Capture Reactions with Halo EFT

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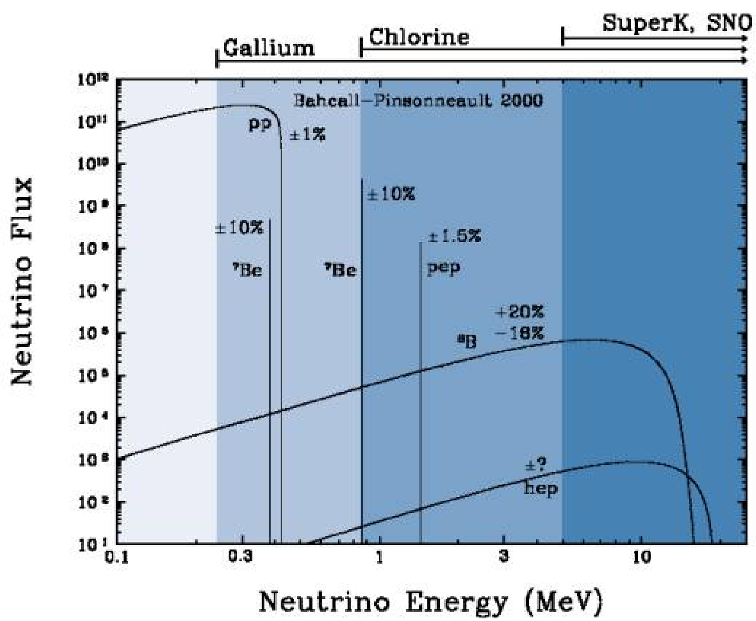
Critical Stability

Santos, October 14, 2014

Outline

- motivation
- n-$^7\mathrm{Li}$ system:
  - low-energy structure
  - low-energy approaches
- halo EFT for $n + {}^7\mathrm{Li} \rightarrow {}^8\mathrm{Li} + \gamma$
  - E_1 capture
  - M_1 capture
- Summary and outlook



- $\mathrm{p} + {}^7\mathrm{Be} \rightarrow {}^8\mathrm{B} + \gamma$

  $\hookrightarrow {}^8\mathrm{Be} + e^+ + \nu_e$

  $\Rightarrow$ major uncertainty on ν_e flux

  $\Rightarrow$ $S_{17}(0)$: low-energy extrapolation

  $\Rightarrow$ matter/vacuum oscillations

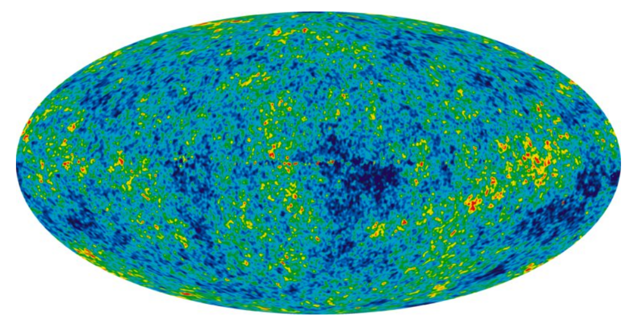
  $\Rightarrow$ direct/inverse hierarchy

- mirror symmetry: ${}^7\mathrm{Li}(n,\gamma){}^8\mathrm{Li}$

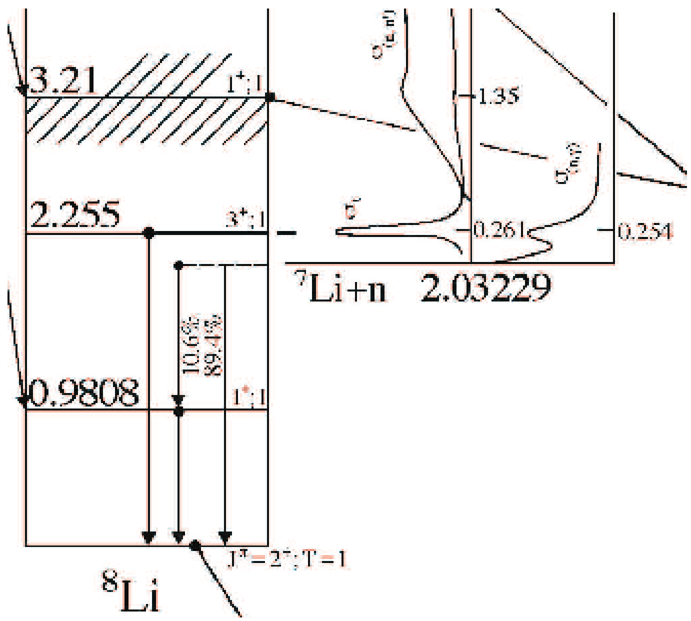
  - non-homogeneous BBN: bridge the $A = 8$ gap

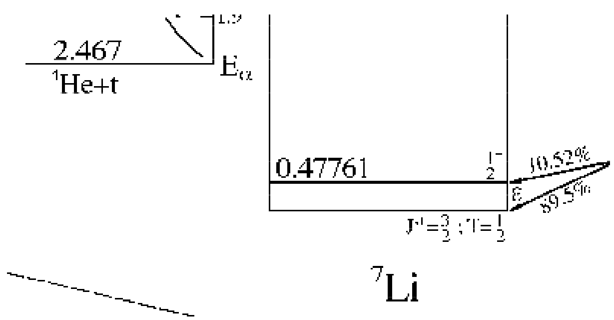
    ${}^1\mathrm{H}(n,\gamma){}^2\mathrm{H}(n,\gamma){}^3\mathrm{H}(d,n){}^4\mathrm{He}(t,\gamma){}^7\mathrm{Li}(n,\gamma){}^8\mathrm{Li}$

