TRIUMF Canada's National Laboratory for Particle and Nuclear Physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

Halo Nuclei in Effective Field Theory

Chen Ji || TRIUMF

Progress in Ab Initio Techniques in Nuclear Physics
TRIUMF, Feb 17-20, 2015

Collaborators

Daniel Phillips
Charlotte Elster
Bijaya Acharya

Ohio University

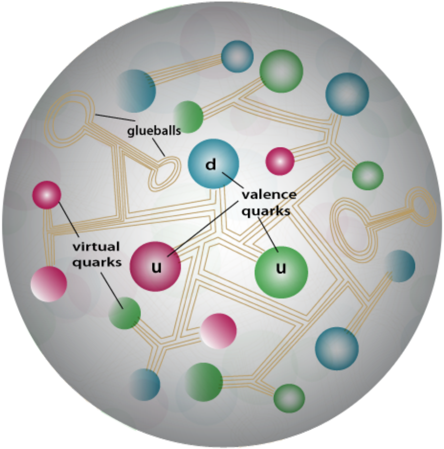
Zhongzhou Ren
Liuyang Zhang
Mengjiao Lyu

Nanjing University

Effective Theories & Resolution Scales

- We study physics at different resolution scales with different effective theories

- describe nucleon structures
  - physics scale: $Q \gtrapprox$ GeV
  - d.o.f.: quarks & gluons
  - effective theory: lattice QCD



Effective Theories & Resolution Scales

- We study physics at different resolution scales with different effective theories

- light/medium mass nuclei
  - physics scale: $Q \sim 200$ MeV
  - d.o.f.: nucleons & pions
  - effective theory: chiral EFT
  - use *ab initio* methods

Effective Theories & Resolution Scales

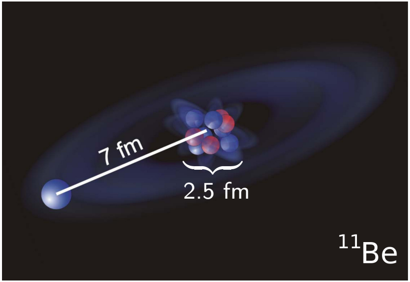
TRIUMF

- We study physics at different resolution scales with different effective theories

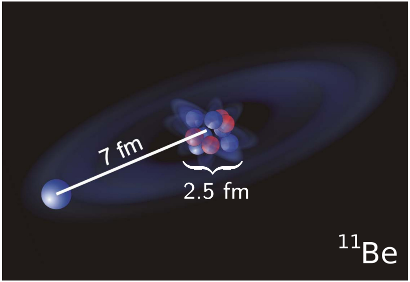
- very light nuclei (d, t, ^{3}He, α)
  - physics scale: $Q \ll m_\pi$
  - d.o.f.: nucleons in contact
  - effective theory: pionless EFT
  - use few-body methods

- **halo nuclei** (core + valence N)
- **separation in length scales**

  $R_{\rm core} \ll R_{\rm halo}$



- **halo nuclei** (core + valence N)
- **separation in length scales**
  $R_{\text{core}} \ll R_{\text{halo}}$

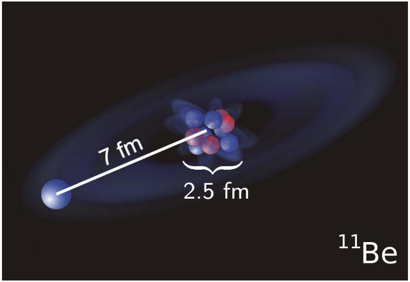


ab initio methods

- capture dynamics inside and outside the core
- numerically expensive for loosely bound systems

Effective Theories for Halo Nuclei

- **halo nuclei** (core + valence N)
- **separation in length scales**
  $R_{\mathrm{core}} \ll R_{\mathrm{halo}}$



ab initio methods

- capture dynamics inside and outside the core
- numerically expensive for loosely bound systems

halo effective field theory

- valence nucleon + core d.o.f.
- systematic expansion in $R_{\mathrm{core}}/R_{\mathrm{halo}}$
- capture only clustering mechanism
- numerically simpler
- complimentary to *ab initio* methods
- explain universal correlations in clustering physics

Halo Effective Field Theory

- We adopt EFT with contact interactions to describe clustering in halo nuclei

$$\mathcal{L} = \psi^\dagger \left(i\partial_0 + \frac{\nabla^2}{2m} \right) \psi + \eta\, d^\dagger \left(i\partial_0 + \frac{\nabla^2}{4m} - \Delta \right) d - \frac{g}{\sqrt{2}} \left(d^\dagger \psi\psi + \text{h.c} \right) + h d^\dagger d \psi^\dagger \psi + \cdots$$

$\cdots$ are higher orders in $R_{\text{core}}/R_{\text{halo}}$ expansion

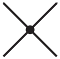
Halo Effective Field Theory

- We adopt EFT with contact interactions to describe clustering in halo nuclei

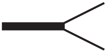
$$\mathcal{L} = \psi^\dagger \left(i\partial_0 + \frac{\nabla^2}{2m} \right) \psi + \eta\, d^\dagger \left(i\partial_0 + \frac{\nabla^2}{4m} - \Delta \right) d - \frac{g}{\sqrt{2}} \left(d^\dagger \psi\psi + \text{h.c} \right) + h d^\dagger d \psi^\dagger \psi + \cdots$$

$\cdots$ are higher orders in $R_{\text{core}}/R_{\text{halo}}$ expansion

- 2-body contact (LO) introduce a two-body field



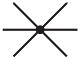
$= -iC_0 \quad \xrightarrow{C_0 = g^2/\Delta}$



$= -i\sqrt{2}g$

g determined by a 2-body observable

- 3-body contact (LO)



$= -iD_0 \quad \xrightarrow{D_0 = -3hg^2/\Delta^2}$

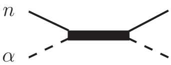
$= ih$

h determined by a 3-body observable Bedaque, Hammer, van Kolck '99

One-Neutron Halo Systems

- **EFT for $1n$ halo**

- **^{5}He shallow resonance ($P_{3/2}$)**



$$= \frac{1}{4\pi^2\mu_{n\alpha}} \frac{\vec{p}\cdot\vec{q}}{-1/a_1 + r_1 k^2/2 - ik^3}$$

