Electromagnetic Properties of One-Neutron Halo Nuclei in Halo EFT

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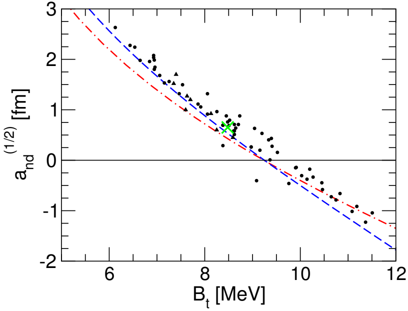
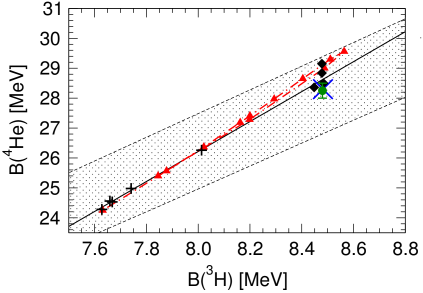
Outline

1. Motivation
2. Halo EFT for ^{15}C
   - extension to *D*-wave states
   - electric form factor and B(E2) results
3. Correlation between E2 observables
   - combine Halo EFT with IT-NCSM data
4. E1 neutron capture for ^{17}C
5. Magnetic observables
6. Summary

Universal Correlations for Shallow Bound States

- **universal correlations** between observables for loosely bound few-body systems
  $\Rightarrow$ **Phillips** (Phillips, 1968) and **Tjon Line** (Tjon, 1975) in few nucleon systems





- correlation universal: nucleons, ^{4}He atoms, ...

Ab Initio and Halo EFT Approaches

- *ab initio* approaches **successful tool** to calculate nuclear observables
  $\Rightarrow$ **limited** by the computational complexity of the nuclear many-body problem
- exotic isotopes as **halo nuclei** important for our understanding of nuclear structure

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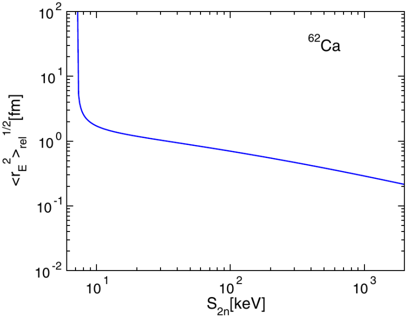
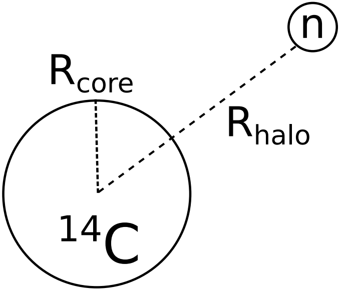
- *ab initio* approaches **successful tool** to calculate nuclear observables
  ⇒ **limited** by the computational complexity of the nuclear many-body problem
- exotic isotopes as **halo nuclei** important for our understanding of nuclear structure
- Halo EFT as a **complementary approach** to *ab initio* methods
  ⇒ useful tool to identify **universal correlations** between observables
  ⇒ combine with *ab initio* results (or experimental) for predictions
- correlations for ^{60}Ca-n-n system [Hagen et al., 2013]



One-Neutron Halo Nuclei

- study of electric properties of one-neutron Halo nuclei provide insights in **universal properties** $\rightarrow$ ^{15}C as example
- one-neutron Halo EFT already for *s*- & *p*-waves $\rightarrow$ extension to *d*-waves
- neutron separation energy of $\frac{1}{2}^+$ $\left[\frac{5}{2}^+\right]$ state of ^{15}C is 1218 [478] keV
- first excitation of ^{14}C is 6.1 MeV above 0^+ ground state



