Radiative capture study by combining EFT with ab initio calculations: $^{7}\mathrm{Li}(n,\gamma)^{8}\mathrm{Li}$ and $^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$

Xilin Zhang (Ohio University)

Nuclear Theory Group Seminar, LANL, Jan 15, 2014

X. Z, K. M. Nollett and D. R. Phillips, arXiv:1311.6822; 1401.xxxx

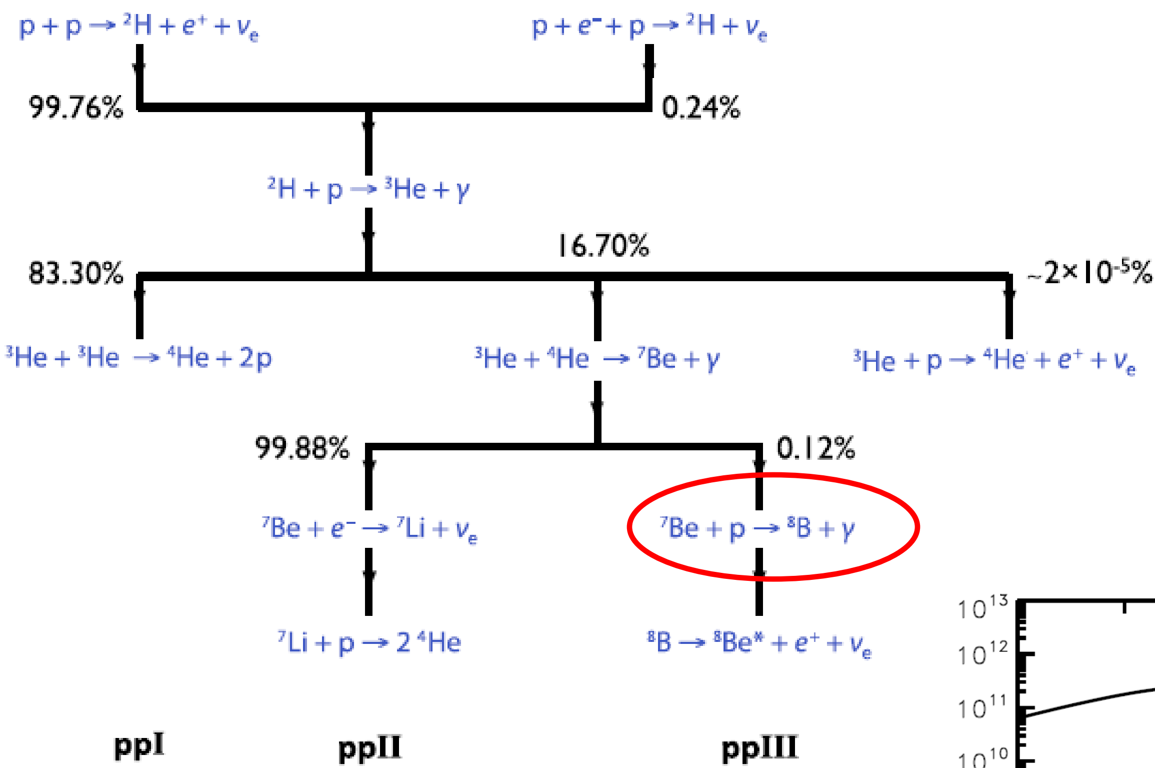
Outline

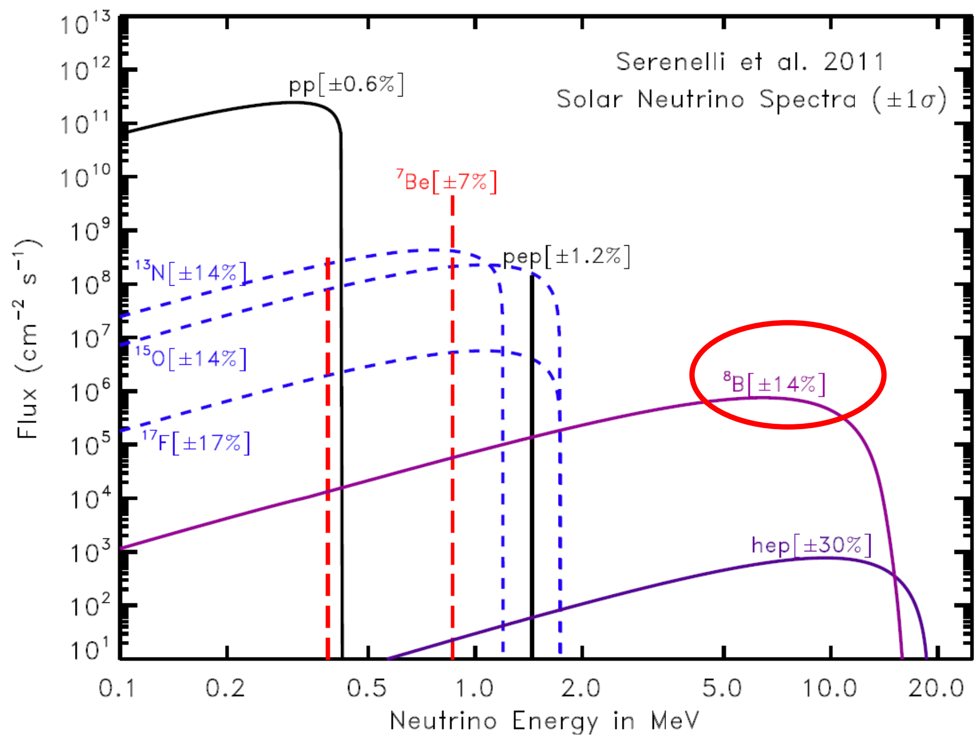
- Motivations
- A toy model: spinless nucleon and core
- Li7 capture: spins, core excitation, leading order (LO) results
- Be7 capture: nonperturbative Coulomb, LO results
- Outlook: Next-to-LO
- My other works: neutrino-nucleus, jet quenching in heavy ion collision, cold nuclear matter

Motivations

Astrophysics

Solar neutrino generation





Not experimentally accessible

W. C. Haxton et.al., arXiv:1208.5723

SENSITIVITY OF *r*-PROCESS NUCLEOSYNTHESIS TO LIGHT-ELEMENT NUCLEAR REACTIONS

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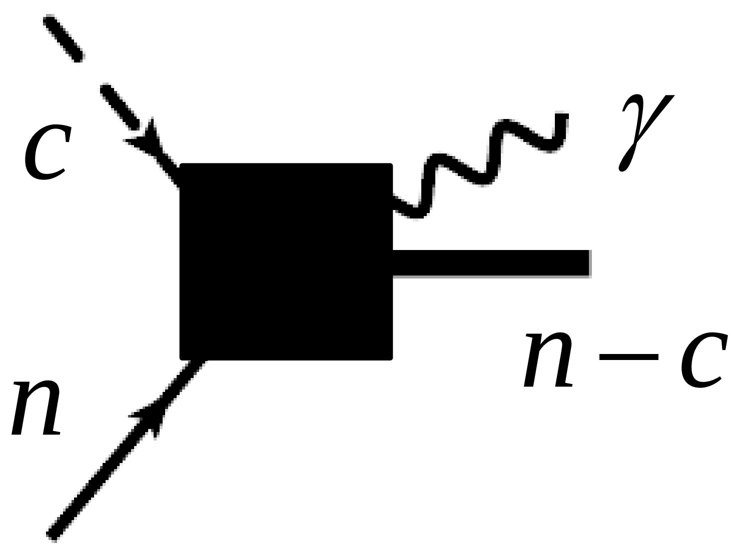
AND

MOST IMPORTANT 18 LIGHT-MASS NUCLEAR REACTIONS, ADOPTED "STANDARD" THERMONUCLEAR REACTION RATES $\lambda_i(0)$, AND UNCERTAINTIES

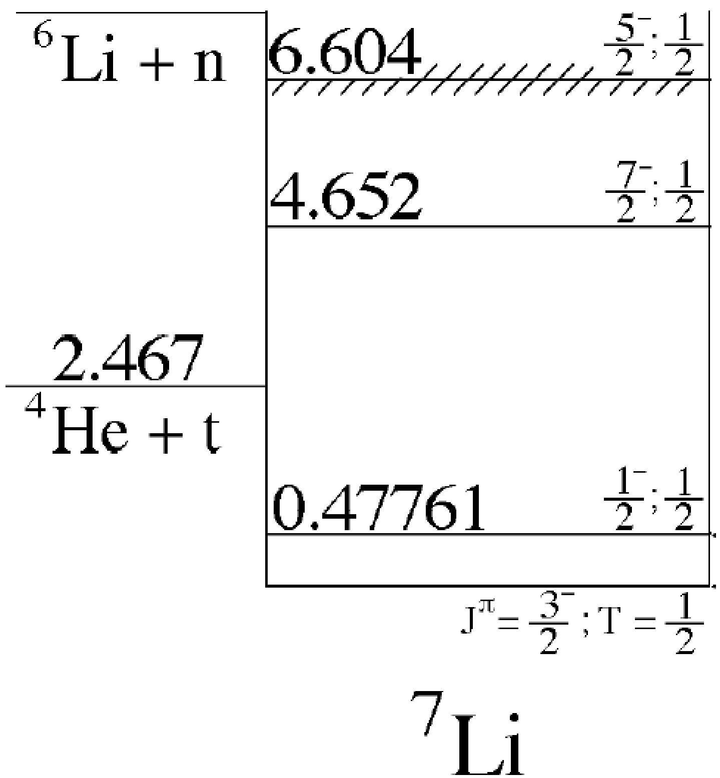
No.	Reaction	$N_{Av}\langle\sigma v\rangle$	1 σ[a]	Reference[b]
(1)........................	$\alpha(\alpha n,\gamma)^9Be$	$N_{Av}^2\langle\alpha\alpha n\rangle = 2.43\times10^9 T_9^{-2/3}\exp[-13.490T_9^{-1/3} - (T_9/0.15)^2](1+74.5T_9)$ $+6.09\times10^5 T_9^{-3/2}\exp(-1.054/T_9)(1-58.80T_9-1.794\times10^4T_9^2$ $+2.969\times10^6T_9^3-1.535\times10^8T_9^4+2.610\times10^9T_9^5)$	±35%	1
(2)........................	$\alpha(t,\gamma)^7Li$[c]	$3.032\times10^5T_9^{-2/3}\exp(-8.09/T_9^{1/3})(1.0+0.0516T_9^{1/3}+0.0229T_9^{2/3}$ $+8.28\times10^{-3}T_9-3.28\times10^{-04}T_9^{4/3}-3.01\times10^{-04}T_9^{5/3})$ $+5.109\times10^5T_{9*}^{5/6}T_9^{-3/2}\exp(-8.068/T_{9*}^{1/3})$	±30%	2
(3)........................	$^7Li(n,\gamma)^8Li$	$4.90\times10^3+9.96\times10^3T_9^{-3/2}\exp(-2.62/T_9)$	±35%	3

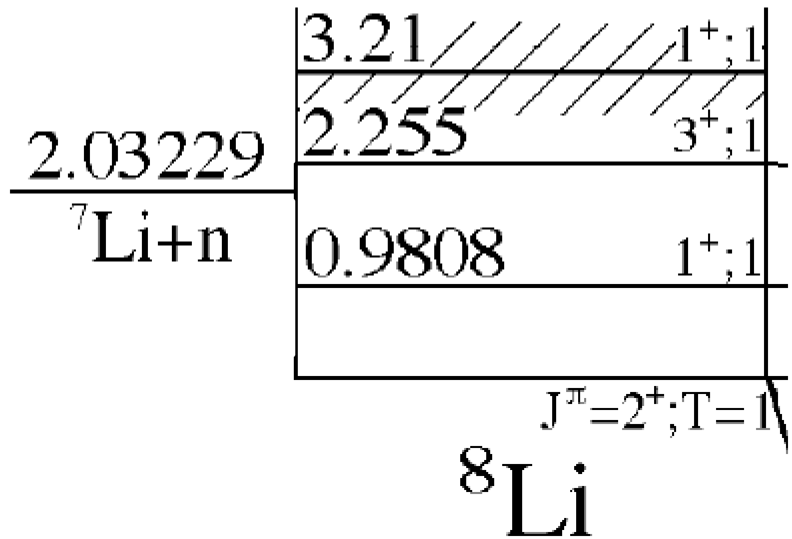
Li7 capture is used to constrain models of Be7 capture.