    ${}^7\mathrm{Li}(n,\gamma){}^8\mathrm{Li}(\alpha,n){}^{11}\mathrm{B}(n,\gamma){}^{12}\mathrm{B}(\beta^-){}^{12}\mathrm{C}\ \ldots$



the n-$^7\mathrm{Li}$ system





⇒ Bound states:

- 2^+ (-2.03 MeV): $\frac{1}{\sqrt{2}}[{}^5P_2 + {}^3P_2]$ $(p_{3/2})$
- 1^+ (-1.05 MeV): $\frac{1}{\sqrt{2}}[{}^5P_2 - {}^3P_2]$ $(p_{1/2})$

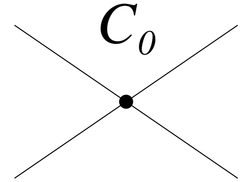
⇒ Scattering states:

- ${}^5S_2$: $a_0^{(2)} = -3.63 \pm 0.05$ fm
- ${}^3S_1$: $a_0^{(1)} = 0.87 \pm 0.07$ fm
- ${}^3P_3$: $E_R = 0.222$ MeV, $\Gamma_R = 0.031$ MeV

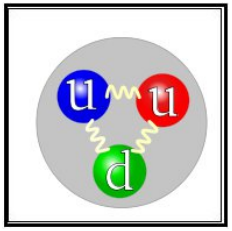
⇒ Radiative capture:

- ${}^5S_2, {}^5S_2 \to 2+$ (E1, 89.4%)
- ${}^5S_2, {}^5S_2 \to 1+$ (E1, 10.6%)
- ${}^5P_3 \to 2+$ (M1)

potential models vs EFT

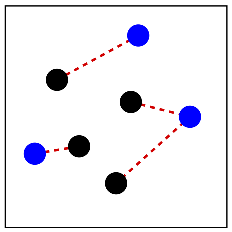
	V_{WS}	EFT
	$V_{WS}(r) = \frac{-V_0}{1+\exp\left(\frac{r-R}{d}\right)}$	
bound state	Sch. Eq. for V_0^B, SF/ANC	Feynman graphs, resum., $\mathcal{Z}$
scatt. states	Sch. Eq. for $V_0^{S,\nu}$	Feynman graphs (resum.), a, r
EM	$\mathcal{O}_{E1} = Z_C \frac{\mu}{M_C} e\, r\, Y_{1m}(\hat{r})$	QED

EFT: basic ideas



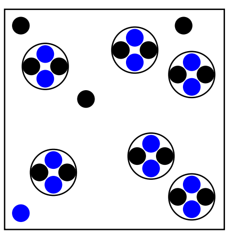
$1 \rightarrow 10$ GeV

- QCD/SM: quarks, gluons vs. hadrons



100 MeV $\rightarrow 1$ GeV

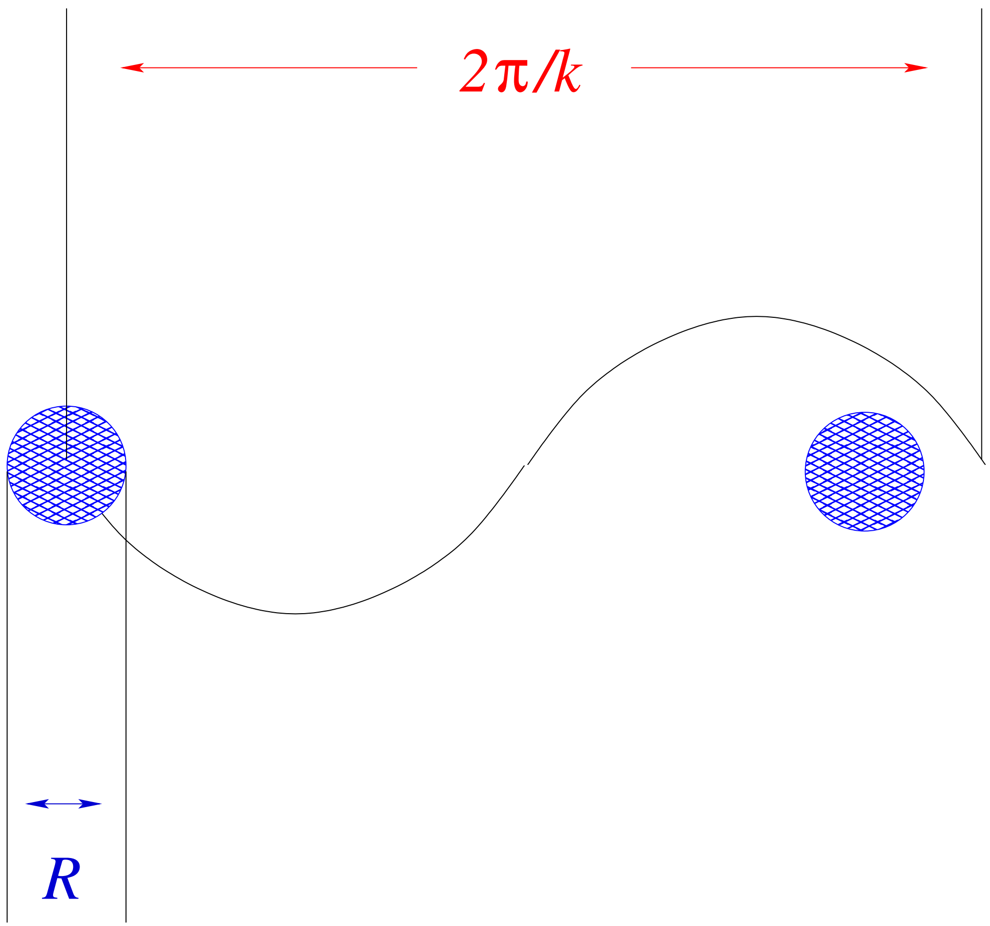
- χEFT, phenomenology (meson theory)

