of indistinguishable particles. Therefore, a subset of A distinguishable particles obeys Bose statistics and can lay on a symmetrical spatial wave functions, as stipulated in the introduction. These arrangements will be referred to as $A \oplus 1$ as this notation has the advantage of immediately exposing the number of particle A that, in a shell model representation, can be arranged in a single shell (*e.g.*, the S -shell). We approach the unitarity limit in these systems by increasing the ratio $v := B(3)/B(2)$, we assume exact unitarity with $B(2) = \epsilon$ in combination with $B(3) = 3$ MeV, and a deviation from it with $B(2) = 1$ MeV and $B(3) \in \{3, 4\}$ MeV. The nuclear case is renormalized to yield the deuterium and triton binding energies of $B(2) = 2.22$ MeV and $B(3) = 8.48$ MeV, respectively. We choose to drop any spin and isospin dependence of the interaction in accordance with the recent formulation [22] of S -shell nuclei in an expansion around the unitarity limit whose LO is (iso)spin symmetric.

The necessary fits for D^Λ employ Stochastic-Variational (SVM, [23]) and Resonating-Group (RGM, [24, 25]) variational diagonalizations. C^Λ is de-

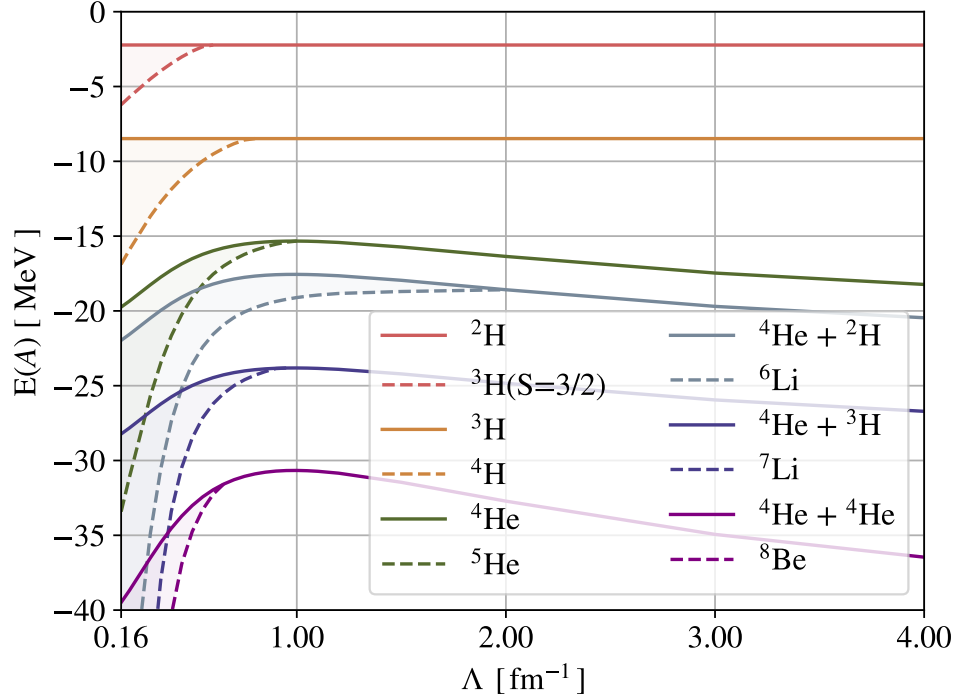


Figure 1: Cutoff dependence of nuclear ground-state energies obtained in LO EFT(π). For $A < 5$, solid lines represent nuclei with spatially symmetric ground-state wave functions. For $A > 4$, solid lines mark the lowest decay threshold into two spatially symmetric fragments. The convergence of the energy with respect to the cut-off was verified, up to $\Lambda \sim 10 \text{ fm}^{-1}$, to be in agreement with the expected $E \propto \frac{1}{\Lambda}$ behaviour [18, 26], however, large cut-offs are omitted in the figure for sake of clarity.

terminated via a Numerov-type integration of the appropriate one-dimensional radial Schrödinger equation.