A toy model



Gross features: p-wave





$$\Lambda \sim \sqrt{2M_{43}B_{Li7}} \sim 100\ \mathrm{MeV}$$

$$\gamma \sim \sqrt{2M_{71}B_{Li8}} = 57.8\ \mathrm{MeV}$$

$$\frac{\gamma}{\Lambda} \sim 0.5$$

Shallow p-wave bound state

Gross features: s-wave

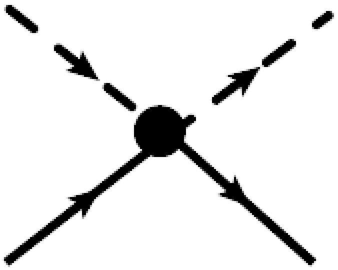
Parameter	Channel	Value	Assigned scaling
$a_{(^5S_2)}$	S-wave, $S=2$	$-3.63(5)$ fm	$1/\gamma$
$a_{(^3S_1)}$	S-wave, $S=1$	$0.87(7)$ fm	$1/\Lambda$

$$\Lambda \approx 100 \text{ MeV}$$

Large s-wave scattering length

L. Koester, K. Knopf, and W. Waschkowski, Z. Phys. A 312, 81 (1983)

S-wave in EFT



$$T = \frac{2\pi}{M_{\rm R}} \frac{1}{-k\cot\delta_0 + ik}$$

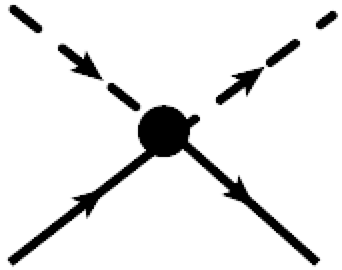
Effective range expansion (ERE): $$-k\cot\delta_0 = \frac{1}{a_0} - \frac{1}{2} r_0 k^2 + \ldots$$

$$T = \frac{2\pi}{M_{\rm R}} a_0 \left[1 - i a_0 k + \left(\frac{a_0 r_0}{2} - a_0^2\right) k^2 + \ldots\right]$$

Natural

$$a_0 \sim \frac{1}{\Lambda} \text{ and } r_0 \sim \frac{1}{\Lambda}$$

S-wave in EFT



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Natural

$$a_0 \sim \frac{1}{\Lambda} \text{ and } r_0 \sim \frac{1}{\Lambda}$$

$$T = \frac{2\pi}{M_{\rm R}} \frac{1}{a_0^{-1} + ik} \left(1 + \frac{r_0 k^2}{2} \frac{1}{a_0^{-1} + ik} + \ldots \right)$$

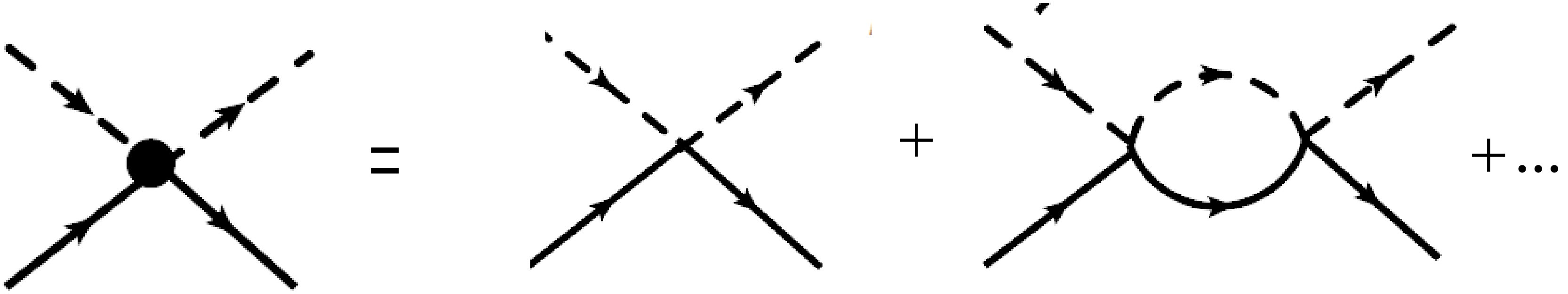
Unnatural

$$a_0 \sim \frac{1}{\gamma} \text{ but } r_0 \sim \frac{1}{\Lambda}$$

S-wave in EFT

$$\mathcal{L}_0 = n^\dagger \left(i\partial_t + \frac{\nabla^2}{2M_\mathrm{n}} \right) n + c^\dagger \left(i\partial_t + \frac{\nabla^2}{2M_\mathrm{c}} \right) c$$

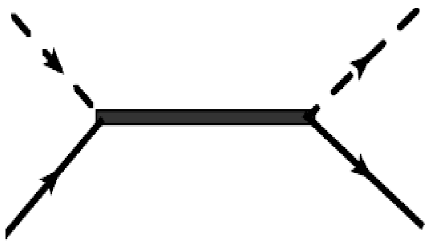
$$\mathcal{L}_S = g c^\dagger n^\dagger c n \qquad g(\mu) = \frac{2\pi}{M_\mathrm{R}\left(2\mu - \frac{1}{a_0}\right)}$$



$$T = \frac{2\pi}{M_\mathrm{R}} \frac{1}{a_0^{-1} + ik}$$

One parameter: g (or a0)

P-wave in EFT



$$\langle \boldsymbol{p}'|T(E)|\boldsymbol{p}\rangle = \frac{6\pi}{M_{\rm R}} \frac{\boldsymbol{p}' \cdot \boldsymbol{p}}{a_1^{-1} - \frac{1}{2} r_1 k^2 + i k^3}$$

$$k^3 \cot \delta_1 = -\frac{1}{a_1} + \frac{1}{2} r_1 k^2 + \ldots$$

Shallow p-wave bound state: $$\frac{1}{a_1} + \frac{1}{2} r_1 \gamma^2 + \gamma^4 = 0$$

$$a_1 \sim \frac{1}{\Lambda \gamma^2} \text{ and } r_1 \sim \Lambda$$

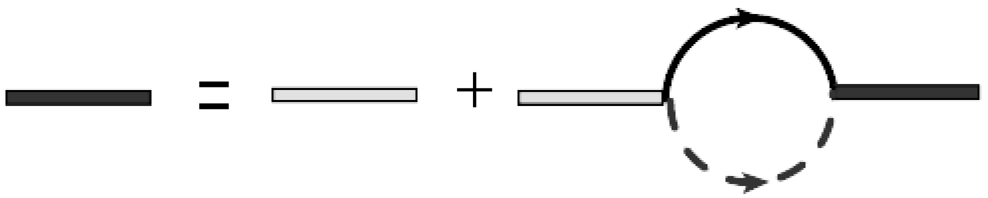
Unnatural Natural

P-wave in EFT

$$\mathcal{L}_P \;=\; \pi^{\dagger i}\left(i\partial_t + \frac{\nabla^2}{2M_{\rm nc}} + \Delta\right)\pi_i + h\pi^{\dagger i} n i\left(\boldsymbol{V}_n - \boldsymbol{V}_c\right)_i c + \text{C.C.}\;.$$

P-wave in EFT

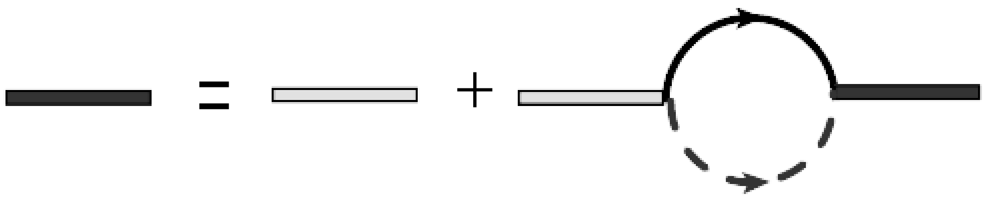
$$\mathcal{L}_P = \pi^{\dagger i}\left(i\partial_t + \frac{\nabla^2}{2M_{\rm nc}} + \Delta\right)\pi_i + h\pi^{\dagger i} n i\left(\boldsymbol{V}_n - \boldsymbol{V}_c\right)_i c + \text{C.C.}\ .$$



$$\Sigma_i^j(p^0, \boldsymbol{p}) \equiv \delta_i^j \Sigma(p^0, \boldsymbol{p}) = -\delta_i^j \frac{h^2}{6\pi M_{\rm R}} k^2\left(ik + 3\mu\right)$$

P-wave in EFT

$$\mathcal{L}_P = \pi^{\dagger i}\left(i\partial_t + \frac{\nabla^2}{2M_{\rm nc}} + \Delta\right)\pi_i + h\pi^{\dagger i} n i \left(\boldsymbol{V}_n - \boldsymbol{V}_c\right)_i c + \text{C.C.}\ .$$



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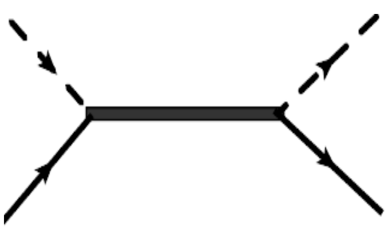
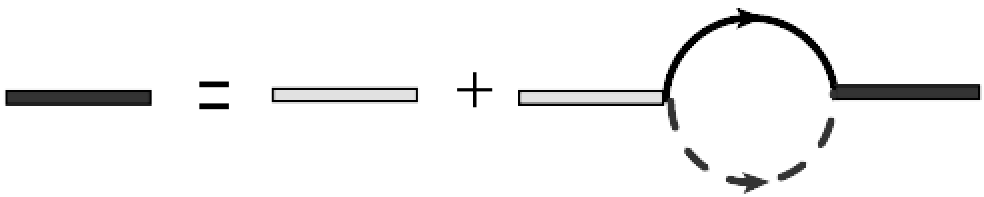
$$\Delta \frac{6\pi M_{\rm R}}{h^2} = \frac{1}{a_1} \qquad \frac{3\pi}{h^2} + 2\mu = -\frac{1}{2} r_1$$



$$\langle \boldsymbol{p}'|T(E)|\boldsymbol{p}\rangle = \frac{h^2}{M_{\rm R}^2}\left(\boldsymbol{p}'\cdot\boldsymbol{p}\right) D(E,\boldsymbol{0}) = \frac{6\pi}{M_{\rm R}} \frac{\boldsymbol{p}'\cdot\boldsymbol{p}}{a_1^{-1} - \frac{1}{2}r_1 k^2 + ik^3}$$