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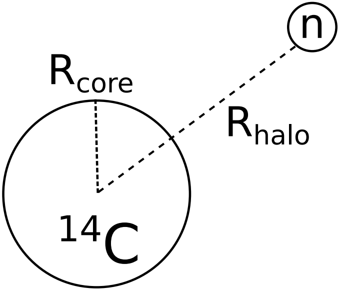
- exploit **separation of scales** in weakly-bound nuclei $\Rightarrow R_{core} \ll R_{halo}$
- compute observables in a **Halo EFT** in powers of $\mathbf{R_{core}/R_{halo} \approx 0.3}$
- relevant degrees of freedom: **core** and **halo neutron**



Halo EFT Formalism

- follow the approach of [Hammer and Phillips, 2011] for ^{11}Be (*s*- & *p*-waves) and [Rupak et al., 2012, Fernando et al., 2015] for ^{15}C (*s*-waves)
- include strong *s*-wave and *d*-wave interaction through **auxiliary spinor fields** σ and *d*, respectively

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$$\mathcal{L} = c^\dagger \left(i\partial_t + \frac{\nabla^2}{2M} \right) c \; + \; n^\dagger \left(i\partial_t + \frac{\nabla^2}{2m} \right) n + \sigma^\dagger \left[\eta_0 \left(i\partial_t + \frac{\nabla^2}{2M_{nc}} \right) + \Delta_0 \right] \sigma$$

$$+ d^\dagger \left[c_2 \left(i\partial_t + \frac{\nabla^2}{2M_{nc}} \right)^2 + \eta_2 \left(i\partial_t + \frac{\nabla^2}{2M_{nc}} \right) + \Delta_2 \right] d$$

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$$-g_0 \left[c^\dagger n^\dagger \sigma + \sigma^\dagger n c\right] - g_2 \left[d^\dagger n \overleftrightarrow{\nabla}^2 c + c^\dagger \overleftrightarrow{\nabla}^2 n^\dagger d\right]$$

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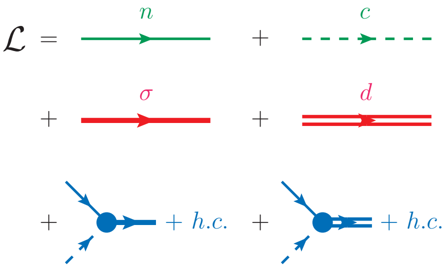
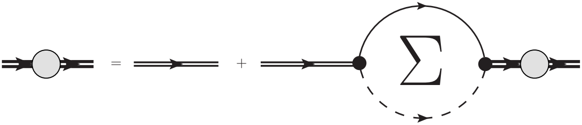


Dressing the D-Wave State



- **nc loops** must be **resummed** to compute the full *d* propagator
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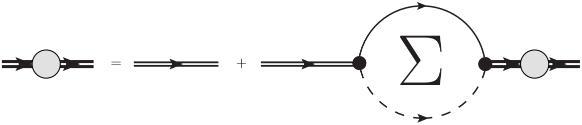

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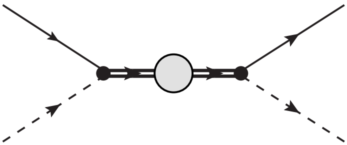
- match scattering amplitude to the **effective-range expansion**



$$t_2(\mathbf{p}', \mathbf{p}; E) = \frac{15\pi}{m_R} \frac{\left(\mathbf{p} \cdot \mathbf{p}'\right)^2 - \frac{1}{3}\mathbf{p}^2\mathbf{p}'^2}{1/a_2 - \frac{1}{2}r_2k^2 + \frac{1}{4}\mathcal{P}_2k^4 + ik^5}$$