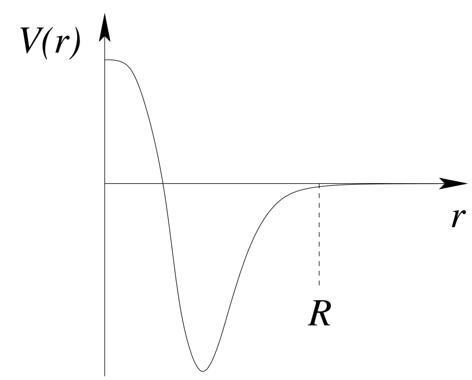


< 50 MeV

- $\not\pi$EFT, Halo/cluster EFT, phenomenology

EFT: basic ideas

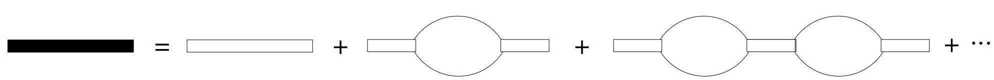




halo/cluster EFT for n-$^7\mathrm{Li}$ (scatt. states)

$$\mathcal{L}_{\mathrm{kin}} = N^\dagger\left[i\partial_0+\frac{\vec{\nabla}^2}{2M_N}\right]N+C^\dagger\left[i\partial_0+\frac{\vec{\nabla}^2}{2M_C}\right]C\,,$$

$$\mathcal{L}_{\mathrm{int},s} = \phi_i^{(s)\dagger}\Bigg[\underbrace{i\partial_0+\frac{\vec{\nabla}^2}{8\mu}}_{\sim C_2}-\underbrace{\Delta}_{\sim C_0}\Bigg]\phi_i^{(s)}+g_0\left[\phi_i^{(s)\dagger}N^T\tilde{P}_i^{(s)}C+\mathrm{H.c.}\right]+\cdots\,,$$



$$\Delta\sim\frac{M_{hi}^2}{\mu}\quad\rightarrow\quad iD_s^{(0)}=\frac{i}{-\Delta+i\epsilon}\sim\frac{\mu}{M_{hi}^2}\qquad({}^3S_1)$$

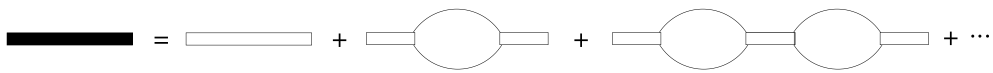
$$\Delta\sim\frac{M_{hi}^2}{\mu}\,\frac{M_{lo}}{M_{hi}}\quad\rightarrow\quad iD_s^{(0)}=\frac{i}{-\Delta+i\epsilon}\sim\frac{\mu}{M_{hi}M_{lo}}\qquad({}^5S_2)$$

halo/cluster EFT for n-$^7\mathrm{Li}$ (bound state)

p-wave: Bertulani, Hammer, van Kolck; Bedaque, Hammer, van Kolck

- two operators at LO!

$$\mathcal{L}_{\mathrm{int},p} = \phi_{ij}^{(p)\dagger}\left[i\partial_0 + \frac{\vec{\nabla}^2}{8\mu} - \Delta\right]\phi_{ij}^{(p)} + g_1\left[\phi_{ij}^{(p)\dagger} N^T \tilde{P}_{ij}^{(p)} C + \mathrm{H.c.}\right] + \cdots\,,$$

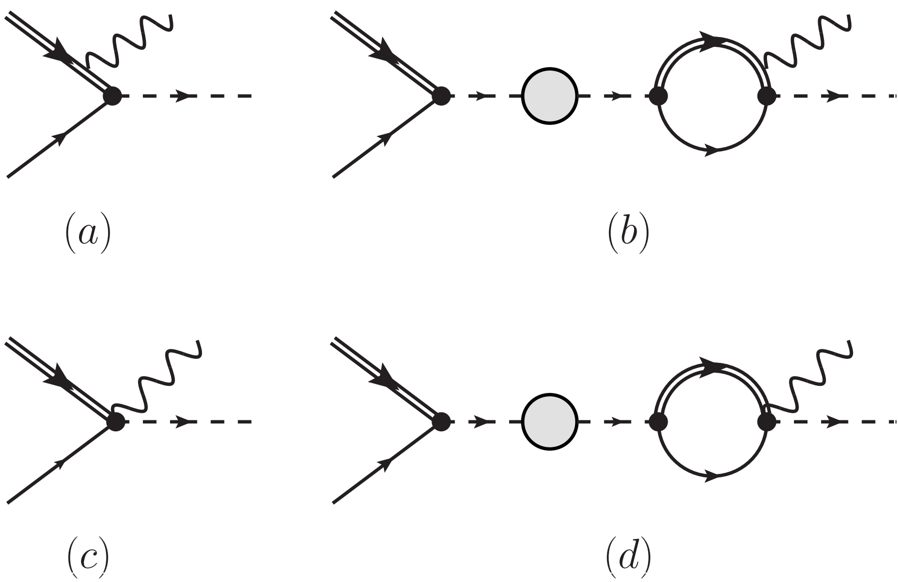


$$\Delta \sim M_{lo}^2/\mu \quad \rightarrow \quad iD_p^{(0)} = \frac{i}{q_0 - \boldsymbol{q}^2/8\mu - \Delta + i\epsilon} \sim \frac{\mu}{M_{lo}^2} \qquad ({}^3P_2, {}^5P_2)$$

$$\mathbf{D}_p = \frac{i}{q_0 - \boldsymbol{q}^2/8\mu - \Delta - 6g_1^2 L} \quad \Rightarrow \quad \mathcal{Z}^{-1} \equiv \frac{\partial}{\partial q_0}\left[\mathbf{D}_p^{-1}\right]_{\mathrm{pole}} = \frac{-2\pi}{3(\gamma_B + r_1)}$$

pole: $\boldsymbol{q} = 0$; $q_0 = -\gamma_B^2/2\mu$

E_1 radiative capture



(a) (b) (c) (d)