P-wave in EFT

$$\mathcal{L}_P = \pi^{\dagger i}\left(i\partial_t + \frac{\nabla^2}{2M_{\rm nc}} + \Delta\right)\pi_i + h\pi^{\dagger i} n i\left(\boldsymbol{V}_n - \boldsymbol{V}_c\right)_i c + \text{C.C.}\ .$$



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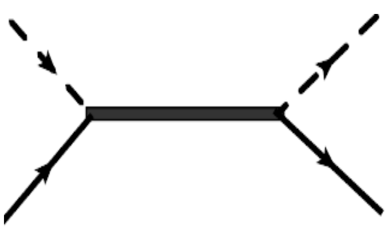

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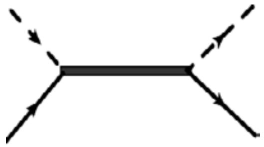
Two parameters: Delta and h (or a1 and r1)

P-wave in EFT



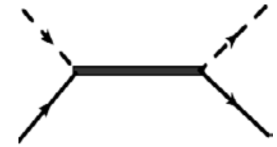
$$\langle r^{'}|\frac{1}{E-H}|r\rangle = \langle r^{'}|\frac{1}{E-H_0} + \frac{1}{E-H_0}T\frac{1}{E-H_0}|r\rangle$$

$$\xrightarrow{E\to -B} C^2 \times \sum_j \frac{\phi_j(r^{'})\phi_j^*(r)}{E+B}\ .$$

Asymptotic normalization coefficient (ANC)

$$\phi_j(\mathrm{r}) = \left(1+\frac{1}{\gamma r}\right) Y_{1j}(\hat{r})\frac{e^{-\gamma r}}{r}$$

P-wave in EFT



$$\langle r'|\frac{1}{E-H}|r\rangle = \langle r'|\frac{1}{E-H_0} + \frac{1}{E-H_0}T\frac{1}{E-H_0}|r\rangle$$

Asymptotic normalization coefficient (ANC)

$$\xrightarrow{E\to -B} C^2 \times \sum_j \frac{\phi_j(r')\phi_j^*(r)}{E+B}\ .$$

$$\phi_j(\mathrm{r}) = \left(1+\frac{1}{\gamma r}\right) Y_{1j}(\hat{r})\frac{e^{-\gamma r}}{r}$$

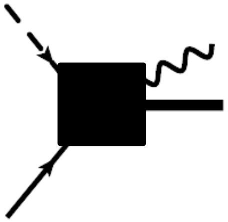
$$D(E,0) \rightarrow \frac{Z}{E+B} \quad \Rightarrow \quad h^2\frac{\gamma^2 Z}{3\pi} = C^2$$

$$C^2 = \sqrt{\frac{-2\gamma^2}{r_1+3\gamma}}$$

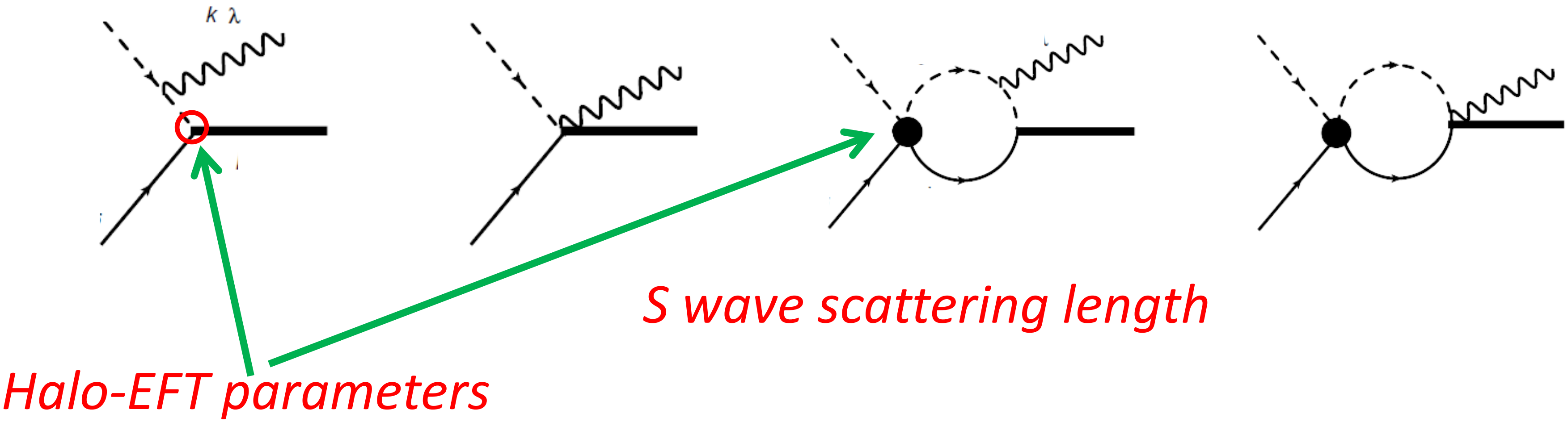
$$\frac{1}{a_1}+\frac{1}{2}r_1\gamma^2+\gamma^3=0$$

} a_1 and r_1 (or h and Δ)

K. M. Nollett et.al., PRC 83, 041001 (2011)

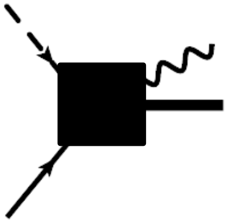


Radiative capture: LO

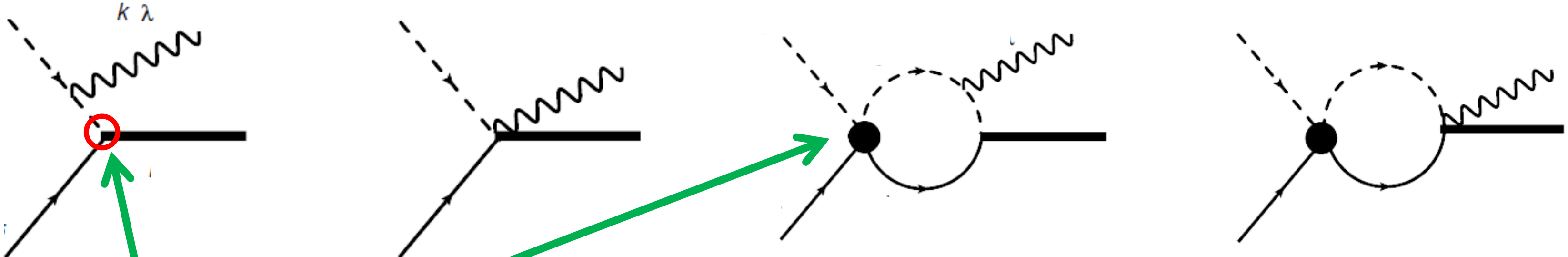


$$\mathcal{M} \sim i e_c h \sqrt{Z} \left[\frac{\boldsymbol{\epsilon}^*(\lambda) \cdot \boldsymbol{V}_c}{p_c^0 - \omega - \frac{(\boldsymbol{p}_c - \boldsymbol{k})^2}{2M_c} + i\epsilon} \left(\frac{\boldsymbol{p}_c}{M_\mathrm{R}} - \frac{\boldsymbol{k}}{M_\mathrm{c}} \right)_j + (1 + X(p_c; \gamma, a_0) \frac{\boldsymbol{\epsilon}^*(\lambda)_j}{M_\mathrm{c}} \right]$$

$$X(p_c; \gamma, a) \equiv \frac{(-)i}{a^{-1} + i p_c} \left[p_c - \frac{2}{3} i \frac{\gamma^3 - i p_c^3}{\gamma^2 + p_c^2} \right]$$



Radiative capture: LO



S wave scattering length

Halo-EFT parameters

$$\mathcal{M} \sim i e_c h\sqrt{Z}\left[\frac{\epsilon^*(\lambda)\cdot \boldsymbol{V}_c}{p_c^0-\omega-\frac{(\boldsymbol{p}_c-\boldsymbol{k})^2}{2M_c}+i\epsilon}\left(\frac{\boldsymbol{p}_c}{M_{\rm R}}-\frac{\boldsymbol{k}}{M_c}\right)_j+(1+X(p_c;\gamma,a_0)\frac{\epsilon^*(\lambda)_j}{M_c}\right]$$

$h\sqrt{Z} \Rightarrow C$

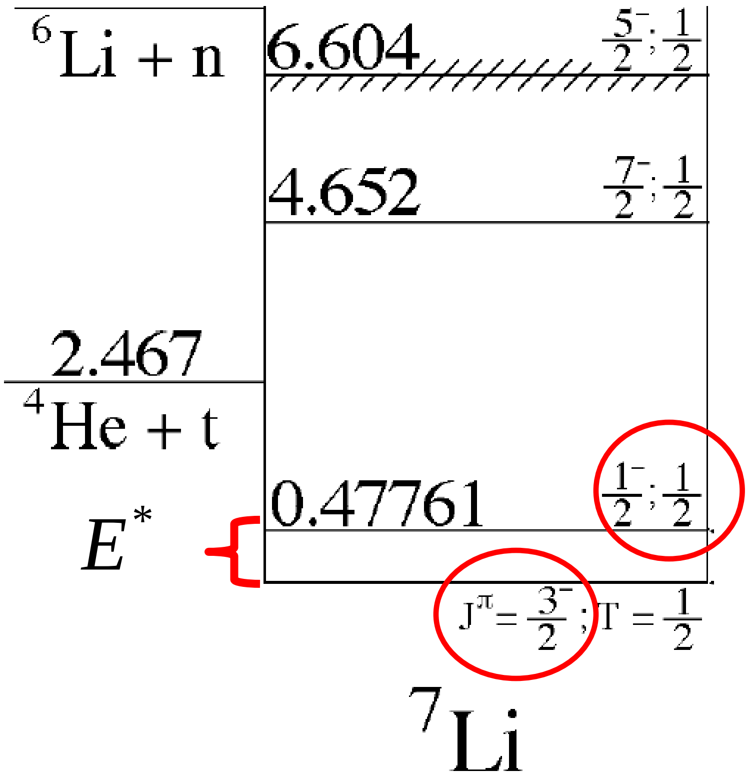
$$X(p_c;\gamma,a)\equiv\frac{(-)i}{a^{-1}+ip_c}\left[p_c-\frac{2}{3}i\frac{\gamma^3-ip_c^3}{\gamma^2+p_c^2}\right]$$

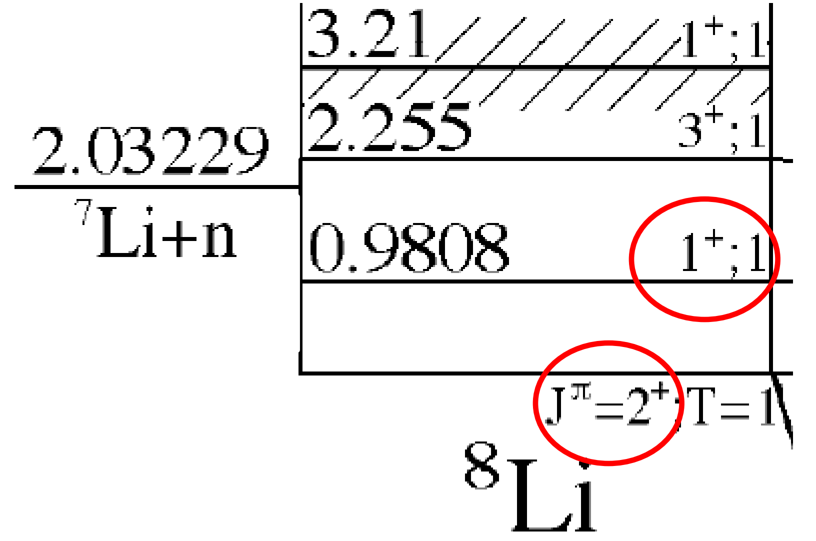
$$a\sim\frac{1}{\gamma}\Rightarrow X\sim 1,\quad a\sim\frac{1}{\Lambda}\Rightarrow X\sim\frac{\gamma}{\Lambda}$$