Power-Counting Scheme for Shallow Bound States

- power-counting scheme for arbitrary l-th partial wave shallow bound states
- **(l + 1) ERE parameters** needed at LO for matching due to higher divergences
- **minimal number** of fine tunings $\rightarrow$ **l fine tunings** for $l \geq 1$
- every additional fine tuning less likely in nature $\rightarrow$ proof that shallow bound states for higher partial waves **less likely to occur** in nature

$$\gamma_l \sim 1/R_{halo} \qquad a_l \sim \begin{cases} R_{halo}, & l = 0 \\ R_{halo}^{2l}\, R_{core}, & l > 0 \end{cases}$$

$$r_l \sim \begin{cases} R_{core}^{1-2l}, & l = 0 \\ 1/\left(R_{halo}^{2l-2}\, R_{core}\right), & l > 0 \end{cases} \qquad \mathcal{P}_l \sim \begin{cases} R_{core}^{3-2l}, & l \leq 1 \\ 1/\left(R_{halo}^{2l-4}\, R_{core}\right), & l > 1 \end{cases}$$

Electromagnetic Interactions

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- include electromagnetic interactions via **minimal substitution** in the Lagrangian $\partial_\mu \to D_\mu = \partial_\mu + ie\hat{Q}A_\mu$
- add **local gauge-invariant** operators involving the electric field $\mathbf{E} = \nabla A_0 - \partial_0 \mathbf{A}$ and the magnetic field $\mathbf{B} = \nabla \times \mathbf{A}$

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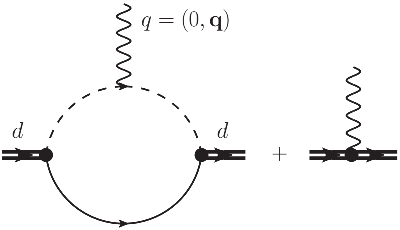
- add **local gauge-invariant** operators involving the electric field $\mathbf{E} = \nabla A_0 - \partial_0 \mathbf{A}$ and the magnetic field $\mathbf{B} = \nabla \times \mathbf{A}$
- compute electric form factors in the **Breit frame** $q = (0, \mathbf{q})$
- electric form factors get contributions only from irreducible **Γ_0 vertex** up to NLO
- for d-wave obtain $G_E(|\mathbf{q}|)$, $G_Q(|\mathbf{q}|)$ & $G_H(|\mathbf{q}|)$ form factors



Electric Form Factors

- need additional local gauge-invariant operators for $r_E \sim L^{(d)}_{C0E}$ and $\mu_Q \sim L^{(d)}_{C0Q}$ at LO to regularize arising divergences for $G_E(|\mathbf{q}|)$ and $G_Q(|\mathbf{q}|)$

$$G_E(|\mathbf{q}|) \approx 1 - \frac{1}{6}\langle r_E^2\rangle\,|\mathbf{q}|^2 + \ldots \quad \xrightarrow{\text{LO}} \quad \langle r_E^2\rangle^{(d)} = -\frac{6\tilde{L}^{(d)\,\text{LO}}_{C0E}}{r_2 + \gamma_2^2\mathcal{P}_2}$$

$$G_Q(|\mathbf{q}|) \approx \mu_Q\left(1 - \frac{1}{6}\langle r_Q^2\rangle\,|\mathbf{q}|^2 + \ldots\right) \quad \xrightarrow{\text{LO}} \quad \mu_Q^{(d)} = \frac{40\tilde{L}^{(d)\,\text{LO}}_{C0Q}}{3\left(r_2 + \mathcal{P}_2\gamma_2^2\right)}$$

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$$G_E(|\mathbf{q}|) \approx 1 - \frac{1}{6}\left\langle r_E^2\right\rangle |\mathbf{q}|^2 + ... \quad \xrightarrow{\text{NLO}} \quad \left\langle r_E^2\right\rangle^{(d)} = -\frac{12\tilde{L}^{(d)\,\text{NLO}}_{C0E} - 35\gamma_2 f^2}{2\left(r_2 + \mathcal{P}_2\gamma_2^2 - 5\gamma_2^3\right)}$$