Results:

Our results as obtained with the above defined theory for the lowest energy eigenvalues of nuclear systems of up to eight nucleons are shown in fig. 1, where we find particle-stable P -wave nuclei (dashed lines) only below a critical cutoff $\Lambda_c < 2 \text{ fm}^{-1}$. For larger cutoffs, *i.e.*, shorter-ranged interactions, the unphysical quartet state of ${}^3\text{H}$ is unstable *wrt.* a decay into deuterium plus neutron, ${}^4\text{H} \rightarrow {}^3\text{H} + n$, ${}^5\text{He} \rightarrow \alpha + n$, ${}^6\text{Li} \rightarrow \alpha + {}^2\text{H}$,

${}^7\text{Li} \rightarrow \alpha + {}^3\text{H}$, and ${}^8\text{Be} \rightarrow \alpha + \alpha$. The precise cutoff value below which a bound state exists is system dependent. For systems with a decay channel into a single nucleon plus a composite, this critical range decreases as follows: $\Lambda_c({}^3\text{H}) < \Lambda_c({}^4\text{H}) < \Lambda_c({}^5\text{He})$. Whether this increase is driven by the decreasing spatial extend of the composite and/or the number of distinguishable particles bound therein shall be discussed below (fig. 3).

Replacing the point-like nucleon with an α particle in the decay channel – note the implied increase in the number of nucleons with identical (iso)spin orientation – the trend is opposite for the positive-parity states: $\Lambda_c({}^8\text{Be}) < \Lambda_c({}^6\text{Li})$. Qualitatively, the exchange interaction between the decay fragments, which supports the nucleon-nucleon attraction, can partially explain this hierarchy. The absence of an effective angular momentum barrier further increases the attraction between the fragments. Apparently, the critical decrease of interaction strength between certain pairs of nucleons (those with identical (iso)spin) in the zero-range limit, is reached at shorter distances if the spatial extend of a fragment and its accompanying exchange interaction compensate. It is beyond the scope of this work to quantify this observation, but the study below (fig. 3) is a first step towards a deeper understanding of the interplay between the established EFT scales (m_π and Λ) and the statistical properties which might in combination lead to additional low-energy scales.

For the applicability of the pionless EFT to a nucleus the magnitude of Λ_c when it decays from bound to unbound matters. For all considered nuclei, we found this transition to occur at interaction ranges which are of the same order or even smaller than the inverse nuclear breakdown scale (expected to be around the pion mass m_π). The stability, *i.e.*, the amplitude pole location on a fixed Riemann sheet, is therefore not invariant *wrt.* appropriate renormalization-group (RG) transformations ($\Lambda \gg m_\pi$), *i.e.*, in regions where the cutoff is expected to parametrize unobservable high-energy behaviour. Hence, the three-parameter theory postdicts correctly only the experimentally established instability of nuclei in the ${}^3\text{H}(\frac{3}{2}^-)$, 3n , ${}^4\text{H}$, ${}^3,4\text{Li}$, and ${}^5\text{He}$ channels. The isotopes ${}^{6,7}\text{Li}$ and ${}^8\text{Be}$ with $J^\pi = 1^+$, $\frac{3}{2}^-$, and 0^+ , which are known to sustain stable states¹ are not correctly reproduced in that aspect. Interestingly, once a bound ${}^8\text{Be}$ ground state is found with $J^\pi = 0^+$ at $\Lambda < \Lambda_c$ the theory orders excited states in the

¹ ${}^8\text{Be}$ is considered to be stable without Coulomb repulsion [27, 28]

rotational spectrum correctly, namely, 0^+ , 2^+ , and 4^+ . The latter two states emerge in form of bound excited states for $\Lambda < 0.4 \text{ fm}^{-1}$.

Is this apparent inability of a contact EFT to stabilize a system of particles which includes an undistinguishable pair dependent upon the fact that the nuclear interaction, which we used above to exemplify this conjecture, realizes the unitarity condition only approximately? In order to assess the potential effect of the finite two-body scale (the deuteron), we employed recalibrated EFTs (theory section) to obtain at unitarity ($v \rightarrow \infty$) a ratio $B(4)/B(3)$ in agreement with Refs. [29, 30] as a benchmark. In addition, $B(A)/B(3)\big|_{v=3} < B(A)/B(3)\big|_{v=4}$, implying that the universal ratios between the A - and 3-body energies is approached from below when taking the unitary limit.

Beyond distinguishable particles, we find systems with $A \oplus 1$ symmetry not stable in states with total orbital angular momentum $L_{\text{total}} = 0$. This confirms the intuitive demand for mixed spatial symmetry due to the presence of an identical fermionic pair. When projecting the spatial component of the wave function onto $L_{\text{total}} = 1$, we find $A \oplus 1$ systems for A between 2 and 6 to sustain stable states ($B(A \oplus 1) > B(A)$) for small cutoffs (see fig. 2 for $v < \infty$). In approaching the contact limit by increasing the cutoff the $A \oplus 1$ systems become unbound at some critical value Λ_c . This Λ_c increases for an interaction which realizes the universal limit $v \rightarrow \infty$ more accurately and will thus support stable systems for a wider range of cutoffs (blue and the red lines in fig. 2). For fixed v , Λ_c 's increase approximately linearly with the system size: $\Lambda_c \propto A < 7$. These observations suggest the existence of a finite Λ_c close-to and at unitarity for arbitrarily large $A \oplus 1$ systems. Hence, the stability of a given $A \oplus 1$ system is undetermined, even in the universal limit, and dependent upon the range of the two-boson interaction, *i.e.*, an additional scale.