$^{7}\mathrm{Li}\left(n,\gamma\right)^{8}\mathrm{Li}$

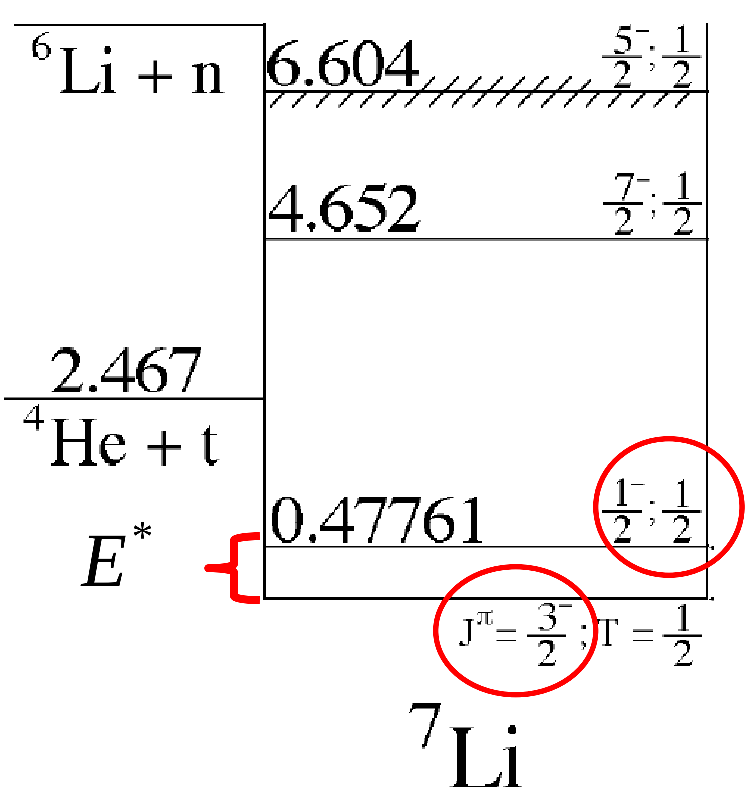
G. Rupak and R. Higa, *Phys. Rev. Lett.* 106, 222501 (2011)

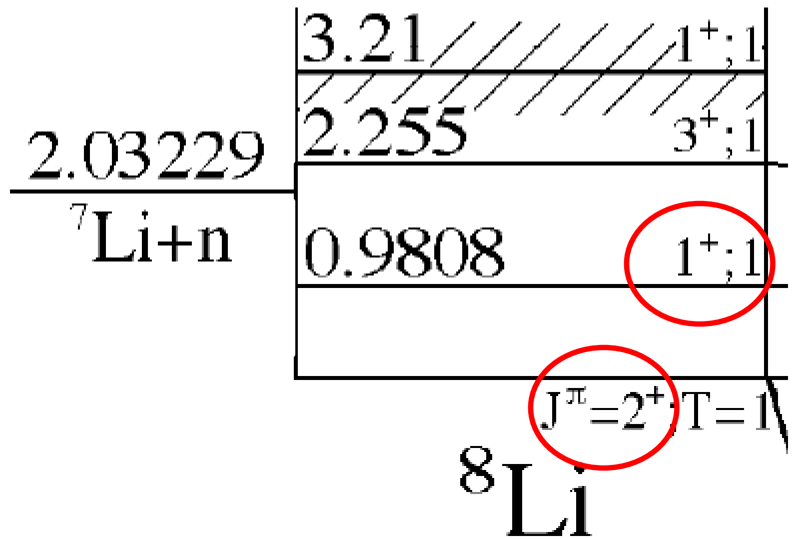
Scales, spins, core excitations





Scales, spins, core excitations

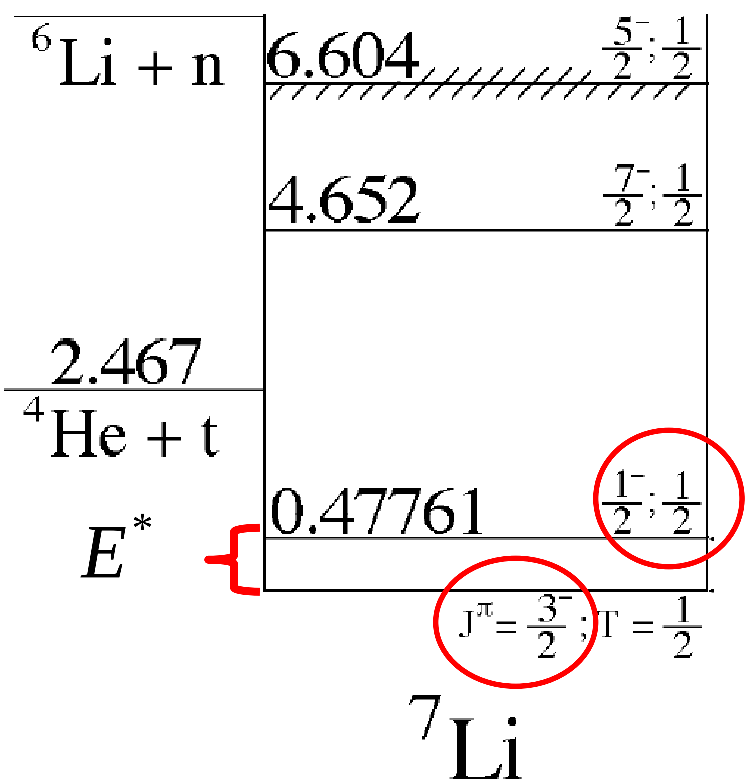


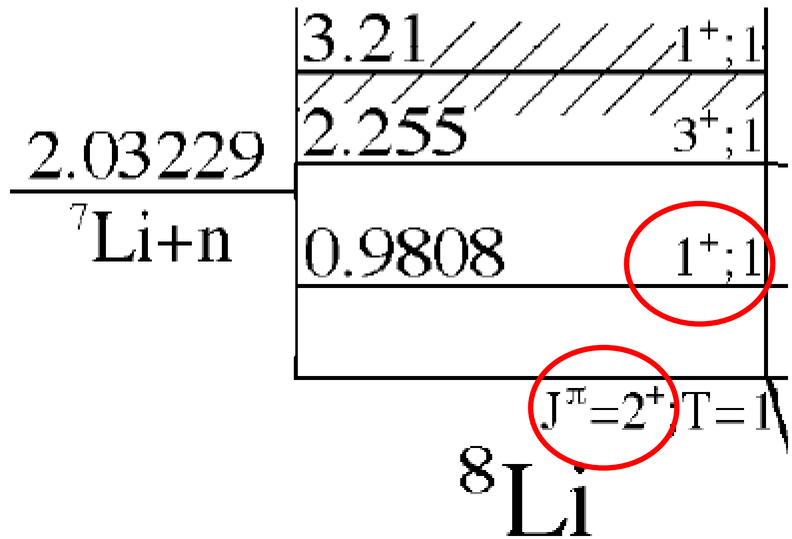


$$\text{IS Li7} + \text{n}: \ {}^3S_1, \ {}^5S_2, D$$

$$\text{IS Li7}^* + \text{n}: \ {}^1S^*{}_0, \ {}^3S^*{}_1$$

Scales, spins, core excitations

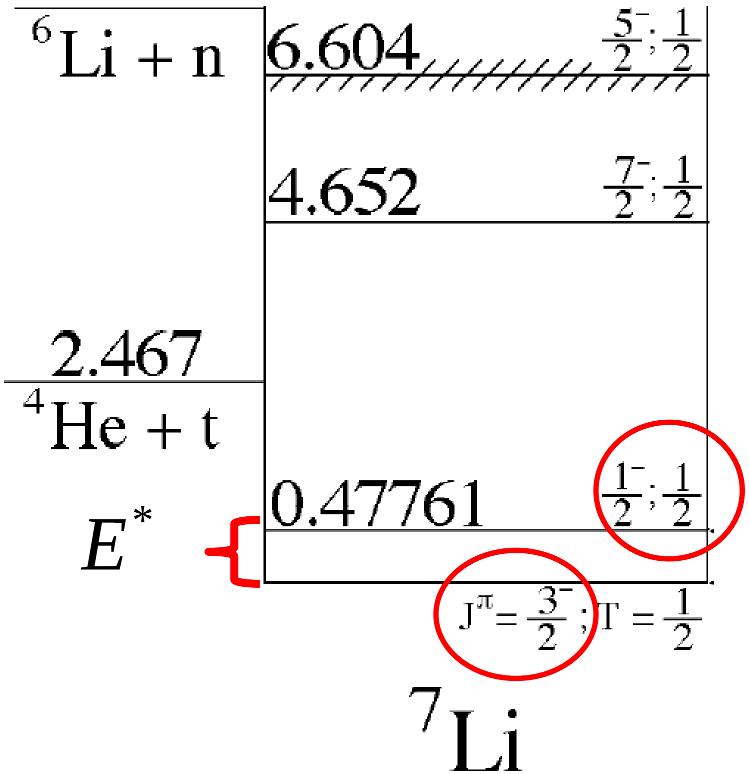


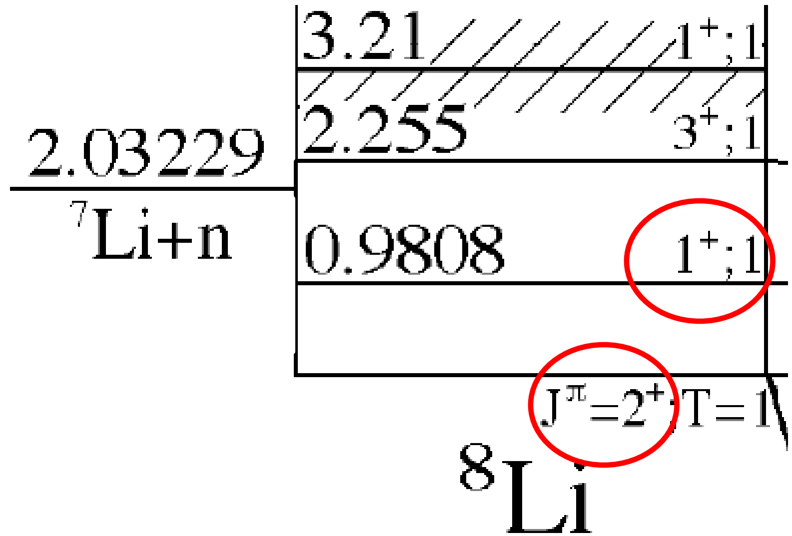


$$\text{IS Li7} + \text{n}: \; {}^3S_1, \; {}^5S_2, D$$
$$\text{IS Li7}^* + \text{n}: \; {}^1S^*{}_0, \; {}^3S^*{}_1$$

$$\text{FS}(2^+)\ \text{Li7} + \text{n}: \; {}^3P_2, \; {}^5P_2$$
$$\text{FS}(2^+)\ \text{Li7}^* + \text{n}: \; {}^3P^*{}_2$$