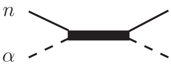
$a_1 = -62.95$ fm^3, $r_1 = -0.8819$ fm^{-1}

Ardnt et al. '73

One-Neutron Halo Systems

- **EFT for $1n$ halo**

- **^{5}He shallow resonance ($P_{3/2}$)**



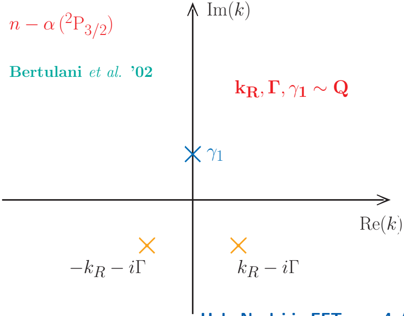
$$= \frac{1}{4\pi^2\mu_{n\alpha}} \frac{\vec{p}\cdot\vec{q}}{-1/a_1 + r_1 k^2/2 - ik^3}$$

$a_1 = -62.95$ fm^3, $r_1 = -0.8819$ fm^{-1}
Ardnt et al. '73

- **$n\alpha$ p-wave EFT power counting**

Bertulani, Hammer, van Kolck '02

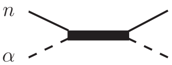
- $a_1 \sim 1/(Q^3)$ $\quad r_1 \sim Q$
- two fine tunings at LO
- shallow resonance: $k_R, \Gamma \sim Q$
- shallow bound state: $\gamma_1 \sim Q$



One-Neutron Halo Systems

- **EFT for $1n$ halo**

- **^{5}He shallow resonance ($P_{3/2}$)**



$$= \frac{1}{4\pi^2\mu_{n\alpha}} \frac{\vec{p}\cdot\vec{q}}{-1/a_1 + r_1 k^2/2 - ik^3}$$

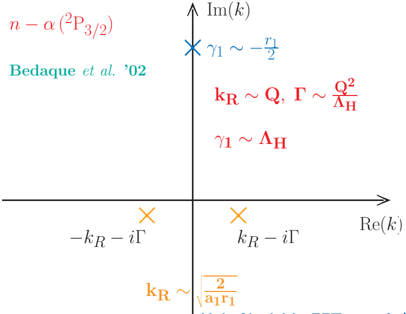
$a_1 = -62.95$ fm^3, $r_1 = -0.8819$ fm^{-1}

Ardnt et al. '73

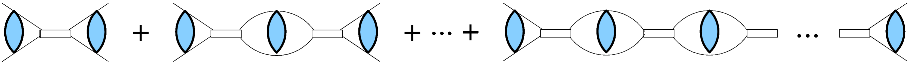
- **$n\alpha$ p-wave EFT power counting**

Bedaque, Hammer, van Kolck '02

- $a_1 \sim 1/(Q^2\Lambda_H)$ $r_1 \sim \Lambda_H$
- $Q/\Lambda_H \sim 0.15$
- one fine tuning at LO
- shallow resonance:
  $k_R \sim Q, \quad \Gamma \sim Q^2/\Lambda_H$
- deep bound state: $\gamma_1 \sim \Lambda_H$



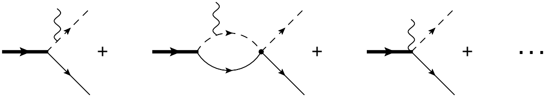
- **EFT for $1p$ halo nucleus**



p-α and α-α scattering [Higa '08]

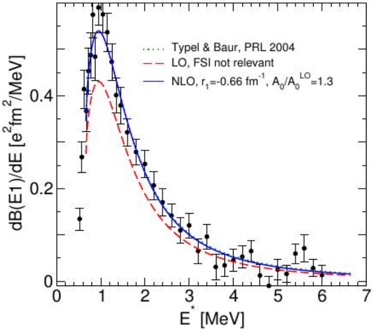
^{17}F [Ryberg, Forssén, Platter '13]

Photo-Dissociation in Halos



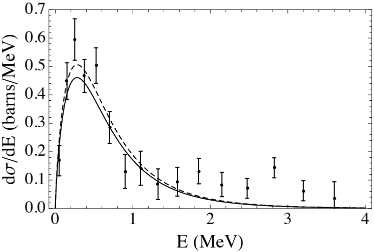
- **E1 transition**

^{11}Be photo-dissociation



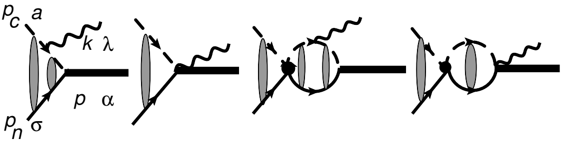
[Hammer, Phillips '11]

^{19}C photo-dissociation



data: Nakamura *et al*, RIKEN '99,'03;
calculation: Acharya, Phillips '13

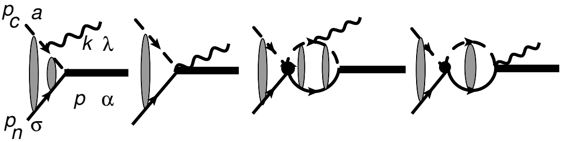
proton captures



$^{7}\mathrm{Li} + n \to {}^{8}\mathrm{Li} + \gamma$ [Rupak, Higga '11, Zhang, Nollett, Phillips '13]
$^{14}\mathrm{C} + n \to {}^{15}\mathrm{C} + \gamma$ [Rupak, Fernando, Vaghani '12]
$^{7}\mathrm{Be} + p \to {}^{8}\mathrm{B} + \gamma$ [Zhang, Nollett, Phillips '14]
$^{16}\mathrm{O} + p \to {}^{17}\mathrm{F}^{*}(1/2^{+}) + \gamma$ [Ryberg, Forssén, Platter '13]