These two evidences seems to support the facts, which will be demonstrated to not be true, that the disintegration of such systems is an emerging effect and that increasing the number of particles might enforce stability.

Results presented thus far, substantiate this hypothesis with results for $A > 6$, only. To investigate conceivable deviations from the linear dependence of Λ_c on A , potential divergences in particular, we employ a two-fragment local single-channel resonating-group approximation (to be detailed in upcoming communication in extension of Refs. [24, 31]). This expansion formulates the $(A \oplus 1)$ -body system as a two-body problem of a “frozen” core

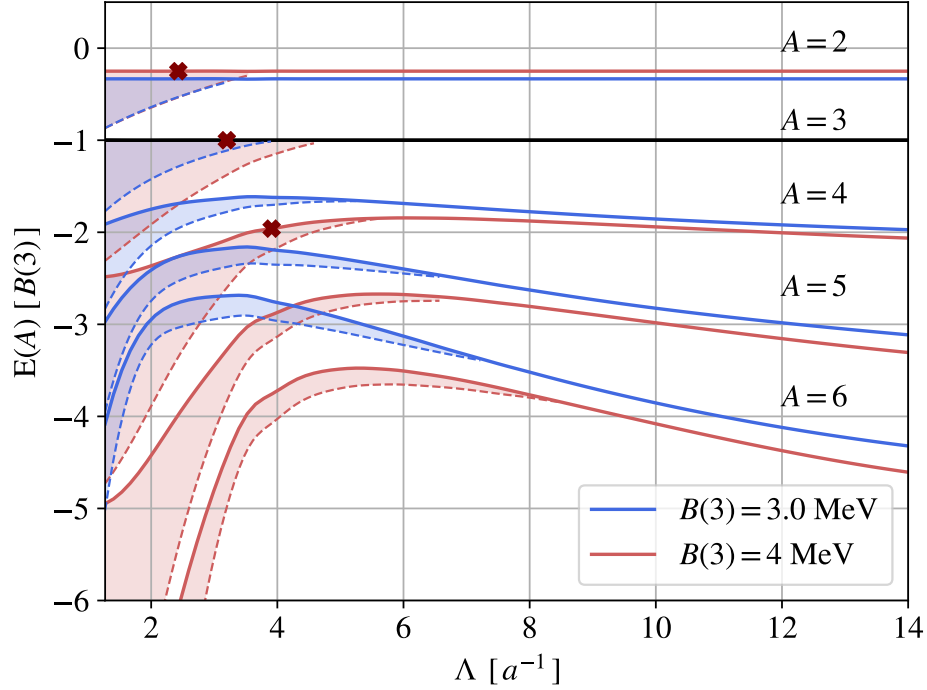


Figure 2: (LO Cutoff dependence of ground-state energies of A spatially symmetric (solid) and $A \oplus 1$ mixed-symmetric systems (dashed) obtained with $B(2) = 1$ MeV and $B(3) = 3$ and 4 MeV (blue and red) from equation 1. The energies and the cut-off are represented in the natural scales, as function of $B(3)$ and scattering length a_0 respectively, this choice make possible the comparison of different v but maks hard to represent the same quantity in the unitary limit with $a_0 \rightarrow \infty$ and $v \rightarrow \infty$. In the case of systems which can support total spatially symmetric ground states, we find convergent behaviour as $\Lambda \rightarrow \infty$ (tested varying the cutoff between $1.2 \text{ a}^{-1} < \Lambda < 60 \text{ a}^{-1}$) consistent with the one described in J.Carlson et al. study [9]. With scattering volume set to zero, the $A \oplus 1$ systems destabilize at smaller Λ_c (red crosses, $B(3) = 4$ MeV). change the graph to have v in the key [and (maybe) we can express Λ in $B(3)$ as whell?]