Scales, spins, core excitations





$$\text{IS Li7} + \text{n}:\ {}^3S_1,\ {}^5S_2, D$$
$$\text{IS Li7}^* + \text{n}:\ {}^1S^*{}_0,\ {}^3S^*{}_1$$

$$\text{FS}(2^+)\ \text{Li7} + \text{n}:\ {}^3P_2,\ {}^5P_2$$
$$\text{FS}(2^+)\ \text{Li7}^* + \text{n}:\ {}^3P^*{}_2$$

$$\text{FS}(1^+)\ \text{Li7} + \text{n}:\ {}^3P_1,\ {}^5P_1$$
$$\text{FS}(1^+)\ \text{Li7}^* + \text{n}:\ {}^1P^*{}_1,\ {}^3P^*{}_1$$

Scales, spins, core excitations

$$\Lambda \approx 100 - 300 \text{ MeV}$$

Momentum scale	Definition	Value
γ	$\sqrt{2M_R B_{^8\text{Li}}}$	57.8 MeV
γ^*	$\sqrt{2M_R(B_{^8\text{Li}} + E^*)}$	65.1 MeV
γ_Δ	$\sqrt{2M_R E^*}$	30.0 MeV
$\tilde{\gamma}$	$\sqrt{2M_R B_{^8\text{Li}*}}$	41.6 MeV
$\tilde{\gamma}^*$	$\sqrt{2M_R(B_{^8\text{Li}*} + E^*)}$	51.3 MeV

Parameter	Channel	Value	Assigned scaling
$a_{(^5S_2)}$	S-wave, $S = 2$	$-3.63(5)$ fm	$1/\gamma$
$a_{(^3S_1)}$	S-wave, $S = 1$	$0.87(7)$ fm	$1/\Lambda$
r	P-wave, $J = 2$	$-1.43(2)$ fm^{-1}	Λ
$\tilde{r}$	P-wave, $J = 1$	$-1.86(6)$ fm^{-1}	Λ

L. Koester, K. Knopf, and W. Waschkowski, Z. Phys. A 312, 81 (1983)

EFT

$$\mathcal{L}_0 = n^{\dagger\sigma}\left(i\partial_t + \frac{\nabla^2}{2M_\mathrm{n}}\right)n_\sigma + c^{\dagger a}\left(i\partial_t + \frac{\nabla^2}{2M_\mathrm{c}}\right)c_a$$
$$+d^{\dagger\delta}\left(i\partial_t + \frac{\nabla^2}{2M_\mathrm{c}}\right)d_\delta + \pi^{\dagger\alpha}\left(i\partial_t + \frac{\nabla^2}{2M_\mathrm{nc}} + \Delta\right)\pi_\alpha$$
$$+\tilde{\pi}^{\dagger i}\left(i\partial_t + \frac{\nabla^2}{2M_\mathrm{nc}} + \tilde{\Delta}\right)\tilde{\pi}_i \ ,$$

EFT

$$\mathcal{L}_0 = n^{\dagger\sigma}\left(i\partial_t + \frac{\nabla^2}{2M_{\rm n}}\right)n_\sigma + c^{\dagger a}\left(i\partial_t + \frac{\nabla^2}{2M_{\rm c}}\right)c_a$$
$$+d^{\dagger\delta}\left(i\partial_t + \frac{\nabla^2}{2M_{\rm c}}\right)d_\delta + \pi^{\dagger\alpha}\left(i\partial_t + \frac{\nabla^2}{2M_{\rm nc}} + \Delta\right)\pi_\alpha$$
$$+\tilde{\pi}^{\dagger i}\left(i\partial_t + \frac{\nabla^2}{2M_{\rm nc}} + \tilde{\Delta}\right)\tilde{\pi}_i \ ,$$

$$\mathcal{L}_S = g_{(^3S_1)} c^{\dagger a'} n^{\dagger\sigma'} T^i_{a'\sigma'} T_i^{a\sigma} c_a n_\sigma$$
$$+g_{(^5S_2)} c^{\dagger a'} n^{\dagger\sigma'} T^\alpha_{a'\sigma'} T_\alpha^{a\sigma} c_a n_\sigma$$
$$+g_{(^3S_1^*)} d^{\dagger\delta} n^{\dagger\sigma'} T^i_{\delta\sigma'} T_i^{a\sigma} c_a n_\sigma + \text{C.C.} \ ,$$

EFT

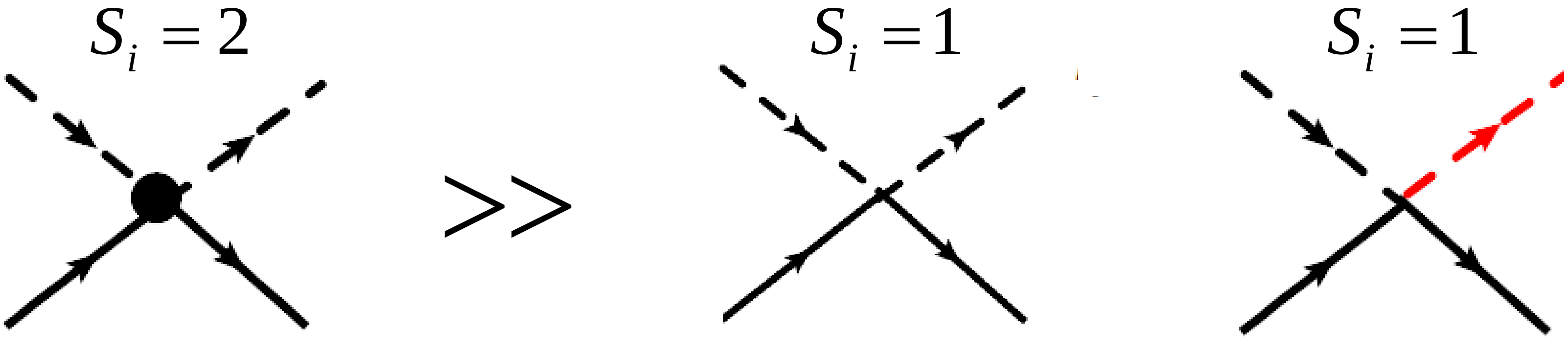
$$\mathcal{L}_0 = n^{\dagger\sigma}\left(i\partial_t + \frac{\nabla^2}{2M_{\rm n}}\right)n_\sigma + c^{\dagger a}\left(i\partial_t + \frac{\nabla^2}{2M_{\rm c}}\right)c_a$$
$$+d^{\dagger\delta}\left(i\partial_t + \frac{\nabla^2}{2M_{\rm c}}\right)d_\delta + \pi^{\dagger\alpha}\left(i\partial_t + \frac{\nabla^2}{2M_{\rm nc}} + \Delta\right)\pi_\alpha$$
$$+\tilde{\pi}^{\dagger i}\left(i\partial_t + \frac{\nabla^2}{2M_{\rm nc}} + \tilde{\Delta}\right)\tilde{\pi}_i \ ,$$

$$\mathcal{L}_S = g_{(^3S_1)} c^{\dagger a'} n^{\dagger\sigma'} T^i_{a'\sigma'} T^{a\sigma}_i c_a n_\sigma$$
$$+g_{(^5S_2)} c^{\dagger a'} n^{\dagger\sigma'} T^\alpha_{a'\sigma'} T^{a\sigma}_\alpha c_a n_\sigma$$
$$+g_{(^3S_1^*)} d^{\dagger\delta} n^{\dagger\sigma'} T^i_{\delta\sigma'} T^{a\sigma}_i c_a n_\sigma + \text{C.C.}$$

$$\mathcal{L}_{P,gs} = h_{(^3P_2)} \pi^{\dagger\alpha} T^{ij}_\alpha T^{\sigma a}_i n_\sigma i\left(\boldsymbol{V}_n - \boldsymbol{V}_c\right)_j c_a$$
$$+h_{(^5P_2)} \pi^{\dagger\alpha} T^{\beta j}_\alpha T^{\sigma a}_\beta n_\sigma i\left(\boldsymbol{V}_n - \boldsymbol{V}_c\right)_j c_a$$
$$+h_{(^3P_2^*)} \pi^{\dagger\alpha} T^{jk}_\alpha T^{\delta\sigma}_k n_\sigma i(\boldsymbol{V}_n - \boldsymbol{V}_{c^*})_j d_\delta + \text{C.C.} \ ,$$

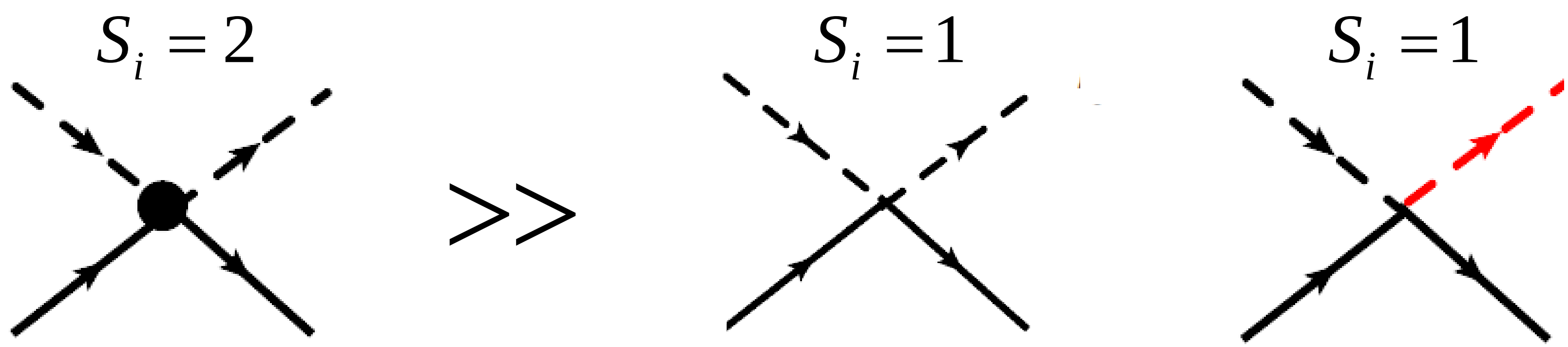
$$\mathcal{L}_{P,es} = \tilde{h}_{(^3P_1)} \tilde{\pi}^{\dagger k} T^{ij}_k T^{\sigma a}_i n_\sigma i\left(\boldsymbol{V}_n - \boldsymbol{V}_c\right)_j c_a$$
$$+\tilde{h}_{(^5P_1)} \tilde{\pi}^{\dagger k} T^{\beta j}_k T^{\sigma a}_\beta n_\sigma i\left(\boldsymbol{V}_n - \boldsymbol{V}_c\right)_j c_a$$
$$+\tilde{h}_{(^1P_1^*)} \tilde{\pi}^{\dagger k} T^{0j}_k T^{\sigma\delta}_0 n_\sigma i\left(\boldsymbol{V}_n - \boldsymbol{V}_{c^*}\right)_j d_\delta$$
$$+\tilde{h}_{(^3P_1^*)} \tilde{\pi}^{\dagger k} T^{ij}_k T^{\sigma\delta}_i n_\sigma i\left(\boldsymbol{V}_n - \boldsymbol{V}_{c^*}\right)_j d_\delta + \text{C.C.} \ .$$