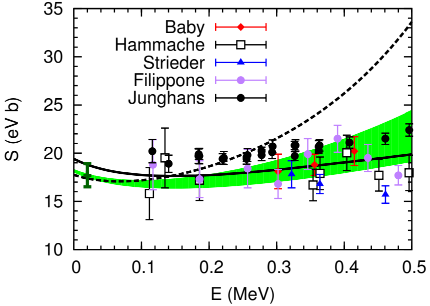
Radiative Nucleon Captures

proton captures



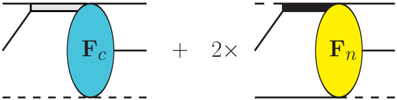
$^7\mathrm{Li} + n \to {}^8\mathrm{Li} + \gamma$ [Rupak, Higga '11, Zhang, Nollett, Phillips '13]
$^{14}\mathrm{C} + n \to {}^{15}\mathrm{C} + \gamma$ [Rupak, Fernando, Vaghani '12]
$^7\mathrm{Be} + p \to {}^8\mathrm{B} + \gamma$ [Zhang, Nollett, Phillips '14]
$^{16}\mathrm{O} + p \to {}^{17}\mathrm{F}^*(1/2^+) + \gamma$ [Ryberg, Forssén, Platter '13]

- **E1 S-factor for ^{7}Be$(p,\gamma)^8$B** [Zhang, Nollett, Phillips '14]
- —— NSCM-GRM result [Navratil, Roth, Quaglioni, PLB '11]
- ---- LO EFT: fit to NSCM-GRM ANC
- LO EFT: fit to ANC from VMC VMC [Nollett, Wiringa, PRC '11]



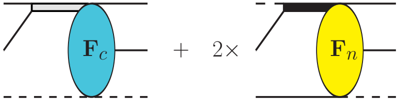
- **2n-halo wave functions**

$\Psi_x(p, q) =$

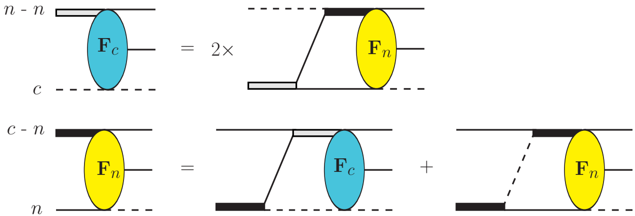


2n-halo wave functions

$\Psi_x(p, q) =$

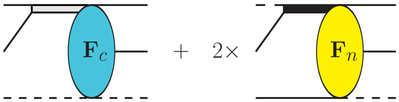


Three-body Faddeev equation

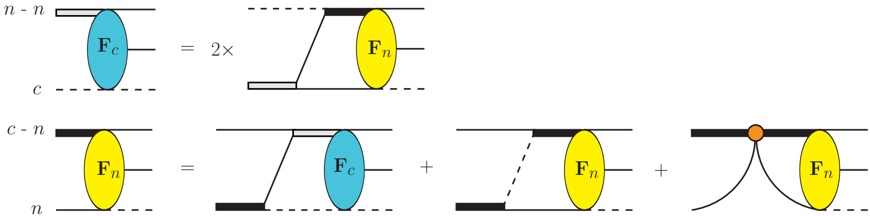


- **2n-halo wave functions**

$\Psi_x(p, q) =$



- **Three-body Faddeev equation**

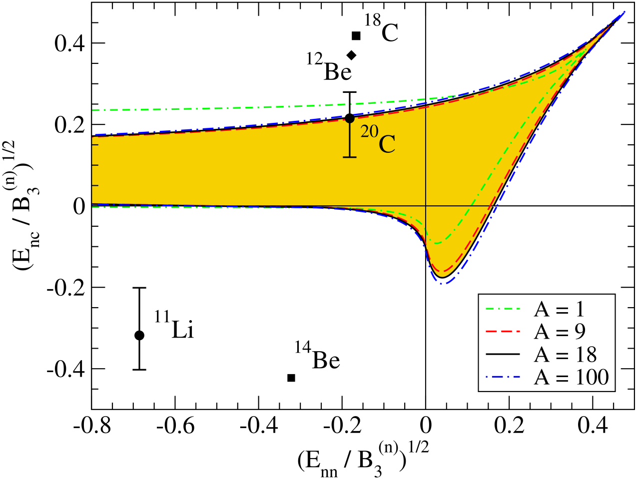


EFT For $2n$ Halos

- n-core in s-wave virtual/real bound state:
  ^{11}Li, ^{12}Be, ^{20}C [Canham, Hammer '08, '10]
  ^{22}C [Yamashita, Carvalho, Frederico, Tomio '11]
  ^{22}C Acharya, C.J., Phillips PLB 723 (2013)
- charge radius of 2n s-wave halos [Hagen, Hammer, Platter '13]
- heaviest 2n s-wave halo:
  ^{62}Ca [Hagen, Hagen, Hammer, Platter '13]
  fit n-^{60}Ca scattering length from coupled-cluster calculations
- ^{6}**He:** n-α in p-wave resonance
  - EFT + Gamow shell model [Rotureau, van Kolck, Few Body Syst. '13]
  - EFT + Faddeev Equations C.J., Elster, Phillips, PRC **90**, 044004 (2014)

Universality in $2n$ s-wave halo

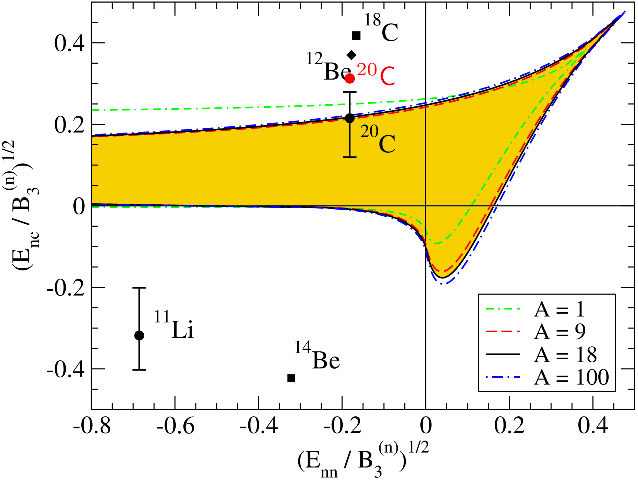
- Implication of excited Efimov halo
  assume excited states $S_{2n} = 0$



Canham, Hammer EPJA 2008

Universality in $2n$ s-wave halo

- Implication of excited Efimov halo
  assume excited states $S_{2n} = 0$



Canham, Hammer EPJA 2008

^{22}C: $2n$ Halo

	^{20}C	^{21}C	^{22}C
bound/unbound	bound		
ground state	0^+		
binding/virtual energy	S_{2n}=4.76 MeV Ozawa et al. '11		
matter radius r_m	2.97(5) fm Ozawa et al. '01		

