Proton halos in Cluster effective field theory

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1. Introduction
   - Effective field theory and proton halos
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What we want to do

- Starting point: Nature is effective.
- Do nuclear physics using effective field theory (EFT).
- Examples of effective degrees-of-freedom:
  - Nucleons and pions (Chiral EFT)
  - Only nucleons (Pionless EFT)
  - Clusters of nucleons (Cluster/Halo EFT)
- Goal: Understand structure and reactions of nuclei (calculate observables).

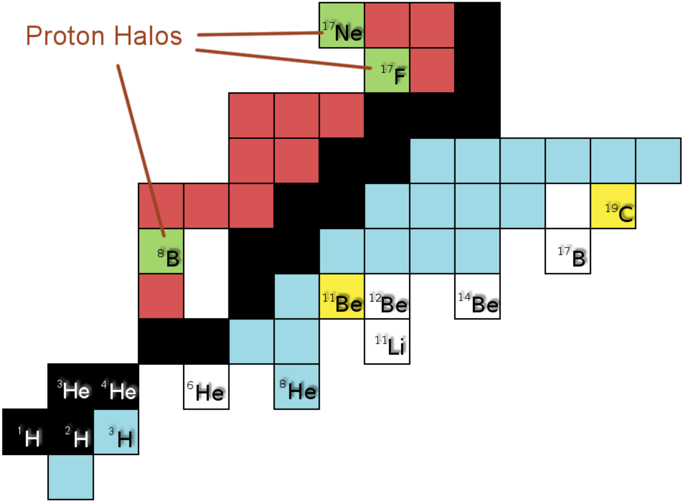
Effective Field Theory

- Describe the physics up to a certain high-momentum scale $k_{\rm hi}$.
  - Use only relevant degrees-of-freedom.
- The high-energy physics (pions, excited states) is implicitly included in the low-energy coefficients of the effective field theory (EFT).
- Need a separation of scales $k_{\rm lo} \ll k_{\rm hi}$.
- Calculate low-energy observables in a systematic expansion $k_{\rm lo}/k_{\rm hi}$.

Proton halos

- Hálōs, from ancient Greek. Ring of light around the sun or the moon.
- Halo, in nuclear physics: Loosely bound system consisting of a core and valence nucleons.
- Focus on one-proton halos. Core and proton as effective degrees of freedom.
  - Core defined as cluster of tightly bound nucleons
- Separation of scales present:
  - Separation energy much smaller than excitation energy of core.
- Both particles charged, very low energies
  $\Rightarrow$ Include Coulomb to infinite order!

Proton halos



Cluster effective field theory

- Effective degrees-of-freedom in Cluster/Halo EFT:
  - proton and neutron
  - clusters of nucleons (structureless point-particles)

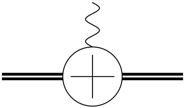
- Need separation of scales:
  - At low enough momentum to not resolve internal structure of cluster.

- Halo physics example:
  - One-nucleon separation energy $\sim 0.1\text{–}1\ \mathrm{MeV}$.
  - Excited states, internal structure $\sim 2\text{–}20\ \mathrm{MeV}$.

Lagrangian for proton and core field:

$$\mathcal{L} = \mathrm{p}^\dagger\left(i\partial_t + \frac{\nabla^2}{2m}\right)\mathrm{p} + \mathrm{c}^\dagger\left(i\partial_t + \frac{\nabla^2}{2M}\right)\mathrm{c} + \mathrm{c}^\dagger\mathrm{p}^\dagger\mathrm{p}\left[C_0 + C_2\overleftrightarrow{\nabla}^2 + \ldots\right]\mathrm{c}$$

Charge form factor



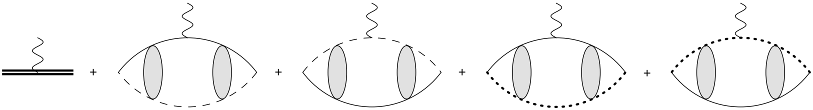
- The charge form factor is defined as

$$\frac{1}{Ze}\langle J^0_{\mathrm{EM}}\rangle = F_{\mathrm{C}}(\mathbf{Q}) = 1 - \frac{r_{\mathrm{C}}^2}{6}\mathbf{Q}^2 + \dots ,$$

- Photon momentum (momentum transfer) $\mathbf{Q}$ and $\omega = 0$ (off-shell photon in Breit frame).

- Charge radius r_{C}: good measure of the size of nucleus.

Charge radius of Boron-8



- Charge radius of $^{8}\mathrm{B}$ planned to be measured using the atomic isotope shift!

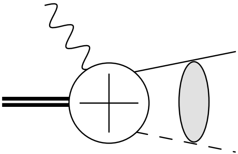
- The leading order Cluster EFT results for the charge radius of $^{8}\mathrm{B}$:

$$r_{\mathrm{C}} = 2.5 \text{ fm}$$

- EFT error of $\sim 14\%$.

- At the next order there is an undetermined short-range operator $\mathrm{d}^{\dagger}\left(\nabla^{2} A_{0}\right) \mathrm{d}$.

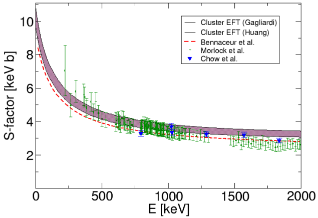
Radiative proton capture



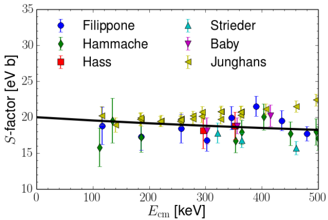
- Capture of a proton on a core, while emitting a photon.
- Cross section exponentially suppressed at low energy.
  - Tunnel through the Coulomb barrier.
- Define: Astrophysical S-factor $S(E) = E \exp(2\pi\eta)\sigma_{\mathrm{tot}}(E)$.

Radiative proton capture in Cluster EFT

$^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}^*$



$^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$



- Low-energy S-factors well described by Cluster EFT.
- Application: Astrophysics and stellar nucleosynthesis!

Summary

- Cluster (Halo) EFT
  - Treat the core as an effective degree-of-freedom, structureless.
- Observables considered:
  - Charge radius of $^{8}\mathrm{B}$ (and $^{17}\mathrm{F}^{*}$).
  - Radiative proton capture $^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}^{*}$ and $^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$.

Outlook

- 3-body systems
  - Hoyle state of $^{12}\mathrm{C}$
    $\Rightarrow$ need 3-body Coulomb propagators
  - Two-neutron halo $^{26}\mathrm{O}$
    Resonant $^{24}\mathrm{O}$+neutron D-wave interaction