EFT

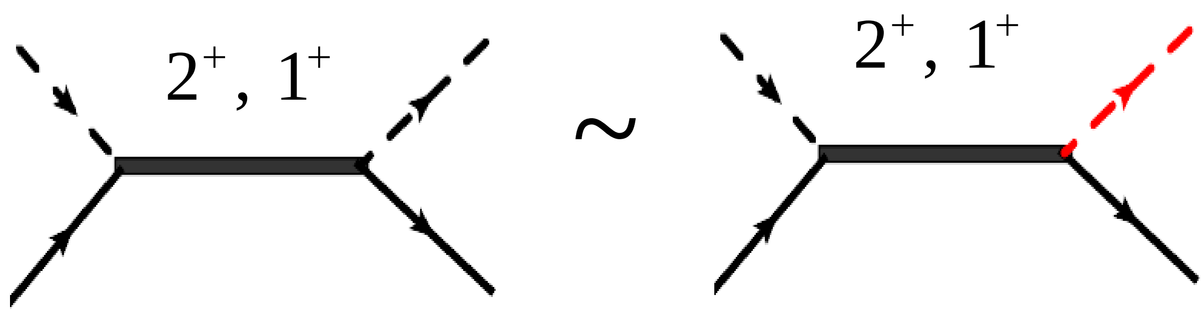


One fine tuning in S wave

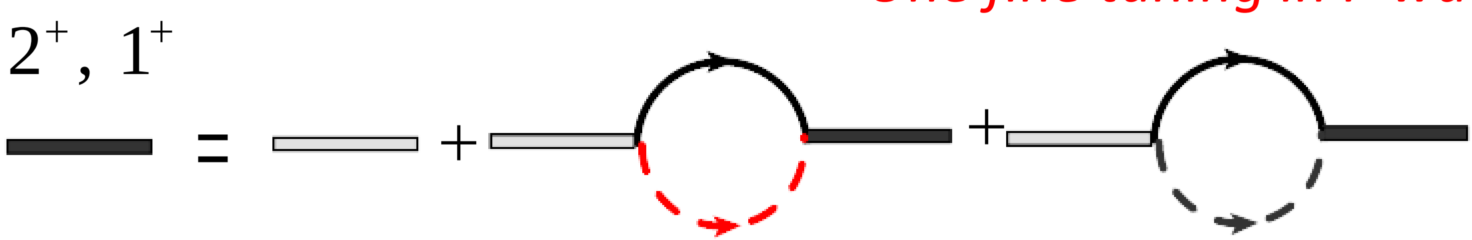
EFT



One fine tuning in S wave



One fine tuning in P wave



P-wave

$$D^{-1}\frac{6\pi M_{\mathrm{R}}}{h_t^2} = \frac{1}{a} - \frac{h^2_{(^3P_2^*)}}{h_t^2}\gamma_\Delta^3 - \frac{1}{2}\left(r - 3\frac{h^2_{(^3P_2^*)}}{h_t^2}\gamma_\Delta\right)k^2 + i\left[k^3 + \frac{h^2_{(^3P_2^*)}}{h_t^2}(k^2-\gamma_\Delta^2)^{\frac{3}{2}}\right]$$

$$Z = \frac{(-)6\pi}{h_t^2(r+3\gamma) + 3h^2_{(^3P_2^*)}(\gamma^* - \gamma_\Delta)}$$

$$\frac{C^2_{(^3P_2)}}{h^2_{(^3P_2)}\gamma^2} = \frac{C^2_{(^5P_2)}}{h^2_{(^5P_2)}\gamma^2} = \frac{C^2_{(^3P_2^*)}}{h^2_{(^3P_2^*)}\gamma^{*2}} = \frac{Z}{3\pi}$$

	$C_{(^3P_2)}$	$C_{(^5P_2)}$	$C_{(^3P_2^*)}$
Nollett	$-0.283(12)$	$-0.591(12)$	$-0.384(6)$
	$-0.284(23)$	$-0.593(23)$	

L. Trache,et.al., Phys. Rev. C 67, 062801(R) (2003)

P-wave

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$$Z = \frac{(-)6\pi}{h_t^2(r+3\gamma) + 3h^2_{(^3P_2^*)}(\gamma^* - \gamma_\Delta)}$$

4 parameters: 3 h + 1 Delta, or 3 C + gamma

$$\frac{C^2_{(^3P_2)}}{h^2_{(^3P_2)}\gamma^2} = \frac{C^2_{(^5P_2)}}{h^2_{(^5P_2)}\gamma^2} = \frac{C^2_{(^3P_2^*)}}{h^2_{(^3P_2^*)}\gamma^{*2}} = \frac{Z}{3\pi}$$

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P-wave

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4 parameters: 3 h + 1 Delta, or 3 C + gamma

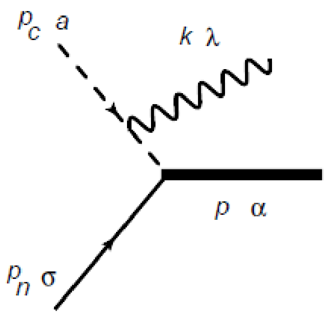
$$\frac{C^2_{(^3P_2)}}{h^2_{(^3P_2)}\gamma^2} = \frac{C^2_{(^5P_2)}}{h^2_{(^5P_2)}\gamma^2} = \frac{C^2_{(^3P_2^*)}}{h^2_{(^3P_2^*)}\gamma^{*2}} = \frac{Z}{3\pi}$$

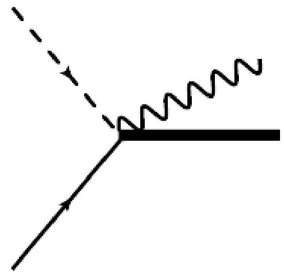
5 parameters

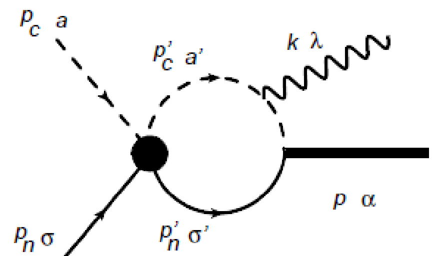
	$C_{(^3P_2)}$	$C_{(^5P_2)}$	$C_{(^3P_2^*)}$	$\tilde{C}_{(^3P_1)}$	$\tilde{C}_{(^5P_1)}$	$\tilde{C}_{(^1P_1^*)}$	$\tilde{C}_{(^3P_1^*)}$
Nollett	$-0.283(12)$	$-0.591(12)$	$-0.384(6)$	$0.220(6)$	$0.197(5)$	$-0.195(3)$	$-0.214(3)$
	$-0.284(23)$	$-0.593(23)$		$0.187(16)$	$0.217(13)$		

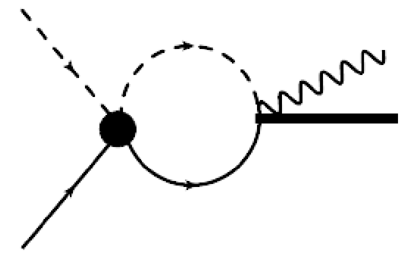
L. Trache,et.al., Phys. Rev. C 67, 062801(R) (2003)

Radiative captures: LO

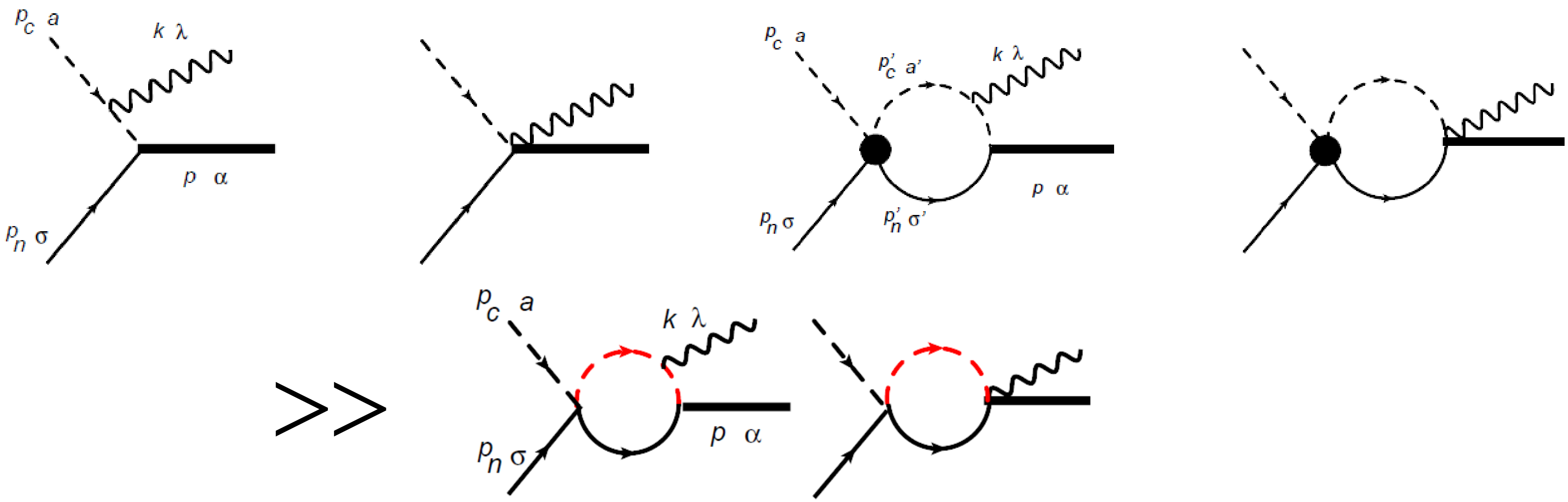




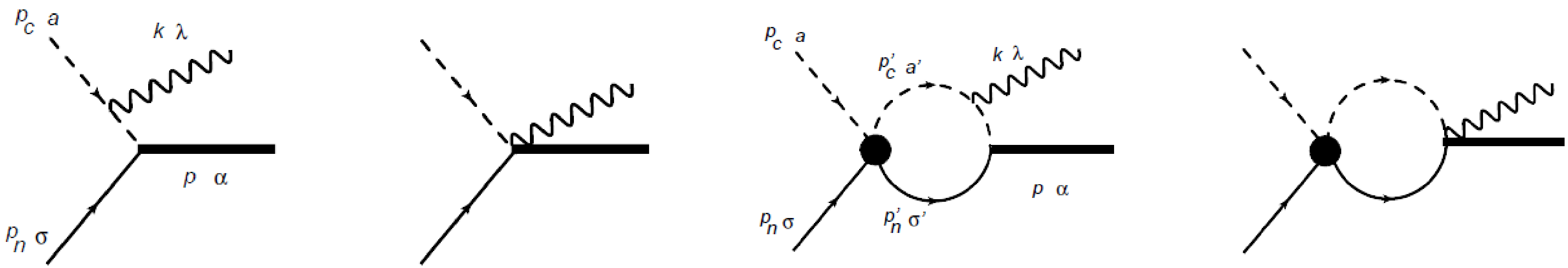




Radiative captures: LO



Radiative captures: LO



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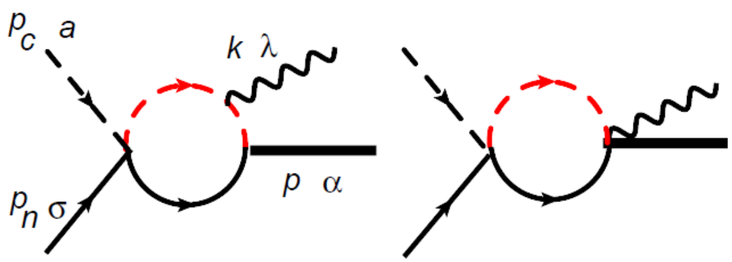