^{22}C: $2n$ Halo

	^{20}C	^{21}C	^{22}C
bound/unbound	bound	unbound	
ground state	0^+	$S_{1/2}$	
binding/virtual energy	S_{2n}=4.76 MeV Ozawa et al. '11	$E_{nc} > 2.9$ MeV Mosby et al. '13 ??	
matter radius r_m	2.97(5) fm Ozawa et al. '01	—	

^{22}C: $2n$ Halo

	^{20}C	^{21}C	^{22}C
bound/unbound	bound	unbound	bound
ground state	0^+	$S_{1/2}$	0^+
binding/virtual energy	S_{2n}=4.76 MeV Ozawa et al. '11	$E_{nc} > 2.9$ MeV Mosby et al. '13 ??	S_{2n}=0.42(94) MeV Audi et al. '03 S_{2n}=−0.14(46) MeV Gaudefroy et al. '12
matter radius r_m	2.97(5) fm Ozawa et al. '01	—	5.4(9) fm Tanaka et al. '10

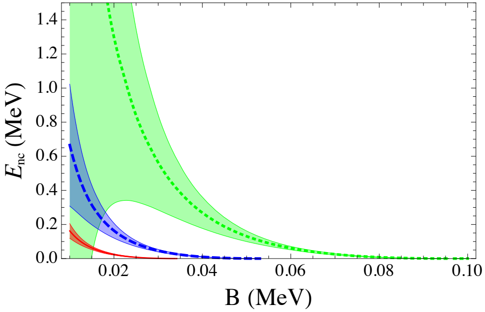
^{22}C: $2n$ Halo

	^{20}C	^{21}C	^{22}C
bound/unbound	bound	unbound	bound
ground state	0^+	$S_{1/2}$	0^+
binding/virtual energy	S_{2n}=4.76 MeV Ozawa et al. '11	$E_{nc} > 2.9$ MeV Mosby et al. '13 ??	S_{2n}=0.42(94) MeV Audi et al. '03 S_{2n}=−0.14(46) MeV Gaudefroy et al. '12
matter radius r_m	2.97(5) fm Ozawa et al. '01	—	5.4(9) fm Tanaka et al. '10

- Halo EFT [Acharya, C.J., Phillips, PLB **723** 196 (2013)]
  we fit to ^{22}C matter radius to constrain:
  - E_{nc} in ^{21}C $(a < 0)$
  - S_{2n} in ^{22}C

Constraints On ^{21}C and ^{22}C

Input: $r_m[^{22}\mathrm{C}] = 5.4^{+0.9}_{-0.9}$ fm

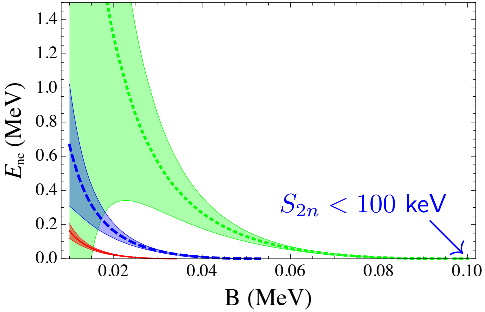


bands: uncertainty from higher-order EFT

Acharya, C.J., Phillips, PLB **723** 196 (2013)

Constraints On ^{21}C and ^{22}C

Input: $r_m[^{22}\mathrm{C}] = 5.4^{+0.9}_{-0.9}$ fm

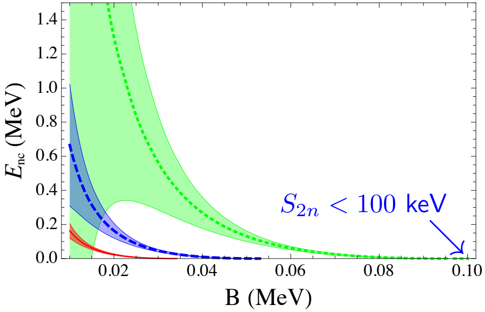


bands: uncertainty from higher-order EFT

Acharya, C.J., Phillips, PLB **723** 196 (2013)

Constraints On ^{21}C and ^{22}C

Input: $r_m[^{22}\mathrm{C}] = 5.4^{+0.9}_{-0.9}$ fm



c.f. Yamashita et al. '11 (theo)
$\rightarrow S_{2n} < 120$ keV

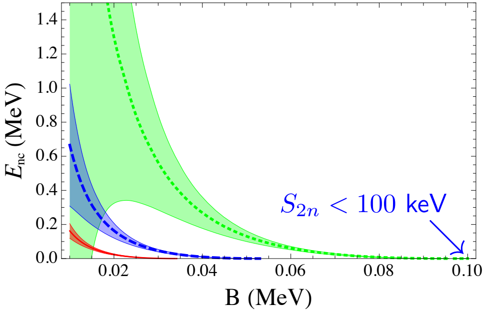
Fortune & Sherr '12 (theo)
$\rightarrow S_{2n} < 220$ keV

Gaudefroy et al. '12 (expt)
$\rightarrow S_{2n} < 320$ keV

bands: uncertainty from higher-order EFT

Acharya, C.J., Phillips, PLB **723** 196 (2013)

Input: $r_m[^{22}\mathrm{C}] = 5.4^{+0.9}_{-0.9}$ fm



bands: uncertainty from higher-order EFT

c.f. Yamashita et al. '11 (theo)
$\rightarrow S_{2n} < 120$ keV

Fortune & Sherr '12 (theo)
$\rightarrow S_{2n} < 220$ keV

Gaudefroy et al. '12 (expt)
$\rightarrow S_{2n} < 320$ keV

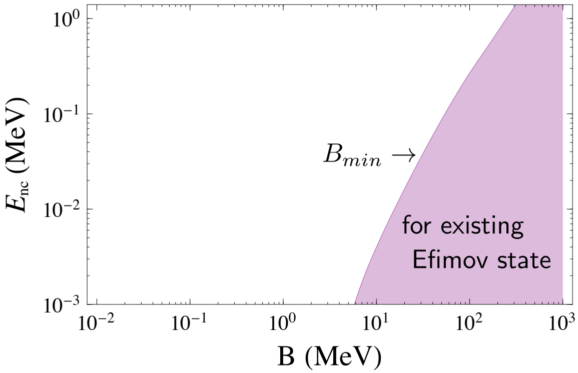
Mosby et al. '13 $E_{nc} > 2.9$ MeV

Halo EFT $\rightarrow S_{2n} < 20$ keV
(inconsistent with other measurements)