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$$\xrightarrow{\text{LO}} \quad \langle r_Q^2\rangle^{(d)} = \frac{90}{7}\,\frac{f^4}{\gamma_2\left(r_2 + \mathcal{P}_2\gamma_2^2\right)}$$

$$G_H(|\mathbf{q}|) \approx \mu_H\left(1 - \frac{1}{6}\langle r_H^2\rangle |\mathbf{q}|^2 + ...\right) \quad \xrightarrow{\text{LO}} \quad \mu_H^{(d)} = -\frac{2}{3}\,\frac{f^4}{\gamma_2\left(r_2 + \mathcal{P}_2\gamma_2^2\right)}$$

- **obtain correlations** between different electric observables: $\langle r_Q^2\rangle^{(d)} \sim \mu_H^{(d)}$

E2 Transition

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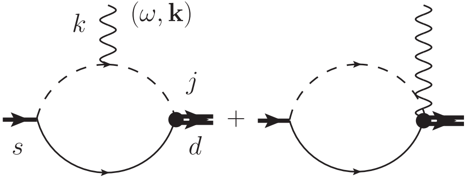
- calculate irreducible **$\Gamma_{j\mu}$ vertex** for E2 transition from the $1/2^+$ to the $5/2^+$ state at LO
- neutron spin unaffected
- **divergences cancel**



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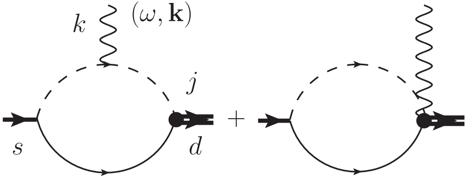


$$B(E2) = \frac{4}{5\pi} \frac{Z_{eff}^2 e^2}{r_2 + \mathcal{P}_2 \gamma_2^2} \frac{-\gamma_0}{1 - r_0 \gamma_0} \left[\frac{3\gamma_0^2 + 9\gamma_0\gamma_2 + 8\gamma_2^2}{(\gamma_0 + \gamma_2)^3} \right]^2$$

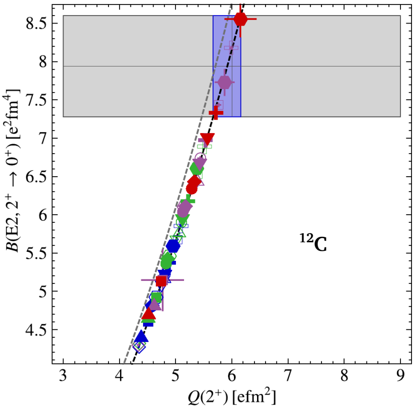
- **experimental result** for B(E2) = 2.90(7) e^2 fm^4
  $\rightarrow$ extract $1/\left(r_2 + \mathcal{P}_2 \gamma_2^2\right)$
- **numerical predictions** for $\langle r_Q^2 \rangle^{(d)} = -0.324$ fm^4 and $\mu_H^{(d)} = 0.017$ fm^4

Correlation between E2 observables

- robust **correlation** between $\mathbf{Q}^{(d)}$ and **B(E2)** in *ab initio* calculations

- interpreted by **rigid rotor** model (Bohr and Mottelson, 1975)

$$B(E2, J_i \to J_f) = f(J_i, J_f, J) \left(\frac{Q_{0,t}}{Q_{0,s}} \right)^2 Q^{(d)}(J)^2$$



[Calci and Roth, 2016]

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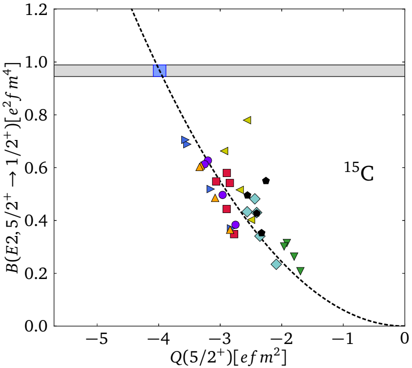
- use correlation for **prediction of** $\mathbf{Q}^{(d)}$ for ^{15}C $\to$ fit $Q_{0,t}/Q_{0,s} \approx 0.5$