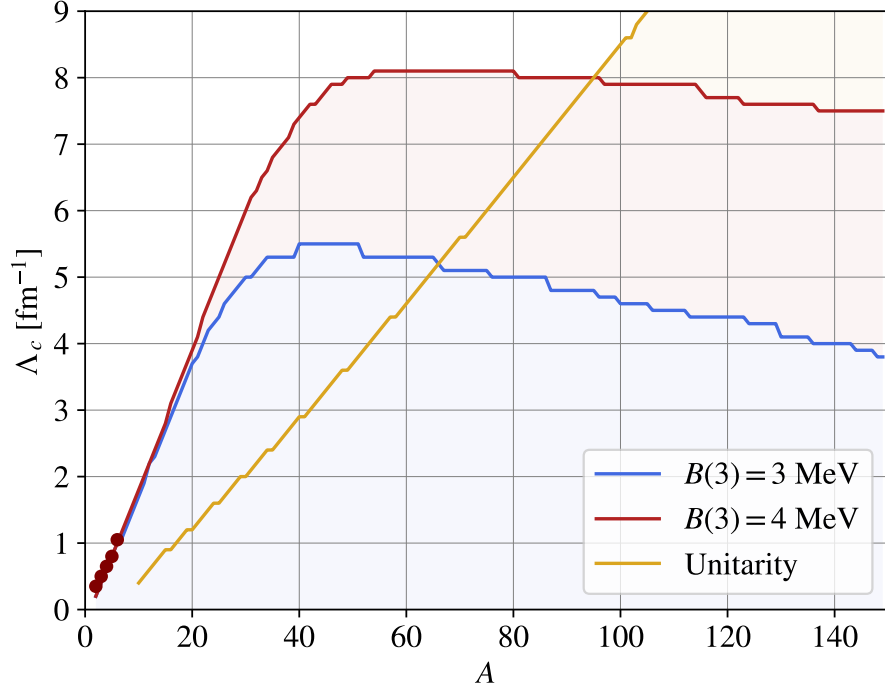


Figure 3: Dependence of the critical cutoff Λ_c on the number of core particles A . SVM few-body results are shown for $A < 7$ (dots, $B(3) = 4$ MeV) along with single-channel resonating-group approximations for $A < 150$ (lines). The unitarity limit (yellow) was realized with $B(2) = \epsilon$ and $B(3) = 3$ MeV and deviations from it with $B(2) = 1$ MeV and $B(3) \in \{3, 4\}$ MeV (blue, red). In the shaded regions, the respective theories do sustain bound $A \oplus 1$ states, while systems above the lines are unstable. The critical cut-off Λ_c is expressed in fm^{-1} (scale defined by the choice of the discrete scale symmetry breaking and the particle mass) to allow the rendering of the unitary limit as well, as each finite cut-off is to be considered extremely hard compared to the scattering length $a_0 \rightarrow \infty$. The step-like change in the curves results from a numerical criterion for the onset of binding and can be removed systematically. the key should be displayed in v [and maybe the cut-off in b_3 ?]

with A particles and a residual fermion which is forced out of their S -wave Pauli shell. The halo character of the systems under consideration motivates a one-parameter representation of the symmetric core as a product of harmonic oscillator ground states, because the increasingly large gap between $B(A)$ and $B(A - 1)$ does not allow for a core excitation by the out-of-shell particle. For $A < 7$, this parameter is fitted to the SVM results for the rms radius of the core. For larger A , we match the core wave function with the drop model formula $r_{\text{rms}} \propto A^{1/3}$ as it was found to be a good description for such systems in ref. [9].

Not at unitarity, we find $\Lambda_c(A)$ to abandon the linear increase found for small A . Λ_c increases up to a maximum number of particles A^* , while this maximum and the associated $\Lambda_c(A^*)$ both increase with v (compare maxima of the blue and red curves in fig. 3). At unitarity, we find a linear dependence recovered with any potential deviation to be found for $A > 100$. The existence of A^* and the deviation from the linear $\Lambda_c \propto A$ relation thus appears to be an effect of deviating from unitarity. In combination with the microscopic results, this confirms the main hypothesis of this work, namely that a system at unitarity cannot support bound states in the zero-range limit if it contains indistinguishable particles.

Revisiting nuclear physics as a specific incarnation of this general class of systems, its description with the EFT(π) will not contain bound states with $A > 4$. In order to allow for the particle-stable character of ${}^6,{}^7\text{Li}$ and ${}^8\text{Be}$ in the zero-range limit as a systematic extension to LO EFT(π), we analyse the mechanism behind the stability of these systems for $\Lambda < \Lambda_c$. Of all artefacts introduced by the finite range of the regulated contact interaction, a finite effective range in the two-body S -wave channel and a non-zero attractive two-body P -wave interaction are expected to dominate. Both contribute to the attraction in the $A \oplus 1$ system but their relative significance in this role is obscure. In other words, the finite-range interaction does not only describe a large S -wave scattering length but also other finite parameters of the effective-range expansion as the effective range r_0 and the scattering volume a_1 . To shed light on their relative importance, we project the two-body interaction into even partial waves. An approximate 50% reduction of Λ_c for all A is observed (purple crosses in fig. 2) as well as a decrease of equal proportion in the relative P -wave binding. We infer from these results a similar significance of the finite r_0 and a_1 for the stability of the nuclear P -wave systems.