Acharya, C.J., Phillips, PLB **723** 196 (2013)

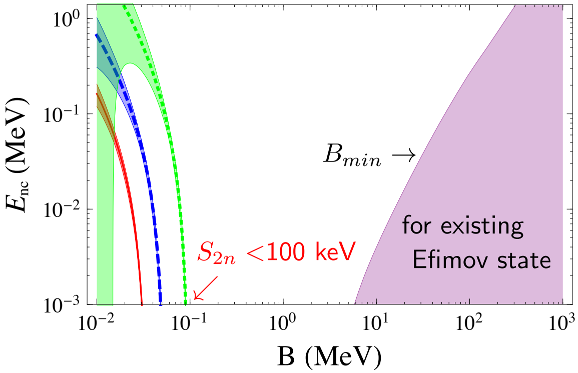
Efimov States In ^{22}C ?

- possibility of finding Efimov excited states in ^{22}C
  Mazumdar *et al.* '00, Frederico *et al.* '12, Acharya, C.J., Phillips, '13
- An Efimov excited state exists if G.S. $S_{2n} > B_{min}$



Efimov States In ^{22}C ?

- possibility of finding Efimov excited states in ^{22}C
  Mazumdar *et al.* '00, Frederico *et al.* '12, Acharya, C.J., Phillips, '13
- An Efimov excited state exists if G.S. $S_{2n} > B_{min}$



- The Efimov excited state only occurs in ^{22}C if:
  $\rightarrow$ the virtual energy of ^{21}C $E_{nc} < 1$ keV (unlikely)

^{23}N: $2n$ Halo Nucleus

	^{21}N	^{22}N	^{23}N
S_{1n} [MeV]	$4.59(11)$	$1.28(21)$	$1.79(36)$
S_{2n} [MeV]	$6.75(10)$	$5.87(20)$	$3.07(31)$

AME2012

^{23}N: $2n$ Halo Nucleus

	^{21}N	^{22}N	^{23}N
S_{1n} [MeV]	$4.59(11)$	$1.28(21)$	$1.79(36)$
S_{2n} [MeV]	$6.75(10)$	$5.87(20)$	$3.07(31)$

AME2012

- **We study ^{23}N in $n + n +^{21}$N cluster model**

  Zhang, Ren, Lyu, C.J., PRC 91, 024001 (2015)

^{23}N: $2n$ Halo Nucleus

TRIUMF

	^{21}N	^{22}N	^{23}N
S_{1n} [MeV]	$4.59(11)$	$1.28(21)$	$1.79(36)$
S_{2n} [MeV]	$6.75(10)$	$5.87(20)$	$3.07(31)$

AME2012

- **We study ^{23}N in $n + n +{}^{21}$N cluster model**

  Zhang, Ren, Lyu, C.J., PRC 91, 024001 (2015)

- **Adopted interactions**
  - realistic nn (Gogny-Pires-De Tourreil (GPT))
  - phenomenological n-^{21}N (Wood Saxon)

$$V_{n\text{-core}}(r) = -\frac{V_0}{1+\exp(\frac{r-r_0}{a})} - \frac{V_{\text{so}}}{ra}\frac{\exp(\frac{r-r_0}{a})}{(1+\exp(\frac{r-r_0}{a}))^2}\mathbf{L}\cdot\mathbf{S}$$

^{23}N: $2n$ Halo Nucleus

TRIUMF

	^{21}N	^{22}N	^{23}N
S_{1n} [MeV]	$4.59(11)$	$1.28(21)$	$1.79(36)$
S_{2n} [MeV]	$6.75(10)$	$5.87(20)$	$3.07(31)$

AME2012

- **We study ^{23}N in $n + n +^{21}$N cluster model**

  Zhang, Ren, Lyu, C.J., PRC 91, 024001 (2015)

- **Adopted interactions**
  - realistic nn (Gogny-Pires-De Tourreil (GPT))
  - phenomenological n-^{21}N (Wood Saxon)

$$V_{n\text{-core}}(r) = -\frac{V_0}{1+\exp(\frac{r-r_0}{a})} - \frac{V_{\text{so}}}{ra}\frac{\exp(\frac{r-r_0}{a})}{(1+\exp(\frac{r-r_0}{a}))^2}\mathbf{L}\cdot\mathbf{S}$$

- **Faddeev equation in hyperspherical harmonics expansion**

  numerical tool: FaCE [Thompson, Nunes, Danilin, Comp. Phys. Comm. '04]

^{23}N G.S. & Excited Halo States

- We tune $V_{n\text{-core}}$ to reproduce

  ^{21}N $S_{1n} = 4.59(11)$ MeV

  ^{22}N $S_{1n} = 1.28^{+21}_{-21}$ MeV

- We predict S_{2n} and r_m

S_{2n} MeV	r_m fm	S^*_{2n} MeV	r^*_m fm
4.13	2.969	0.315	4.272
3.64	2.985	0.185	4.358
3.13	3.004	0.069	4.476

Experiment: $S_{2n} = 3.07(31)$ MeV

^{23}N G.S. & Excited Halo States

- We tune $V_{n\text{-core}}$ to reproduce
  ^{21}N $S_{1n} = 4.59(11)$ MeV
  ^{22}N $S_{1n} = 1.28^{+21}_{-21}$ MeV
- We predict S_{2n} and r_m