- gauge invariance: cancellation of divergences (Phillips and Hammer)

$$\sigma^{E_1}_{\text{capture}} = \frac{\mathcal{Z}}{32\pi M^2}\frac{k_\gamma}{p}\,\alpha_{em}\left(\frac{Z_C M_N}{M}\right)^2 F(p, \gamma_B, M_C, M_N, a_0^{(1)}, a_0^{(2)})$$

Wigner bound

For short-range, S-wave, E-independent V,

$$r_0 \leq 2\left(R - \frac{R^2}{a} + \frac{R^3}{3a^2}\right) \qquad \text{(Wigner 55')}$$

equivalent to

$$\frac{d}{dE}\left[\sqrt{2\mu E}\ \cot\delta(E)\right] \leq 0$$

(Philips *et al.* 1998, Lee and Hammer 2010)

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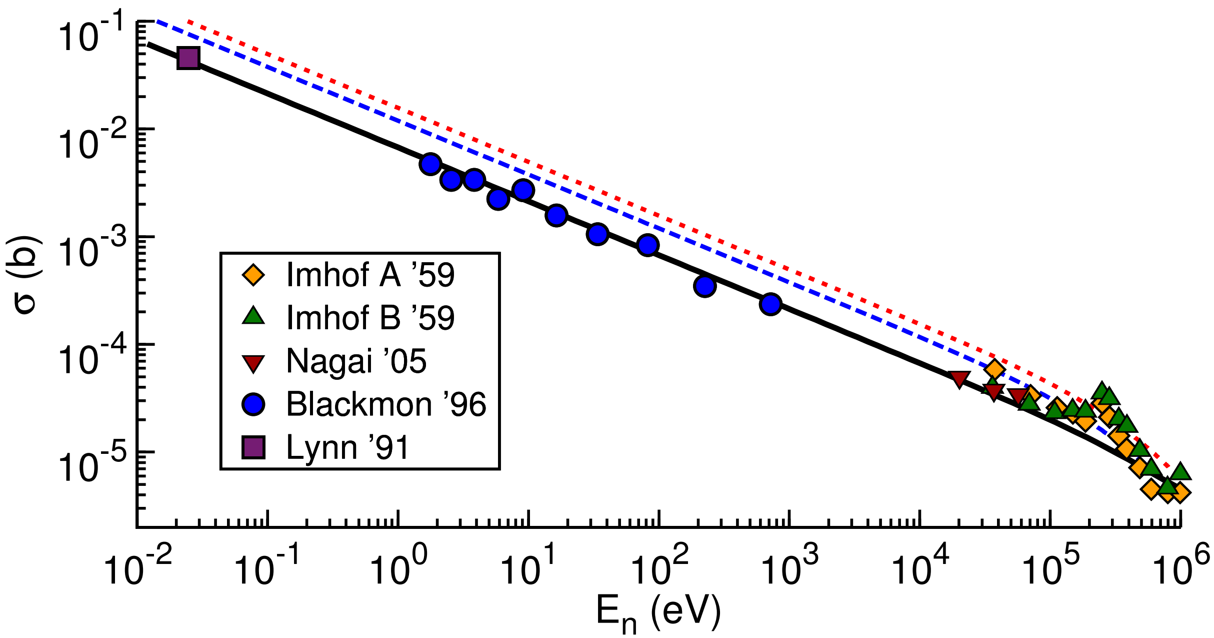
Constraints from divergences of loop integrals

infinities are good!!!

E_1 radiative capture

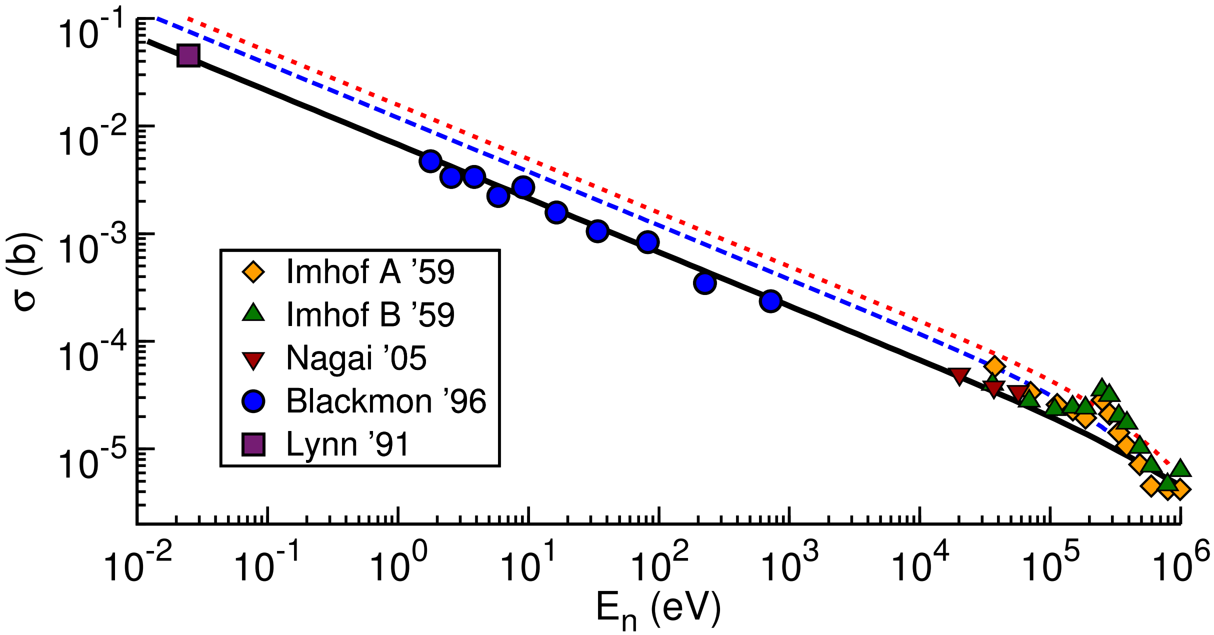


Davids-Typel: $r_1 \approx -0.30$ fm^{-1}

Tombrello: $r_1 \approx -0.46$ fm^{-1}

Wigner bound: $r_1 \lesssim -1$ fm^{-1}

E_1 radiative capture



Davids-Typel: $r_1 \approx -0.30$ fm^{-1}

Tombrello: $r_1 \approx -0.46$ fm^{-1}

EFT: $r_1 = -1.47$ fm^{-1}

(G. Rupak, RH, PRL 106, 222501, 2011)