- approximation for $\tilde{L}^{(d)\,\mathrm{LO}}_{C0Q}$



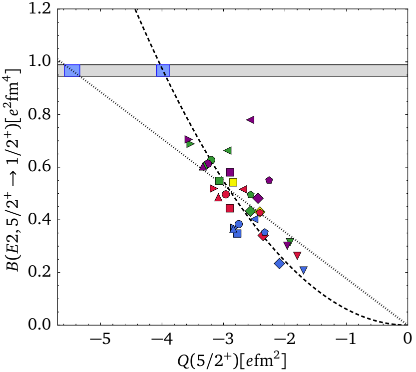
IT-NCSM data from R. Roth

Correlation between E2 observables

- **LO correlation** between **$Q^{(d)}$** and **B(E2)** from Halo EFT

$$\mathrm{B(E2)} = \frac{-1}{50\pi} \frac{Z_{eff}^2 e^2 \gamma_0}{(1 - r_0\gamma_0)} \frac{Q^{(d)}}{\tilde{L}_{C02}^{(d)\,\mathrm{LO}}} \times \left[\frac{3\gamma_0^2 + 9\gamma_0\gamma_2 + 8\gamma_2^2}{(\gamma_0 + \gamma_2)^3}\right]^2$$

- **linear** dependence $\rightarrow$ fit $\tilde{L}_{C0Q}^{(d)\,\mathrm{LO}}$



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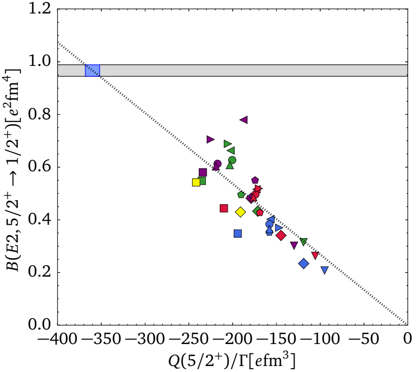
- **linear** dependence $\rightarrow$ fit $\tilde{L}_{C0Q}^{(d)\,\mathrm{LO}}$
- prediction $\mathbf{Q}^{(d)} = -4.21(10)$ **efm**^{2}
- also linear dependence at NLO, but different slope



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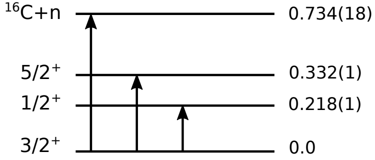
E1 neutron capture

- **halo-like** *D*-wave ground & excited state and *S*-wave excited state in ^{17}**C**



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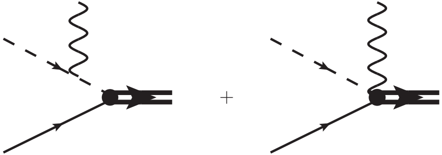
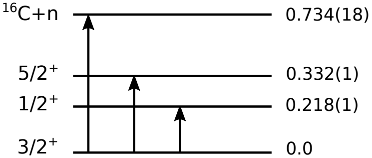
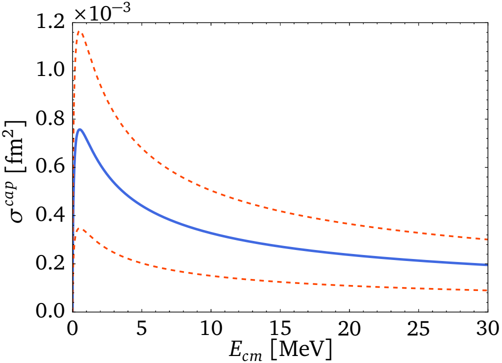




