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Few-body physics: getting more effective

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Background

Over last $\sim$ 20 years: sea change in few-body physics

- ideas of universality, the renormalisation group and effective field theory have become central [König; Endo]
- started with suggestion of Weinberg in context of nuclear forces [Weinberg, Phys Lett B251 (1990) 288; Nucl Phys B363 (1991) 3]
- then took off with van Kolck and Kaplan, Savage and Wise [van Kolck, Nucl Phys A645 (1999) 273; Kaplan, Savage, and Wise, Phys Lett B424 (1998) 390; Nucl Phys B534 (1998) 329; Bedaque, Hammer and van Kolck, Phys Rev Lett 82 (1999) 463; Nucl Phys A646 (1999) 444]
- demonstrated that EFT could be renormalised nonperturbatively (contrast to chiral perturbation theory for mesons, single baryons)

Identified nontrivial fixed point of the renormalisation group

- scale-free system $\rightarrow$ universal features
  (no "memory" of underlying physics)
- describes low-energy scattering of two non-relativistic particles with infinite scattering length, $a \rightarrow \infty$: unitary limit
  [Weinberg, Nucl Phys B363 (1991) 3]
- EFT for systems with scattering lengths much larger than range of interactions
- assumes good separation of scales: deviations from universality expanded in powers of ratios of low-energy scales to scales of underlying physics ("power counting")

$\rightarrow$ systematic calculations with estimates of errors

“Pionless” EFT (only short-range interactions)

Two-body systems

- theory of nonrelativistic particles with contact interactions, builds on effective-range expansion

  [Blatt and Jackson, Phys Rev 76 (1949) 18; Bethe, Phys Rev 76 (1949) 38]
- provides consistent effective operators for currents etc
- can be extended to include Coulomb potential (DW ERE)

  [Kong and Ravndal, Phys Lett B450 (1999) 320; Nucl Phys A665 (2000) 137]

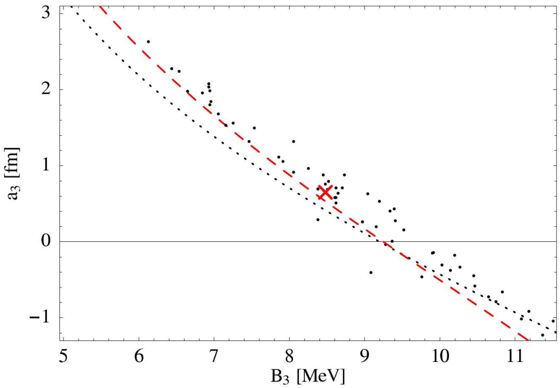
Some lessons from EFT

- off-shell forms of potentials are not physics
- different choices of two-body potential compensated by use of consistent effective operators, many-body forces
- many-body forces, in particular three-body, are unavoidable

  [Sekiguchi; . . .]

Three-body systems

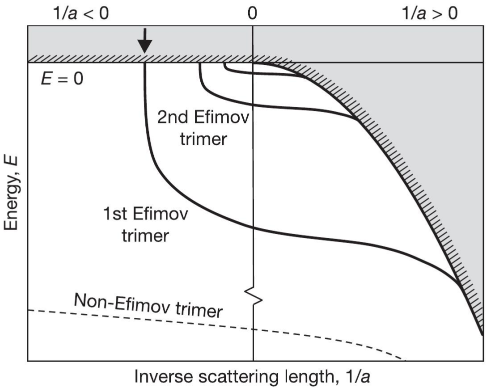
- three-body force needed at leading order (marginal perturbation)
- describes Phillips line [Phillips, Nucl Phys A107 (1968) 209]



nd scattering length against ^{3}H binding energy for model *NN* potentials, compared with LO and NLO pionless EFT [from: Bedaque *et al*, Nucl Phys A714 (2003) 589]

Also describes Efimov effect [Efimov, Sov J Nucl Phys 12 (1971) 589]

- infinite tower of geometrically spaced bound states in unitary limit
- universal ratio: discrete relic of scale invariance (marginal, cycle)
- three-body force fixes energies [Kievsky]



[from: Kraemer *et al*, Nature 440 (2006) 315]

Four- and more-body systems

- no further forces needed at leading order
  [Platter *et al*, Phys Rev A70 (2004) 052101]
- two four-body states below each Efimov three-body state
  [von Stecher *et al*, Nature Phys 5 (2009) 417; Deltuva, Phys Rev A82 (2010) 040701]
- explains Tjon line: correlation between ^{3}H and ^{4}He energies
  [Tjon, Phys Lett B56 (1975) 217]
- matches quite well two 0^+ states of ^{4}He [König]
- similar pairs of states found for $N \geq 4$ particles
  [Gattobigio *et al*, Phys Rev A86 (2012) 042513; A90 (2014) 032504; Dohet-Eraly]
- rely on impressive developments in computational methods
  [Lazauskas; Kievsky; Deltuva; . . .]