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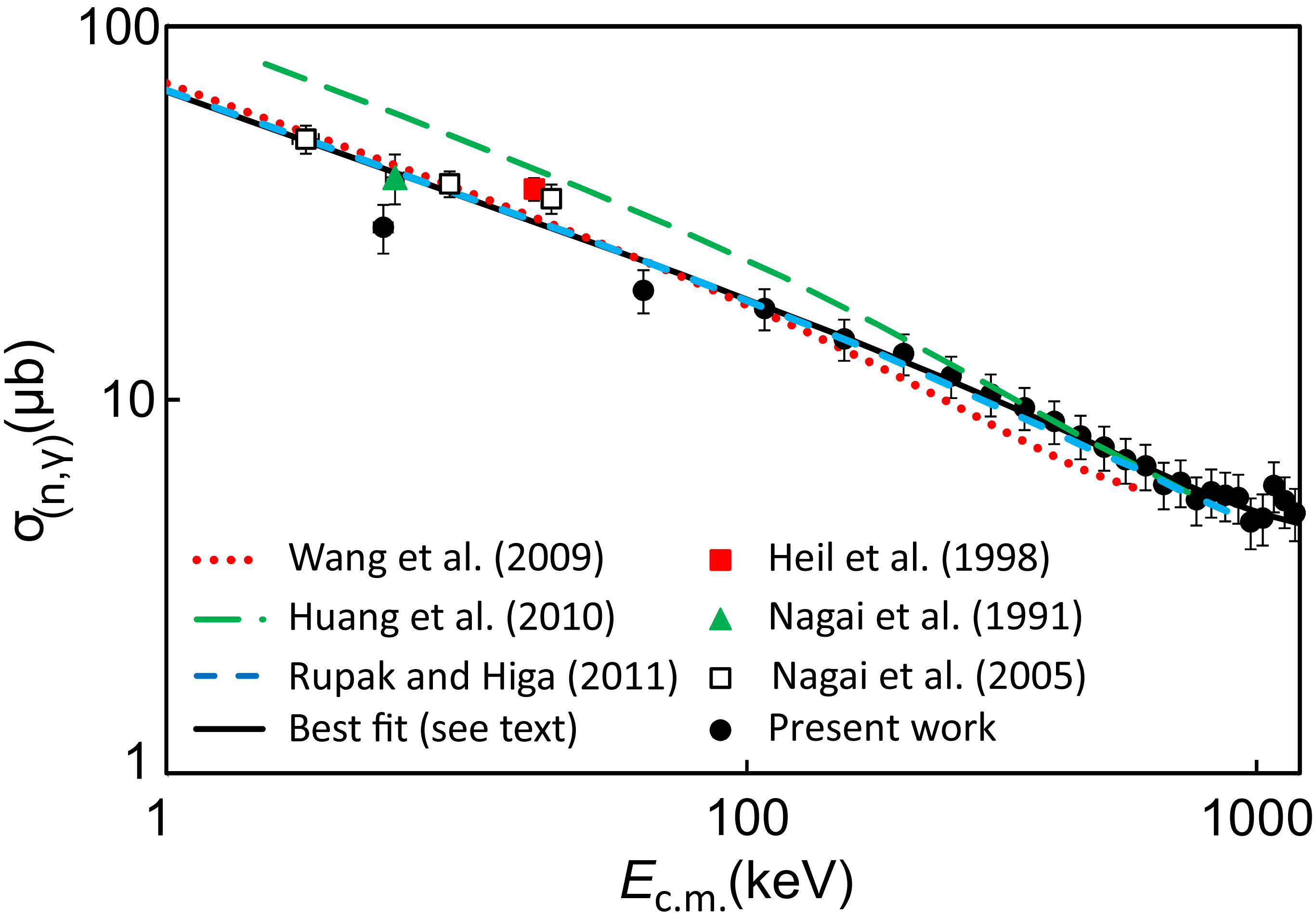
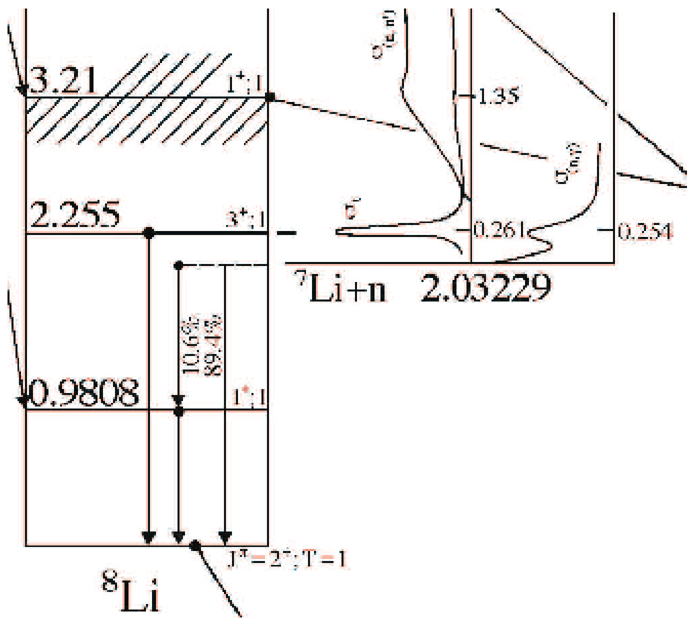
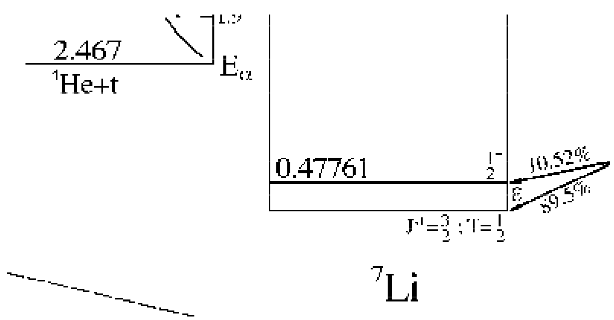