As in principle, theory must yield only the analytic structure of an am-

plitude in its range of validity, without need to place the poles therein on the correct sheets, *i.e.*, RG-stable predictions for the character of a state are unnecessary as long as an RG-invariant pole is predicted at all at LO which assumes its true bound, resonant, etc. character at higher orders. Above, we rules out bound-state poles without considering their fate once they intersect with threshold at the critical cutoffs. As a first step, we investigated the $A \oplus 1$ system with $A = 2$. This numerical study confirms the expectation that at unitarity, a shallow $2 \oplus 1$ pole cannot be fixed to a specific energy. In this limit, *i.e.*, for a scale-invariant system, the resonance pole must not represent a scale and thus its location should either merge with the threshold branch cut or diverge for $\Lambda \rightarrow \infty$ ¹. In the first case, three-body unitarity would be a universal consequence of the resonant two-body interaction. In the second case, the pole is an unphysical artefact which disappears with the regulator. Our numerical results exhibit the latter behaviour. Specifically, the $A \oplus 1$ bound-state pole for $\Lambda < \Lambda_c$ hits threshold at Λ_c and moves away from this threshold for $\Lambda > \Lambda_c$. However, for $A > 2$, scale invariance is broken, and the associated emergence of a scale could in principle pin the resonance to a finite energy. The pole trajectory for $A > 2$ could thus be qualitatively different and it remains to be calculated in order to advance the development of a contact EFT for P -wave systems.

Conclusion

We employ a three-parameter non-relativistic contact EFT at LO for the description of P -wave nuclei with up to eight nucleons. We find no bound states for these nuclei if the cutoff-renormalization scale of the theory exceeds a system-dependent critical value. In addition to nucleons with their large but finite scattering length, we find systems which are arbitrarily close to unitarity and realize discrete scale invariance in multiple ways equally unstable for large enough cutoffs, *i.e.*, in the zero-range limit. We conclude that systems whose dynamics is given by momentum-independent two- and three-body contacts, which are constrained by spatially totally symmetric dimer and trimer states, are stable only if their spatial state is also totally symmetric. States of mixed symmetry, as enforced by the presence of identical fermions in a system, are in turn predicted to be universally unstable.

¹We thank U. van Kolck for clarifying discussions on this issue.

In order to generalize this result, and to assess the role of the ratio of distinguishable particles versus identical particles in the system, we analyse A -body equal-mass systems with only one pair of identical particles within the EFT framework. Thereby, we enforce a momentum-less contact interaction between all the particle pairs and triplets, barring those which include the identical pair. Although, we deem the weakening of the potential attraction due to the statistical properties, thus induced, to be minimal, we find these systems to disintegrate into a totally symmetric $A - 1$ -body core of distinguishable particles and one free particle if the interaction cutoff is increased beyond a finite value. For any finite-range interaction, a number of particles (tested up to $A \sim 150$) can be found which realizes a stable P -wave composite. Furthermore, proximity to the unitary limit supports P -wave stability for finite interactions ranges. However, this range does not seem to converge to zero with either, implying that a pure contact theory is unable to stabilize any mixed-symmetry system. Having thus refuted the possibility of a combinatorial effect to conspire with the contact interactions to yield stable mixed-symmetry states, momentum-dependent corrections left as the only means fit for this purpose. Therefore, for a future refined version of the above EFT which can be applied to systems with stable states of mixed symmetry, nuclei in particular, we assess the effect of additional constraints on the theory: a finite two-body S -wave effective-range, or a finite two-body P -wave scattering volume. Both were found of similar importance for the binding, and our study is thus inconclusive and cannot promote one parameter over the other. Moreover, the way these corrections should be treated – as a perturbation or in a non-perturbative fashion – remains an open question. While shallow, RG-stable poles might be stabilized with perturbative insertions of sub-leading operators, their absence demands for a non-perturbative creation. Whether or not such a mechanism which would pertain to any effective-field-theory formulation of systems close to universality, which exhibit stability with mixed spatial symmetry as nuclei do most prominently, has to be implemented follows logically from this work as a next stage. The answer will eventually allow for a universal understanding of seemingly different fields, where as of now, Bose-like atoms and S -shell nuclei could be paralleled.

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