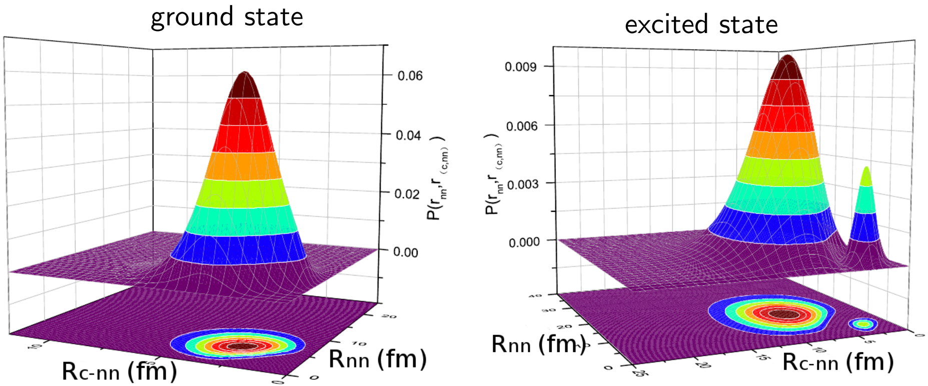
S_{2n}	r_m	S^*_{2n}	r^*_m
MeV	fm	MeV	fm
4.13	2.969	0.315	4.272
3.64	2.985	0.185	4.358
3.13	3.004	0.069	4.476

Experiment: $S_{2n} = 3.07(31)$ MeV

- add 3BF $V_3(\rho) = W_0 e^{-\rho^2/\rho_0^2}$ to reproduce
  ^{23}N $S_{2n} = 3.07$ MeV
- Predictions in S_{2n} and r_m

S_{2n}	r_m	S^*_{2n}	r^*_m
MeV	fm	MeV	fm
3.07	3.022	0.195	4.629
3.07	3.019	0.128	4.790
3.07	3.011	0.064	5.011

^{23}N Probability Density Distributions



$(1s)^2$ 95%

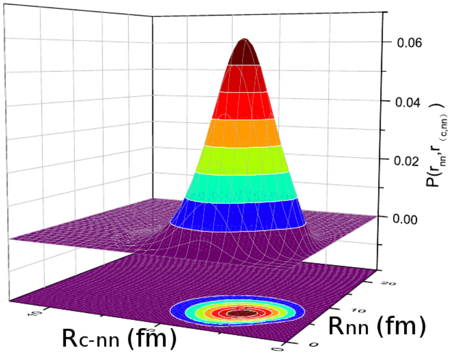
$(0d)^2$ 5%

$(1s)^2$ 77%

$(0d)^2$ 23%

^{23}N Probability Density Distributions

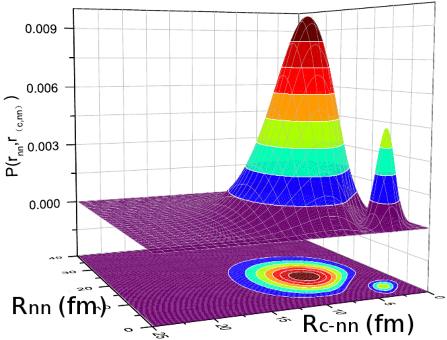
ground state



$(1s)^2$ 95%

$(0d)^2$ 5%

excited state



$(1s)^2$ 77%

$(0d)^2$ 23%

- future work: Halo EFT analysis of universal correlations in ^{23}N

^{6}He: $2n$ Halo

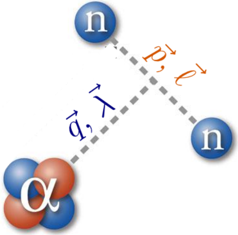
- **experiment in ^{6}He**
  - matter radius Tanihata *et al.* '92, Alkhazov *et al.* '97, Kislev *et al.* '05
  - charge radius Wang *et al.* '04, Mueller *et al.* '07
  - ^{6}He mass Brodeur *et al.* '12

- *ab intio* **calculation**
  - no-core shell model Navrátil *et al.* '01; Sääf, Forssén '14
  - NCSM-RGM Romero-Redondo *et al.* '14
  - Green's function Monte Carlo Pieper *et al.* '01; '08
  - hyperspherical harmonics (EIHH) Bacca *et al.* '12

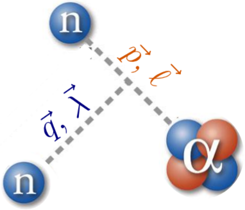
- **halo EFT** C.J., Elster, Phillips, PRC **90**, 044004 (2014)
  - explore **universal correlations** in ^{6}He
  - compare **predictions** with experiments and *ab initio* calculations

- **Jacobi-momentum**

α spectator



n spectator

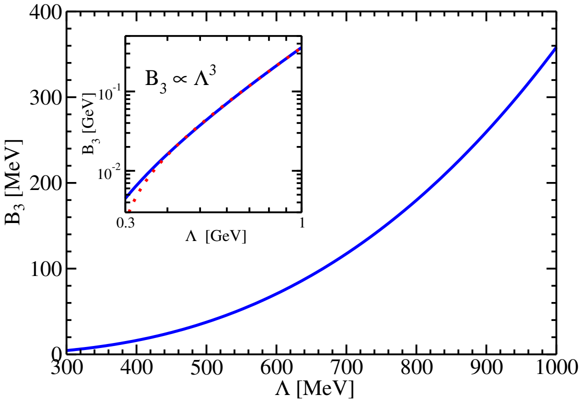


spin-orbit coupling for ^{6}He ($J = 0^+$)

pair, spec	pair	spectator	total L, S	total J
nn, α	$\ell_{nn} = 0$, $s_{nn} = 0$	$\lambda_{\alpha\text{-}nn} = 0$, $s_{\alpha\text{-}nn} = 0$	$L = 0$, $S = 0$	$J = 0^+$
$n\alpha$, n	$\ell_{n\alpha} = 1$, $s_{n\alpha} = \frac{1}{2}$	$\lambda_{n\text{-}n\alpha} = 1$, $s_{n\text{-}n\alpha} = \frac{1}{2}$	$L = 0$, $S = 0$	
			$L = 1$, $S = 1$	

Cutoff Dependence

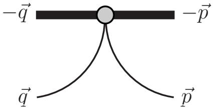
- **without $nn\alpha$ 3-body force:**
  - S_{2n} is strongly cutoff dependent: $S_{2n} \sim \Lambda^3$ $\leftarrow$ need 3body force!