(Izsák *et al.*, arXiv:1312.3498 [nucl-ex], to appear @ PRC)

the n-^{7}Li system





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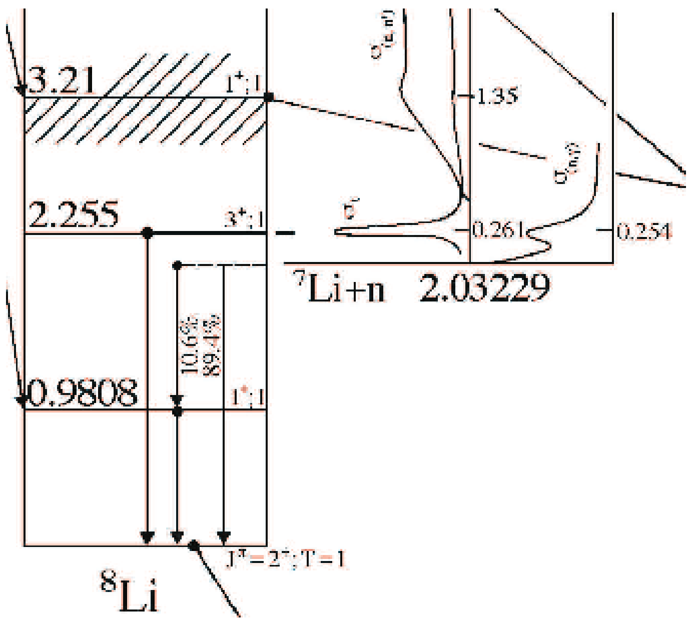

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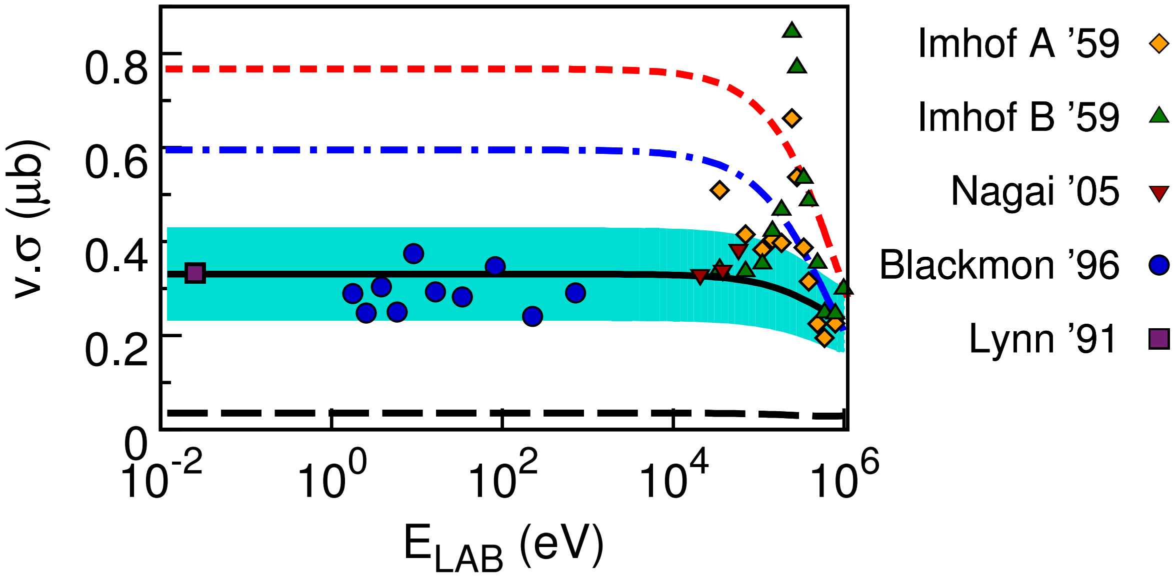
E_1 radiative capture



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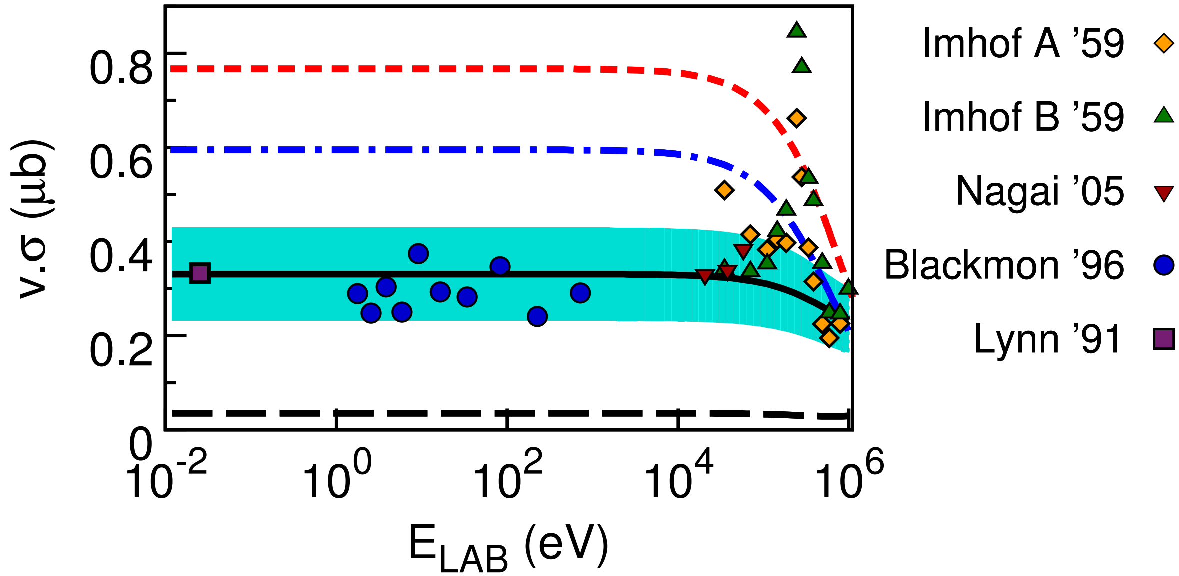
(L. Fernando, RH, G. Rupak, EPJA 48, 24, 2012)