Initial total spin Si=2

$$\mathcal{M} = ie_c h_{(^5P_2)} \sqrt{8Z^{\mathrm{LO}} M_{\mathrm{n}} M_{\mathrm{c}} M_{\mathrm{nc}}} T_{\beta}^{\sigma a} T_{\alpha}^{\beta j} \left[\frac{\boldsymbol{\epsilon}^*(\lambda)\cdot \boldsymbol{V}_c}{p_c^0 - \omega - \frac{(\boldsymbol{p}_c - \boldsymbol{k})^2}{2M_{\mathrm{c}}} + i\epsilon} \left(\frac{\boldsymbol{p}_c}{M_{\mathrm{R}}} - \frac{\boldsymbol{k}}{M_{\mathrm{c}}} \right)_j + (1 + X(p_c; \gamma, a_{(^5S_2)}) \frac{\boldsymbol{\epsilon}^*(\lambda)_j}{M_{\mathrm{c}}} \right]$$

$$X(p_c;\gamma,a) \equiv \frac{(-)i}{a^{-1} + ip_c} \left[p_c - \frac{2}{3} i \frac{\gamma^3 - ip_c^3}{\gamma^2 + p_c^2} \right] \qquad a \sim \frac{1}{\gamma} \Rightarrow X \sim 1, \quad a \sim \frac{1}{\Lambda} \Rightarrow X \sim \frac{\gamma}{\Lambda}$$

$$\sum_{\sigma,a}^{\alpha,\lambda}|\mathcal{M}|^2=\frac{5}{3}64\pi\alpha Z_c^2\frac{3\pi}{\gamma^2}\frac{M_{\rm n}^2}{M_{\rm R}}\left(C^{\rm LO}_{(^5P_2)}\right)^2\left[|1+X(p_c;\gamma,a_{(^5S_2)})|^2-\frac{2\boldsymbol{p}_c^2\sin^2\theta}{\boldsymbol{p}_c^2+\gamma^2}\left(\frac{\gamma^2}{\boldsymbol{p}_c^2+\gamma^2}+\mathrm{Re}\left\{X(p_c;\gamma,a_{(^5S_2)})\right\}\right)\right]$$

$$+\quad\frac{5}{3}64\pi\alpha Z_c^2\frac{3\pi}{\gamma^2}\frac{M_{\rm n}^2}{M_{\rm R}}\left(C^{\rm LO}_{(^3P_2)}\right)^2\left[1-\frac{\boldsymbol{p}_c^2\sin^2\theta}{\boldsymbol{p}_c^2+\gamma^2}\frac{2\gamma^2}{\boldsymbol{p}_c^2+\gamma^2}\right]$$

$$X(p_c;\gamma,a)\equiv\frac{(-)i}{a^{-1}+ip_c}\left[p_c-\frac{2}{3}i\frac{\gamma^3-ip_c^3}{\gamma^2+p_c^2}\right]$$

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$$+\;\frac{5}{3}64\pi\alpha Z_c^2\frac{3\pi}{\gamma^2}\frac{M_{\rm n}^2}{M_{\rm R}}\left(C^{\rm LO}_{(^3P_2)}\right)^2\left[1-\frac{p_c^2\sin^2\theta}{p_c^2+\gamma^2}\frac{2\gamma^2}{p_c^2+\gamma^2}\right]$$

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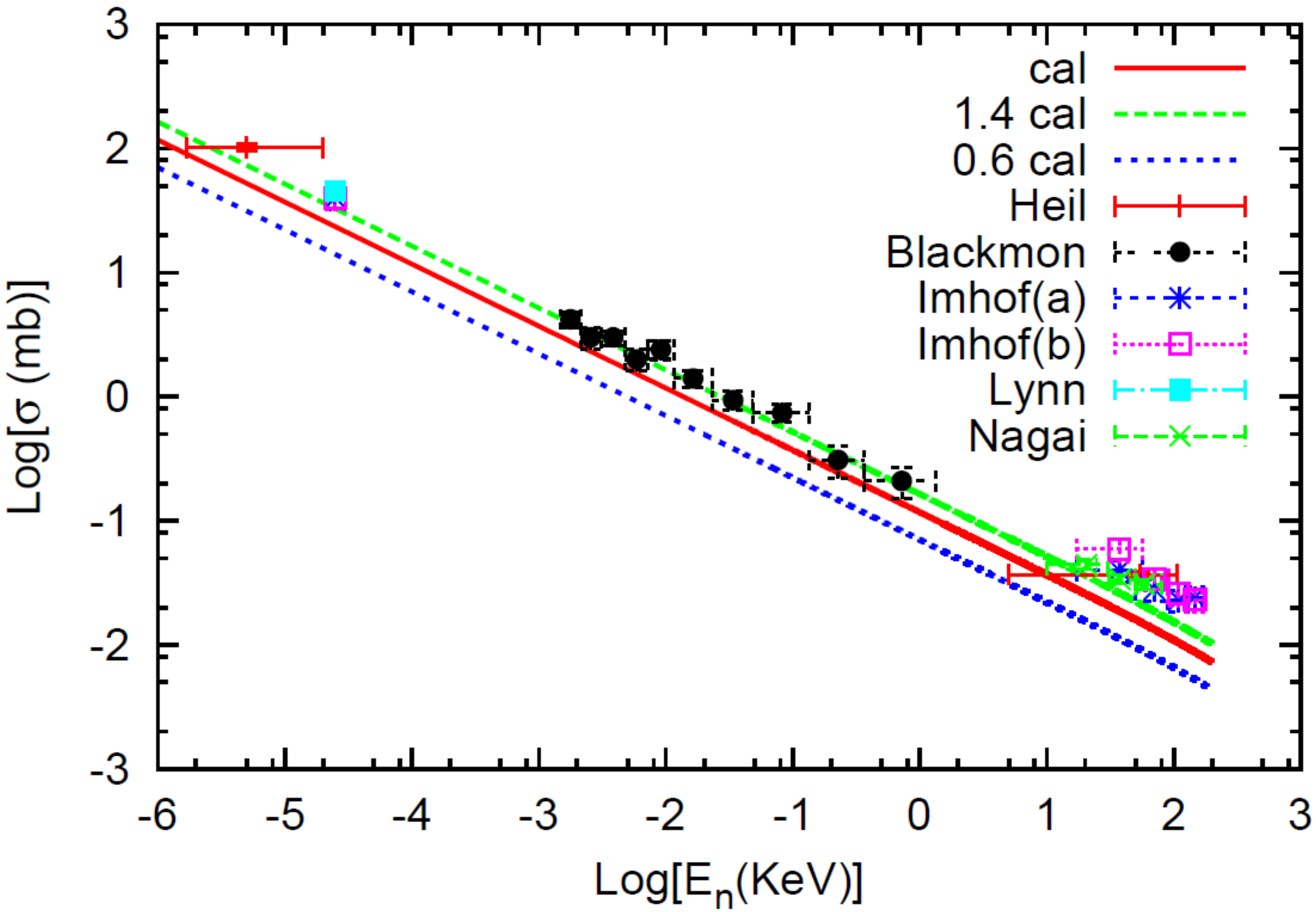
$$\sum_{i,f}|\mathcal{M}|^2\;=\;64\pi\alpha Z_c^2\frac{3\pi}{\tilde{\gamma}^2}\frac{M_{\rm n}^2}{M_{\rm R}}\left\{\left(\tilde{C}^{\rm LO}_{(^3P_1)}\right)^2\left[1-\frac{p_c^2\sin^2\theta}{p_c^2+\tilde{\gamma}^2}\left(\frac{2\tilde{\gamma}^2}{p_c^2+\tilde{\gamma}^2}\right)\right]\right.$$

$$\left.+\left(\tilde{C}^{\rm LO}_{(^5P_1)}\right)^2\left[|1+X(p_c;\tilde{\gamma},a_{(^5S_2)})|^2-\frac{2p_c^2\sin^2\theta}{p_c^2+\tilde{\gamma}^2}\left(\frac{\tilde{\gamma}^2}{p_c^2+\tilde{\gamma}^2}+\mathrm{Re}\left\{X(p_c;\tilde{\gamma},a_{(^5S_2)})\right\}\right)\right]\right\}$$

LO results on Li7(n,gamma)Li8(Li8*)



N. K. Timofeyuk *et.al., PRL* 91, 232501 (2003); D. Howell *et.al., PRC* 88, 025804 (2013);
D. Gul'ko *et.al., SJNP* 6, 477 (1968); E. Lynn *et.al., PRC* 44, 764 (1991);
Y. Nagai *et. al., PRC* 71, 055803 (2005); J. C. Blackmon *et. al., PRC* 54, 383 (1996); J. E. Lynn *et. al., PRC* 44, 764 (1991); M. Heil *et.al., Astro. J.* 507, 997 (1998); W. L. Imhof *et.al., PR* 114, 1037 (1959).

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$$\frac{\sigma[(S_i=1)\to 2^+]}{\sigma[(S_i=2)\to 2^+]} = \frac{\left(C^{\rm LO}_{(^3P_2)}\right)^2}{\left(C^{\rm LO}_{(^5P_2)}\right)^2 (1-\frac{2}{3}\gamma a_{(^5S_2)})^2}$$

$$\Rightarrow \quad \frac{\sigma[(S_i=2)\to 2^+]}{\sigma(\to 2^+)} = 0.93(2)\ [>0.86]$$

A. D. Gul'ko, S. S. Trostin, and A. Hudoklin, *Sov. J. Nucl. Phys.* 6, 477 (1968);
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➡ $$\frac{\sigma[(S_i=2)\to 2^+]}{\sigma(\to 2^+)} = 0.93(2) \ [> 0.86]$$

$$\frac{\sigma[(S_i=2)\to 1^+]}{\sigma(\to 1^+)} = 0.65(6) \ \text{ or } \ 0.75(7),$$

$$\frac{\sigma(\to 1^+)}{\sigma(\to 2^+)} = \frac{3}{5}\frac{\left(\tilde{C}^{\rm LO}_{(^3P_1)}\right)^2 + \left(\tilde{C}^{\rm LO}_{(^5P_1)}\right)^2 |1-\frac{2}{3}a_{(^5S_2)}\tilde{\gamma}|^2}{\left(C^{\rm LO}_{(^3P_2)}\right)^2 + \left(C^{\rm LO}_{(^5P_2)}\right)^2 |1-\frac{2}{3}a_{(^5S_2)}\gamma|^2}$$

➡ $$\frac{\sigma(\to 2^+)}{\sigma} = 0.88(4) \qquad [0.89(1)]$$

A. D. Gul'ko, S. S. Trostin, and A. Hudoklin, *Sov. J. Nucl. Phys.* 6, 477 (1968);
J. E. Lynn, E. T. Jurney, and S. Raman, *Phys. Rev. C* 44, 764 (1991);
Y. Nagai et. al., *Phys. Rev. C* 71, 055803 (2005).