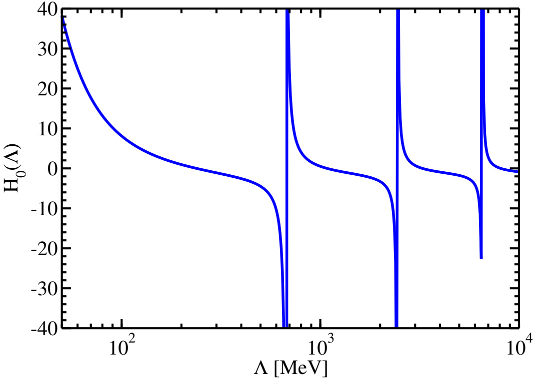
$nn\alpha$ Three-Body Force (3BF)

TRIUMF

- p-wave 3BF:
  reproduce $S_{2n} = 0.973$ MeV

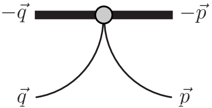


$$= M_n\, qp\, \frac{H(\Lambda)}{\Lambda^2}$$



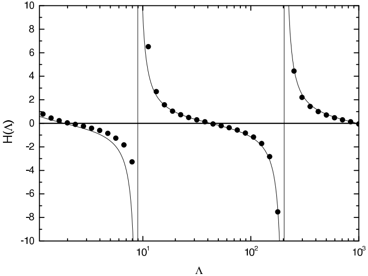
$nn\alpha$ Three-Body Force (3BF)

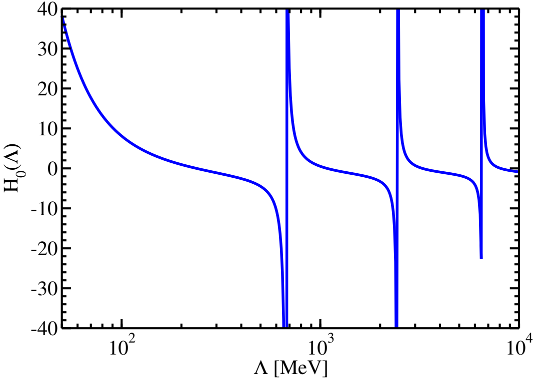
- p-wave 3BF:
  reproduce $S_{2n} = 0.973$ MeV



$$= M_n \, qp \, \frac{H(\Lambda)}{\Lambda^2}$$

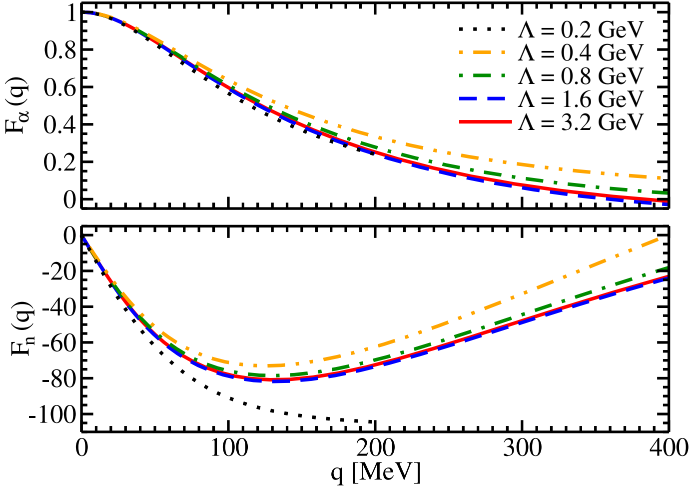
- log oscillation
- No limit cycle
  (c.f. 3-body in S-wave)





Renormalized Faddeev Components

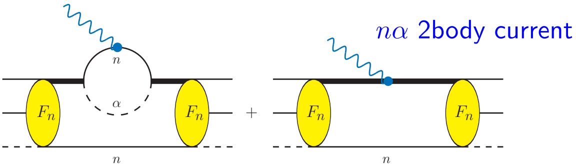
$F_\alpha(\alpha, nn)$ **and** $F_n(n, \alpha n)$ **are cutoff independent**



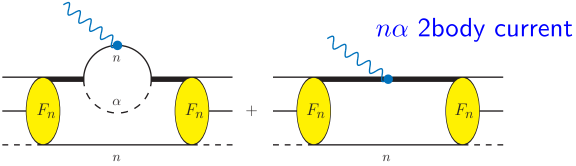
C.J., Elster, Phillips, PRC **90**, 044004 (2014)

^{6}He Form Factors

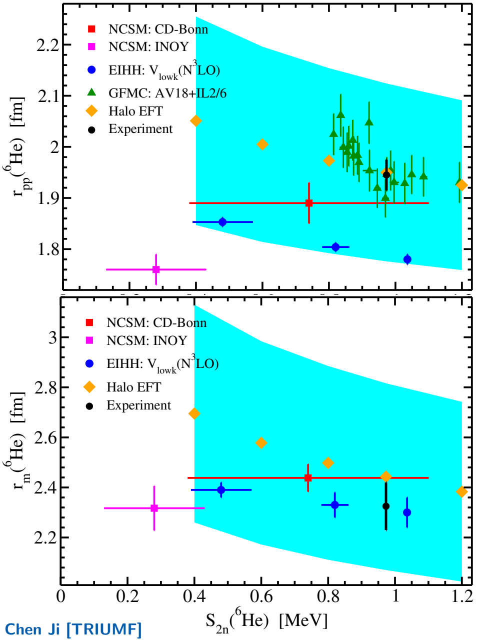
- 3-body form factor (with p-wave n-core interactions)



- 3-body form factor (with p-wave n-core interactions)



- The $n\alpha$ two-body current counterterm is fixed by r_1 in $n\alpha$ $3/2^-$ state
- It does not require an additional 3-body input



[Preliminary]

- He-6 point-proton radius
- He-6 matter radius

compare with

NSCM: Caurier, Navratil, PRC '06

GFMC: Pieper, RNC '08

EIHH: Bacca, Barnea, Schwenk, PRC '12

Halo EFT: preliminary (uncertainty)

Atomic Isotope Shift

- Nuclear polarization in muonic atoms:
  N. Nevo Dinur's talk; O.J. Hernandez's poster

- The nuclear charge radius can also be extracted from the isotope shifts in electronic atoms:

$$\delta_{AA'} = \delta_{AA'}^{MS} + K_{FS}\,\delta\langle r^2\rangle_{AA'}$$

Atomic Isotope Shift

- Nuclear polarization in muonic atoms:
  N. Nevo Dinur's talk; O.J. Hernandez's poster