E_1 radiative capture



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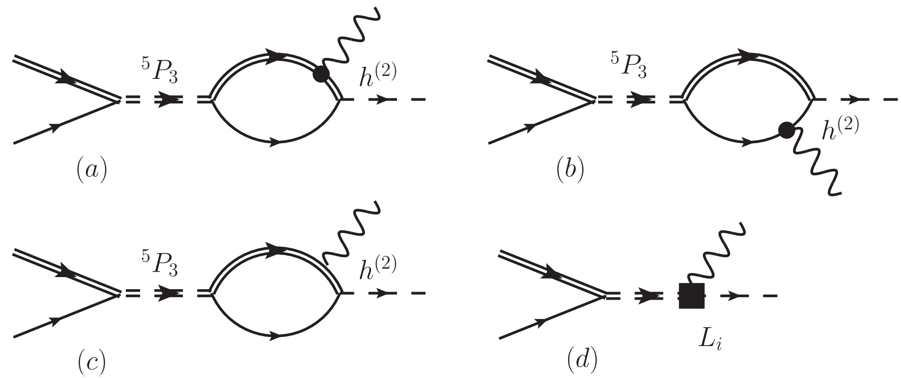
EFT+*ab-initio*: $^5P_2$ - $^3P_2$ weights, $^7\mathrm{Li}^*$

(X. Zhang *et al.*, PRC 89, 024613, 2014)

M_1 radiative capture

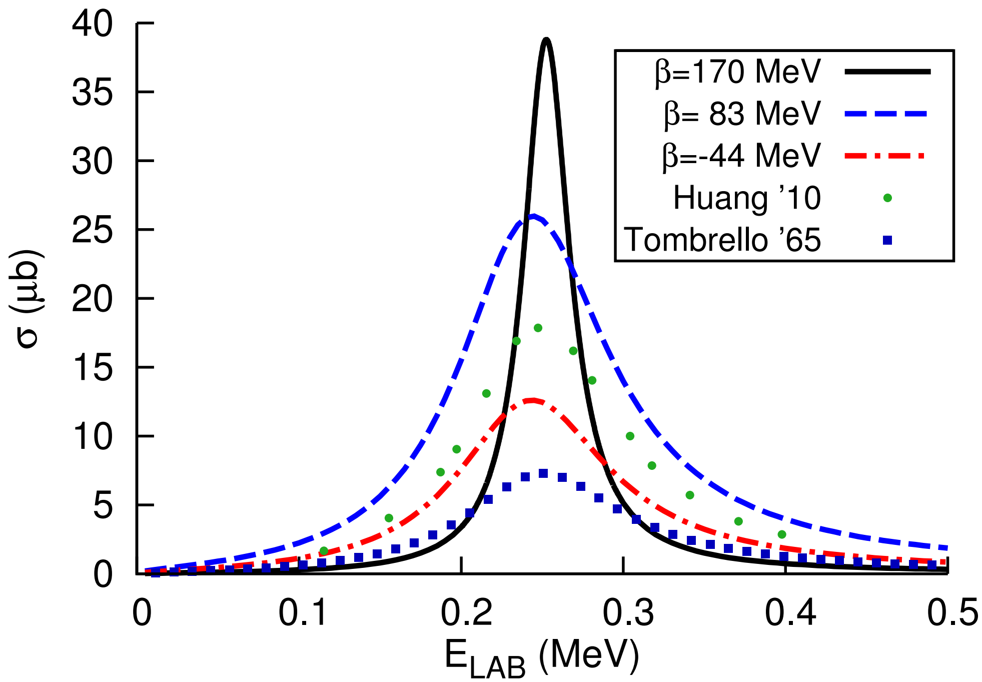


$$\sigma^{M_1}_{\text{capture}} = \frac{\mathcal{Z}}{32\pi M^2}\left[\frac{k_\gamma}{p}\right]^3 p^4\, G(p, \gamma_B, M_C, M_N, a_0^{(1)}, a_0^{(2)}, K^{(1)}, K^{(2)}, \beta)$$

$$K^{(1)} = \sqrt{\frac{3}{2}}\left(\frac{3}{2}g_c - \frac{3}{2}g_n\right), \qquad K^{(2)} = \sqrt{\frac{3}{2}}\left(\frac{3}{2}g_c + \frac{1}{2}g_n + \frac{2\mu Z_c M_n}{M_c^2}\right),$$

$$\left(\frac{\mu M_n Z_c}{M_c^2}\vec{\boldsymbol{L}} + g_c\vec{\boldsymbol{S}}_C + g_n\vec{\boldsymbol{S}}_N\right)_z$$