- neutron capture into *S*- and *D*-wave state predominantly through **E1 capture**
- calculate *S*-wave E1 neutron capture cross section

$$\frac{d\sigma^{cap}}{d\Omega} = \frac{m_R}{4\pi^2}\frac{k}{p}\left|\mathcal{M}^{(1/2)}\right|^2 = \frac{e^2 Z_{eff}^2}{\pi m_R^2}\frac{p\gamma_0 \sin^2\theta}{(p^2+\gamma_0^2)}$$

E1 neutron capture for ^{17}C into $1/2^+$ S-wave state



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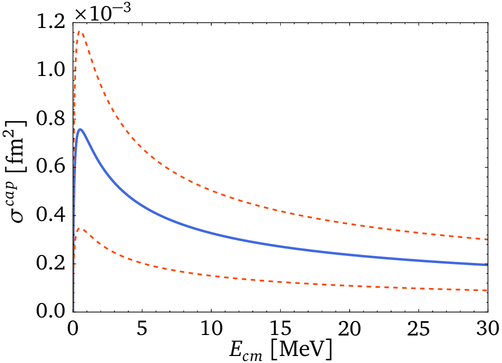
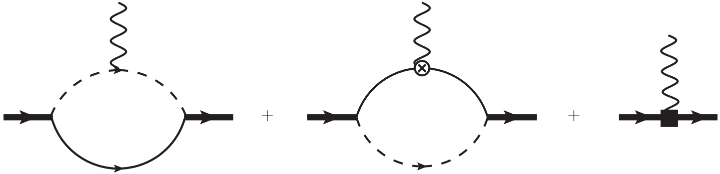


- *D*-wave one **additional input parameters** needed

$$\sigma^{cap} = \frac{\alpha Z_{eff}^2}{-r_2 - \mathcal{P}_2 \gamma_2^2} \frac{32\pi p}{3 m_R^2} \frac{\left(5\gamma_2^4 + 11 p^4 + 14\gamma_2^2 p^2\right)}{\left(\gamma_2^2 + p^2\right)}$$

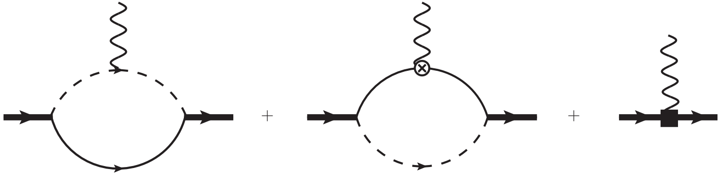
Magnetic Form Factor



- calculate **magnetic moment** of *S*- and *D*-wave state
  follow the approach of [Fernando et al., 2015] (*S*-wave)

$$\mathcal{L}_M = \kappa_n \mu_N n^\dagger \boldsymbol{\sigma} \cdot \mathbf{B} n + 2\mu_N L_M^J \Phi^\dagger \mathbf{S_J} \cdot \mathbf{B} \Phi$$

Magnetic Form Factor



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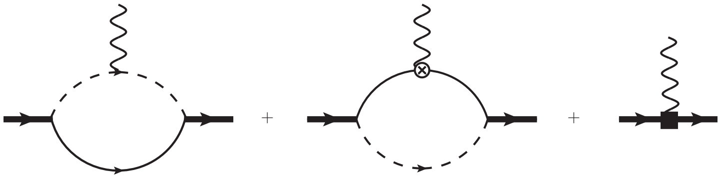
- photon coupling to magnetic moment of neutron $\rightarrow$ LO for S-wave
- 2B-current operator **contributes at LO** for D-wave and **NLO** for S-wave

$$\frac{eZ_c}{2M} G_M(|\mathbf{q}|) \approx \mu_M \left[1 - \frac{1}{6}\langle r_M^2 \rangle |\mathbf{q}|^2 + \ldots\right] \quad \xrightarrow{\text{NLO}} \mu_M^{(\sigma)} = \left(\kappa_n + \tilde{L}_M^\sigma \gamma_0\right)(1 + r_0 \gamma_0)$$