- The nuclear charge radius can also be extracted from the isotope shifts in electronic atoms:

$$\delta_{AA'} = \delta_{AA'}^{MS} + K_{FS}\,\delta\langle r^2\rangle_{AA'}$$

- The nuclear polarization δ_{pol} contribute to the mass shift term $\delta_{AA'}^{MS}$

$$\delta_{pol} = \mathcal{A}\underbrace{\left[\int_0^\infty d\omega\,\frac{\sigma_\gamma(\omega)}{\omega^2}\right]}_{\propto\,\alpha_E} + \mathcal{B}\underbrace{\left[\int_0^\infty d\omega\,\frac{\sigma_\gamma(\omega)}{\omega^2}\ln\frac{2\omega}{m}\right]}_{\propto\,\alpha_{E\log}} + \cdots$$

Pachucki, Moro PRA '07

Atomic Isotope Shift

- Nuclear polarization in muonic atoms:
  N. Nevo Dinur's talk; O.J. Hernandez's poster

- The nuclear charge radius can also be extracted from the isotope shifts in electronic atoms:

$$\delta_{AA'} = \delta^{MS}_{AA'} + K_{FS}\,\delta\langle r^2\rangle_{AA'}$$

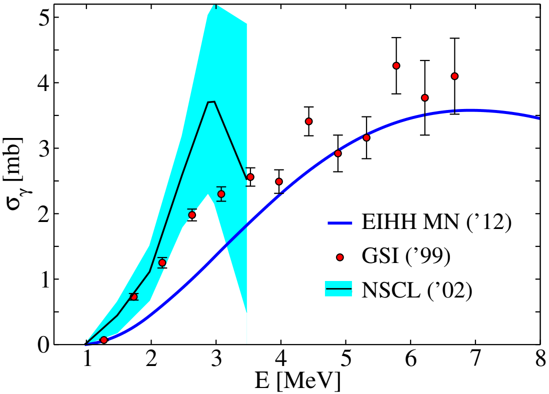
- The nuclear polarization δ_{pol} contribute to the mass shift term $\delta^{MS}_{AA'}$

$$\delta_{pol} = \mathcal{A}\underbrace{\left[\int_0^\infty d\omega\,\frac{\sigma_\gamma(\omega)}{\omega^2}\right]}_{\propto\,\alpha_E} + \mathcal{B}\underbrace{\left[\int_0^\infty d\omega\,\frac{\sigma_\gamma(\omega)}{\omega^2}\ln\frac{2\omega}{m}\right]}_{\propto\,\alpha_{E\log}} + \cdots$$

Pachucki, Moro PRA '07

- δ_{pol} is larger in atoms with unstable nuclear isotopes (lower threshold energy)
  halo nuclei: δ_{pol} is important for accurately extracting nuclear charge radii

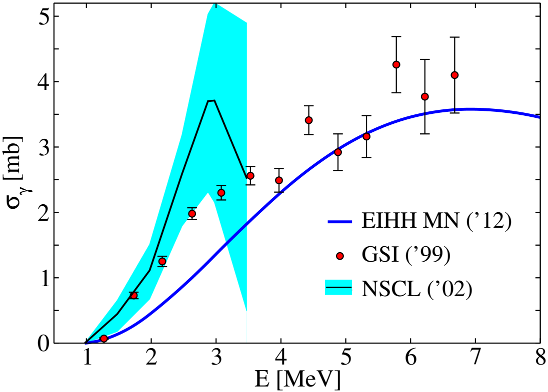
^{6}He Photoabsorption Cross Section



Pic:

Goerke, Bacca, Barnea PRC '12

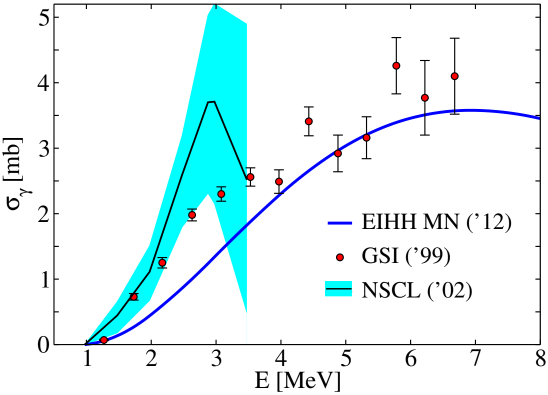
^{6}He Photoabsorption Cross Section



Pic:
Goerke, Bacca, Barnea PRC '12

σ_γ is dominated by physics at $\sim$ few MeVs

^{6}He Photoabsorption Cross Section

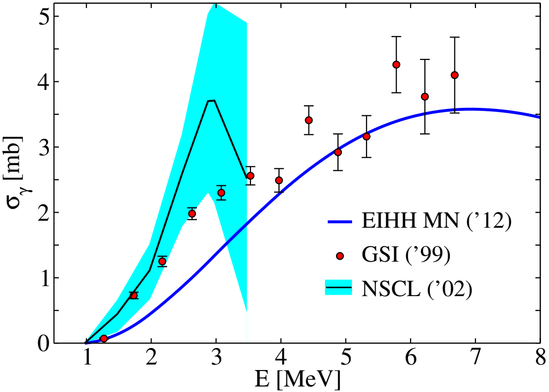


Pic:
Goerke, Bacca, Barnea PRC '12

σ_γ is dominated by physics at $\sim$ few MeVs

current data for $\sigma_\gamma(\omega)$ are not very accurate

^{6}He Photoabsorption Cross Section



Pic:
Goerke, Bacca, Barnea PRC '12

σ_γ is dominated by physics at $\sim$ few MeVs

current data for $\sigma_\gamma(\omega)$ are not very accurate

- *ab initio* methods are computationally expensive for halo systems / continuum
- halo EFT works economically at low energies
- future EFT calculations of σ_γ in ^{6}He ; δ_{pol} in ^{6}He isotope shift

Summary

- Halo EFT describes structure/reaction in halo nuclei in a systematic expansion of R_{core}/R_{halo}

- We studied $2n$-halo nuclei
  - ^{22}C: n-core in s-wave resonance
  - ^{23}N: ground and excited halo
  - ^{6}He: n-α p-wave resonance

- Halo EFT can be complimentary to *ab initio* calculations
  - adopt inputs from *ab initio* results
  - benchmark with *ab initio* calculations
  - explain universal correlations from observables in *ab initio* work