Ultra-cold atoms in traps

- beautiful realisations of this physics [Chin; Endo]
- Feshbach resonances used to tune scattering length $\gg$ range ($\rightarrow$ really good separation of scales)
- first Efimov state observed in 2006
  [Kraemer *et al*, Nature 440 (2006) 315]
- periodic with Efimov factor 22.7
  [Huang *et al*, Phys Rev Lett 112 (2014) 190401]
- then four- and five-body states
  [Ferlaino *et al*, Phys.Rev.Lett. 102 (2009) 140401; Zenesini *et al*, New J Phys 15 (2013) 0430]

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^{4}He atom clusters

- really shallow dimer: 140 neV [Dörner]
- spatial distribution imaged by laser ionisation
  [Zeller *et al*, PNAS 113 (2016) 14651]
- Efimov trimer observed [Kunitski *et al*, Science 348 (2015) 551]

Nuclear physics

Pionless EFT valid only for very low-energy states

- eg very weakly bound nuclei, halo $\gg$ core: “halo” or “cluster” EFT
  [Mathis; Carbonell; Filandri]

Higher energies require pion-exchange forces: chiral EFTs

- KSW added these perturbatively, but . . .
- expansion fails to converge in S and P waves
  [Fleming *et al*, Nucl Phys A677 (2000)] 313; Kaplan, arXiv:1905.07485]
- common work-around: “Weinberg prescription”
- expand potential using perturbative counting and then treat it nonperturbatively [Epelbaum *et al*, Rev Mod Phys 81 (2009) 1773]
- works quite well in practice [Golak; Viviani], but . . .
- no guarantee of consistent counting for observables
- alternative power countings have been proposed
  [Pavon Valderrama, arXiv:1902.08172]

Recent developments

Pionless EFT: no leading four-body force, but exact order unknown

- needed at same order as effective range (NLO)

  [Bazak *et al*, Phys Rev Lett 122 (2019) 143001; Kirscher]

Coulomb potential in pionless EFT

- universal effects in few-body systems being studied

  [Schmickler *et al*, arXiv:1904.00913]

Chiral EFTs

- counting of three-body interactions in presence of pion exchange (and other long-range two-body forces)

  [Odell *et al*, arXiv:1903.00034]

Weinberg approach

- now implemented to 5th order and beyond

  [Reinert *et al*, Eur Phys J A54 (2018) 86; Golak; Reinert]

Hadronic molecules

- $X(3872)$ less than 200 keV from $D^0\overline{D}^{*0}$ threshold
- other states like $Z_c(3900)$, $Z_c(4020)$ ... close to $D\overline{D}$ or $B\overline{B}$ thresholds
- also pentaquarks $P_c(4312)$, $P_c(4440)$, $P_c(4457)$ near $\overline{D}\Sigma_c$
- could be molecules or have large molecular components [Hanhart and Klempt, arXiv:1906.11971; Liu *et al*, Phys Rev Lett 122 (2019) 242001; Ramos]
  (universal features if close enough to threshold)

Cluster scattering and reactions

- resonating group method for scattering in pionless EFT [Naidon et al, J Phys B 49 (2016) 034002]
- scattering in lattice and pionless EFT [Elhatisari et al, Phys Lett B768 (2017) 337; Deltuva, Phys Rev A96 (2017) 022701]
- (d,p) transfer reaction in halo EFT [Schmidt *et al*, Phys Rev C 99 (2019) 054611]

Lessons from EFT

Potentials and wave functions are not observables

- depend on theorists' choices (off-shell form, field representation)

Instead, focus on quantities that are "theory independent":

- asymptotic normalisation coefficients, not spectroscopic factors
  [Mukhamedzhanov *et al*, Phys Rev C63 (2001) 024612; Phys Rev C99 (2019) 024311]
- Tan's "contact" terms, not short-range correlations
  [Tan, Ann Phys 323 (2008) 2952; Weiss *et al*, Phys.Rev. C92 (2015) 054311; Barnea]

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Many-body forces expected in any effective theory

- Phillips line in ^{6}Li: hint of three-body force? [Lei *et al*, Phys Rev C98 (2018) 051001; Elster]
- three-body forces in transfer reactions [Dinmore *et al*, Phys Rev C99 (2019) 064612; Dinmore]

Nuclear reactions

Would like an effective theory for nuclear reactions

- but issues with separation of scales
- inverse core radii are small, $1/R_c \lesssim 60$ MeV $\sim$ low-energy scale?
- Coulomb scale can be large, $\alpha Z_1 Z_2 M_{\mathrm{red}} \sim 140$ MeV ($p + {}^{40}\mathrm{Ca}$)
  $\rightarrow$ contact interactions ineffective
- cannot apply halo EFT to most reactions, even at low energies
  $\rightarrow$ perhaps add $1/R_c$ to list of low-energy scales?
- δ-shell potentials, finite-r boundary conditions often used as regulators, but perhaps we should take them more seriously
- for example: use a version of R-matrix theory? [Tennyson]

Many areas of few-body physics with no good separation of scales
$\rightarrow$ ideas of universality and effective field theory do not apply

But where they do…

Many areas of few-body physics with no good separation of scales
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But where they do…

We should strive to be as effective as possible!