M_1 radiative capture



$\Gamma_{exp} \approx 30$ keV; $\Gamma_{pot} \approx 110$ keV

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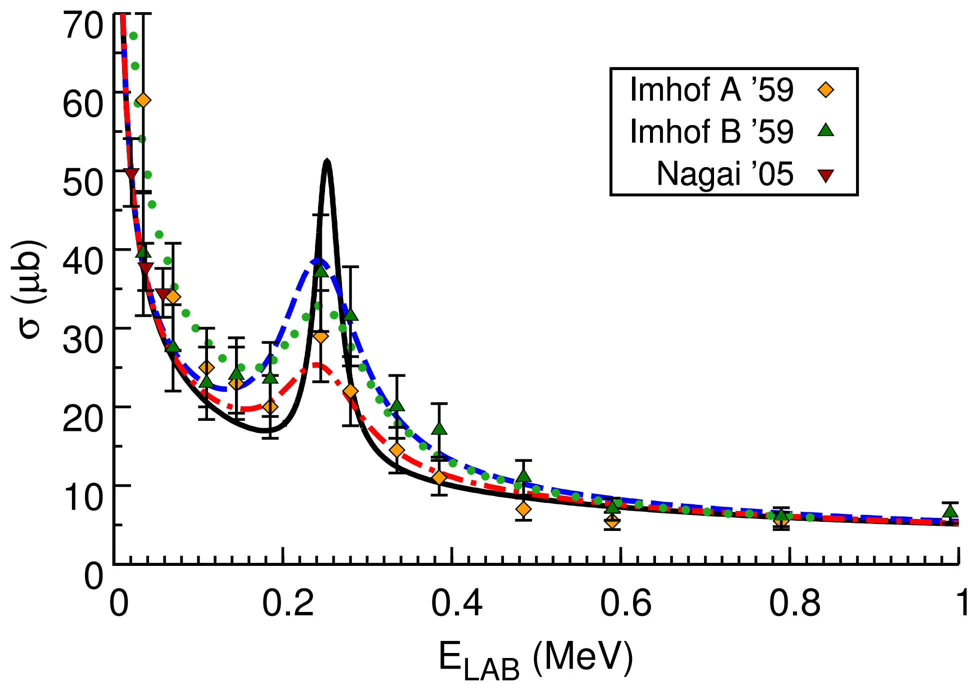

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see also Bennaceur *et al.*, NPA 651, 289, 1999

Summary

- halo/cluster EFT: systematic way of implementing EM currents
- gauge invariance: cancellation of power divergences
- $^{7}\mathrm{Li}(n,\gamma)^{8}\mathrm{Li}$:
  - two operators at LO
  - "normalization" is very sensitive to r_1 (not well-known from elastic scatt.)
  - $r_1 = -1.47$ fm^{-1}: excellent description of previous data, respect the Wigner bound
  - potential models: not so reliable extrapolations at low energies, uncontrolled theoretical uncertainties
  - excellent agreement with most recent MSU data (CD)
  - M_1 capture: missing some structure (degrees of freedom)

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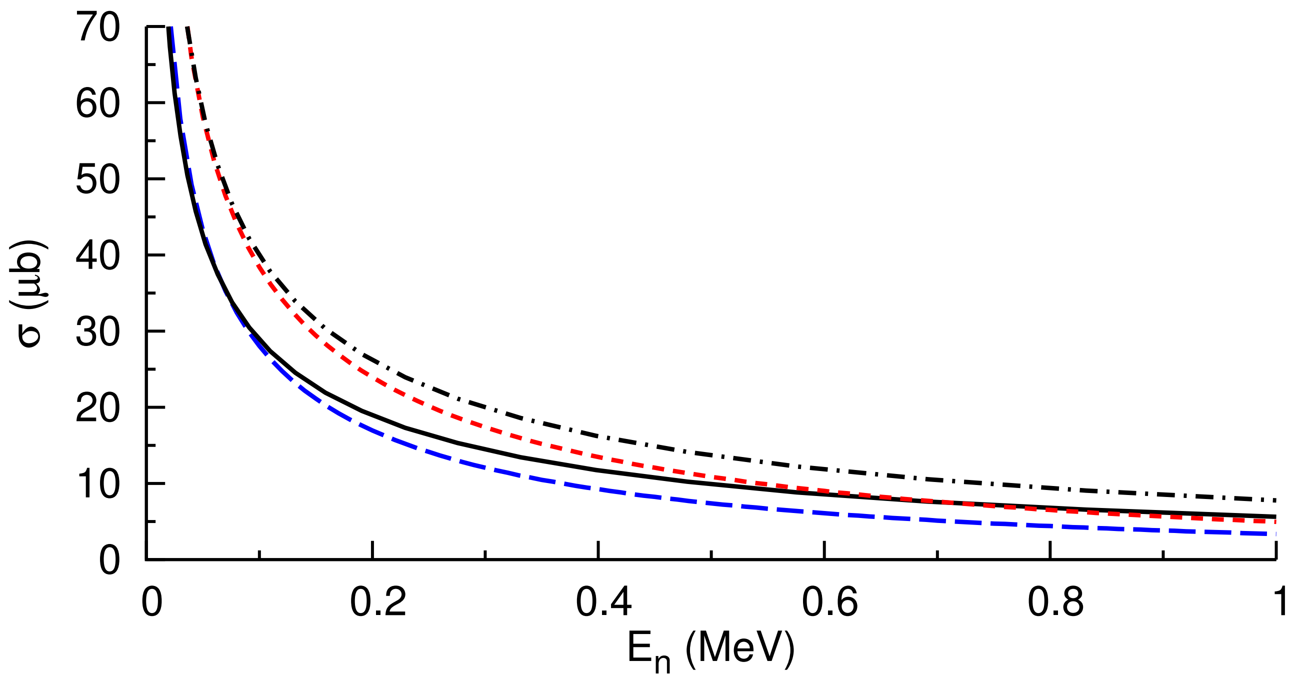
E_1 radiative capture (theory: ${}^5P_2$ only)



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