Magnetic Form Factor



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- photon coupling to magnetic moment of neutron $\rightarrow$ LO for S-wave
- 2B-current operator **contributes at LO** for D-wave and **NLO** for S-wave

$$\frac{eZ_c}{2M} G_M(|\mathbf{q}|) \approx \mu_M \left[1 - \frac{1}{6}\langle r_M^2 \rangle |\mathbf{q}|^2 + \ldots\right] \quad \xrightarrow{\text{LO}} \quad \mu_M^{(d)} = -\frac{\tilde{L}_M^d}{r_2 + \mathcal{P}_2 \gamma_2^2}$$

M1 Transition D $\rightarrow$ D'

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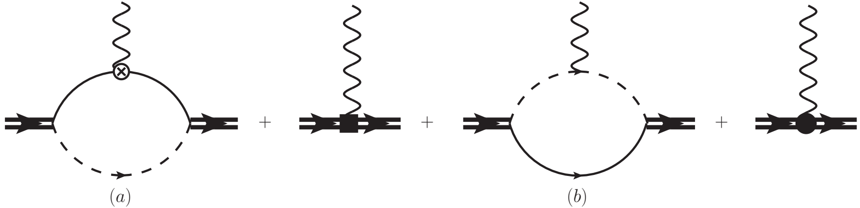

- calculate irreducible **$\Gamma_{m_j m_{j'} \mu}$ vertex** for M1 transition from the $3/2^+$ to the $5/2^+$ state at LO
- photon couples to magnetic moment of neutron and charge of the core
- **2B currents** needed to renormalize divergences **at LO**

$$\mathrm{B(M1)} = \frac{9\mu_N^2}{25\pi} \frac{1}{r_2 + \mathcal{P}_2\gamma_2^2} \frac{1}{r_{2'} + \mathcal{P}_{2'}\gamma_{2'}^2} \left[\tilde{L}_{M1a}^{dd'} + \frac{2\gamma_{2'}^4 \kappa_n}{(\gamma_{2'} + \gamma_2)} + 2\kappa_n \left(\gamma_2 \gamma_{2'}^2 + \gamma_2^3 \right) \right]^2$$

M1 Transition S $\rightarrow$ D

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- in Halo EFT picture M1 transition from $S \rightarrow D$ state forbidden for one-body currents
- experimental result small compared with typical M1 transition strengths in nuclei [Smalley et al., 2015]

$$\mathrm{B}(\mathrm{M1}{:}\ 1/2^{+} \rightarrow 3/2^{+}) = 10.58 \times 10^{-2}\ W.U.$$

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- can predict B(E2) transition using naive dimensional analysis for $\tilde{L}_{M1}^{\sigma d}$

$$\mathrm{B}(\mathrm{E2}\colon 1/2^{+} \rightarrow 3/2^{+}) \approx 3 \times 10^{-2}\ e^2\mathrm{fm}^4$$

Summary

- Halo EFT formalism to calculate electric observables of weakly-bound *S*- & **D-wave** states established
- shallow bound states in lower partial waves more likely
- correlations between electric observables
- combination with *ab initio* calculations to make predictions
- neutron capture and magnetic properties in same way
- number of matching parameters increases for higher partial waves

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Scales and Antisymmetrization

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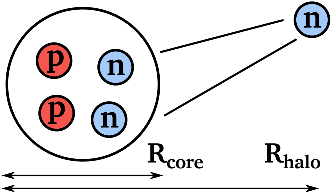
- scales: $R_{halo} \gg R_{core}$
- **antisymmetrization** w.r.t. neutrons in core?
- core neutrons not active dof in Halo EFT



- only contribution if **significant spatial overlap** between wave functions of core and halo nucleon

  $\Rightarrow$ **small** for $R_{halo} \gg R_{core}$

- effects **subsumed in low-energy constants** and included perturbatively in expansion R_{core}/R_{halo}