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

- It is considered as isospin mirror of Li7 capture on the nucleon level
- From EFT/core+proton picture, they are quite different due to strong Coulomb effect

Nonperturbative Coulomb effect

$$k_C \equiv Q_c Q_n \alpha_{EM} M_{\mathrm{R}} \qquad \eta \equiv \frac{k_C}{k} \sim 1$$

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$$\frac{1}{E - H_0 - V_c - V_s} = \frac{1}{E - H_0 - V_c} + \frac{1}{E - H_0 - V_c} V_s \frac{1}{E - H_0 - V_c} + \dots$$

Nonperturbative Coulomb effect

$$k_C \equiv Q_c Q_n \alpha_{EM} M_{\rm R} \qquad \eta \equiv \frac{k_C}{k} \sim 1$$

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$$\chi_{\boldsymbol{k}}^{(\pm)}(\boldsymbol{r}) = e^{-\frac{\pi}{2}\eta} e^{i\boldsymbol{k}\boldsymbol{r}} \Gamma(1 \pm i\eta) M(\mp i\eta, 1; \pm ikr - i\boldsymbol{k}\boldsymbol{r})$$

Kummer function

$$\chi_{\boldsymbol{k}}^{(\pm)*}(r=0)\chi_{\boldsymbol{k}}^{(\pm)}(r=0) = \frac{2\pi\eta}{e^{2\pi\eta} - 1} = C_{\eta,0}^2$$

Coulomb barrier, and phase

$$\chi_{\boldsymbol{k}}^{(\mp)*}(r=0)\chi_{\boldsymbol{k}}^{(\pm)}(r=0) = C_{\eta,0}^2 e^{\pm 2i\sigma_0}$$

$$C_{\eta,l} = \frac{2^l e^{-\frac{\pi}{2}\eta} |\Gamma(l+1+i\eta)|}{\Gamma(2l+2)} \qquad e^{2i\sigma_l} \equiv \frac{\Gamma(l+1+i\eta)}{\Gamma(l+1-i\eta)}$$

ERE in EFT

$$\langle \chi_{\boldsymbol{p}'}^{(-)} | T_{cs}(E) | \chi_{\boldsymbol{p}}^{(+)} \rangle = (-)\frac{2\pi}{M_{\rm R}} \frac{\chi_{\boldsymbol{p}'}^{(-)*}(0)\chi_{\boldsymbol{p}}^{(+)}(0)}{-a_0^{-1} - 2k_C H(\eta)}$$

$$\rightarrow (-)\frac{2\pi}{M_{\rm R}} \frac{C_{\eta,0}^2 e^{2i\sigma_0}}{-a_0^{-1} - 2k_C H(\eta)}$$

$$C_{\eta,0}^2 k(\cot\delta_0 - i) = -\frac{1}{a_0} + \cdots - 2k_C H(\eta) \qquad H(\eta) = \psi(i\eta) + 1/(2i\eta) - \ln(i\eta)$$

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$$\langle \chi_{\boldsymbol{p}'}^{(-)} | T_{cs}(E) | \chi_{\boldsymbol{p}}^{(+)} \rangle = (-)\frac{6\pi}{M_{\rm R}} \frac{\boldsymbol{\partial}\chi_{\boldsymbol{p}'}^{(-)*}(0)\boldsymbol{\partial}\chi_{\boldsymbol{p}}^{(+)}(0)}{-\frac{1}{a_1} + \frac{r_1}{2}k^2 - k^2(1+\eta^2)2k_C H(\eta)}$$

$$\rightarrow (-)\frac{6\pi}{M_{\rm R}} \frac{k^2 C_{\eta,1}^2 e^{2i\sigma_1}}{-\frac{1}{a_1} + \frac{r_1}{2}k^2 - k^2(1+\eta^2)2k_C H(\eta)}$$

$$C_{\eta,1}^2 k^3(\cot\delta_1 - i) = -\frac{1}{a_1} + \frac{r_1}{2}k^2 + \cdots - k^2(1+\eta^2)2k_C H(\eta)$$

ERE in EFT

$$\langle \chi_{\boldsymbol{p}'}^{(-)} | T_{cs}(E) | \chi_{\boldsymbol{p}}^{(+)} \rangle = (-)\frac{2\pi}{M_{\rm R}} \frac{\chi_{\boldsymbol{p}'}^{(-)*}(0)\chi_{\boldsymbol{p}}^{(+)}(0)}{-a_0^{-1} - 2k_C H(\eta)}$$

$$\to (-)\frac{2\pi}{M_{\rm R}} \frac{C_{\eta,0}^2 e^{2i\sigma_0}}{-a_0^{-1} - 2k_C H(\eta)}$$

One parameter: g (or a0)

$$C_{\eta,0}^2 k(\cot\delta_0 - i) = -\frac{1}{a_0} + \cdots - 2k_C H(\eta) \qquad H(\eta) = \psi(i\eta) + 1/(2i\eta) - \ln(i\eta)$$

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$$\to (-)\frac{6\pi}{M_{\rm R}} \frac{k^2 C_{\eta,1}^2 e^{2i\sigma_1}}{-\frac{1}{a_1} + \frac{r_1}{2}k^2 - k^2(1+\eta^2)2k_C H(\eta)}$$

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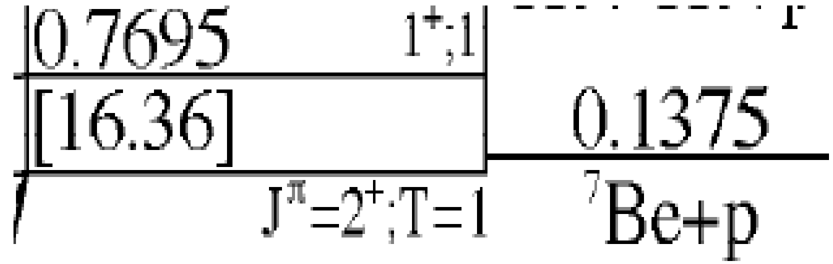
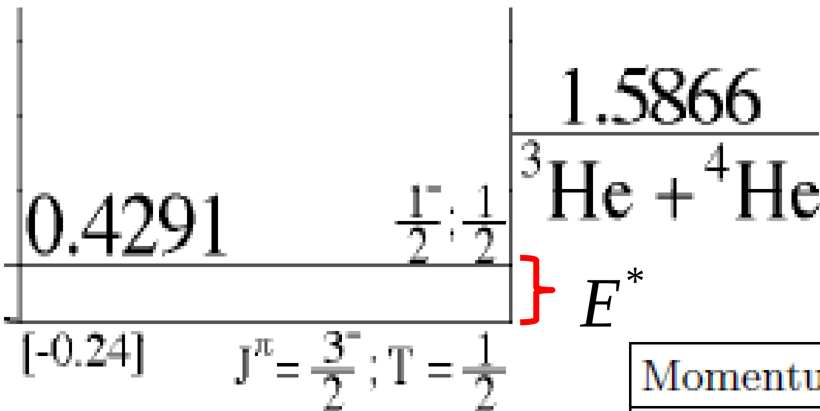
Two parameters: Delta and h (or a1 and r1)

Scales, spins, core excitations



^{8}B

Shallow bound state



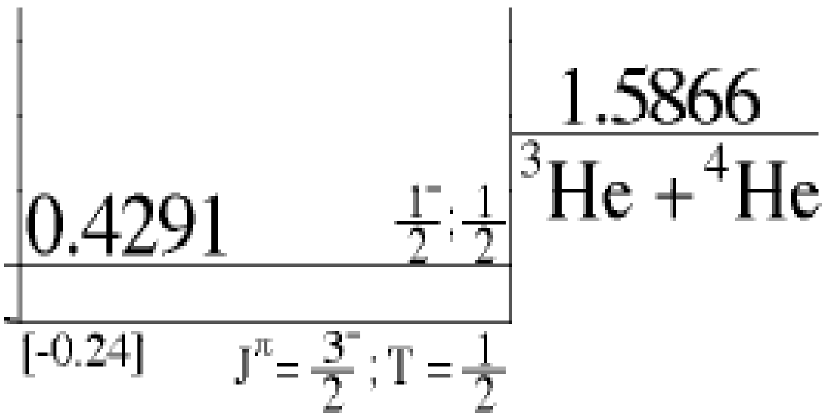
^{7}Be

$$\frac{p_c}{\Lambda},\ \frac{\gamma}{\Lambda},\ \frac{\tilde{\gamma}}{\Lambda} \sim 0.2$$

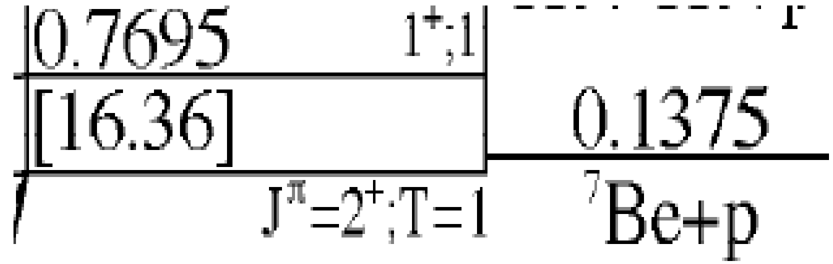
$$\eta = \frac{k_C}{k} \sim 1$$

Momentum scale	Definition	Value
$k_C \sim \gamma$	$Q_c Q_n \alpha_{EM} M_{\mathrm{R}}$	24.02 MeV
γ	$\sqrt{2M_R B_{^8\mathrm{B}}}$	15.04 MeV
Λ	$\sqrt{2M'_R B_{^7\mathrm{Be}}}$	70 MeV
$\gamma^* \sim \gamma$	$\sqrt{2M_R(B_{^8\mathrm{B}} + E^*)}$	30.53 MeV
$\gamma_\Delta \sim \gamma$	$\sqrt{2M_R E^*}$	26.57 MeV
$a_{^3S_1}, a_{^5S_2} \sim 1/\gamma$	scattering lengths	Varies
$r_0 \sim 1/\Lambda$	$l=0$ effective ranges	Varies
$a_1 \sim \gamma^{-2}\Lambda^{-1}$	scattering volume	1054.1 fm^3
$r_1 \sim \Lambda$	$l=1$ effective "range"	-0.34 fm^{-1}

Repeat



^{7}Be

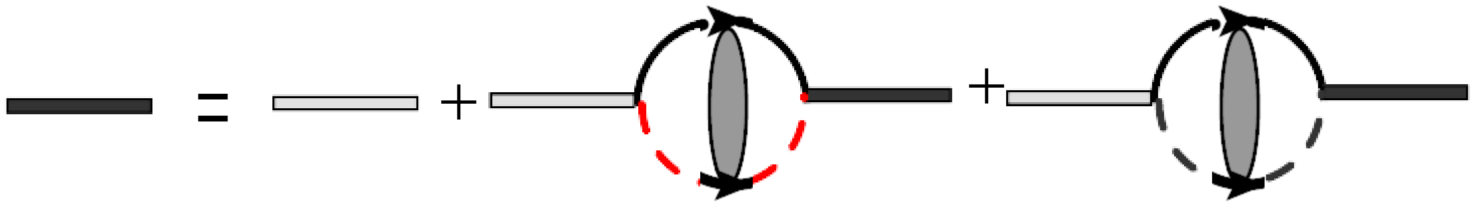


^{8}B

$$\text{IS Be7} + \text{p}: \ {}^3S_1,\ {}^5S_2, D$$
$$\text{IS Be7}^* + \text{p}: {}^1S^*{}_0,\ {}^3S^*{}_1$$

$$\text{FS}(2^+)\ \text{Be7} + \text{p}: \ {}^3P_2,\ {}^5P_2$$
$$\text{FS}(2^+)\ \text{Be7}^* + \text{p}: \ {}^3P^*{}_2$$

P-wave

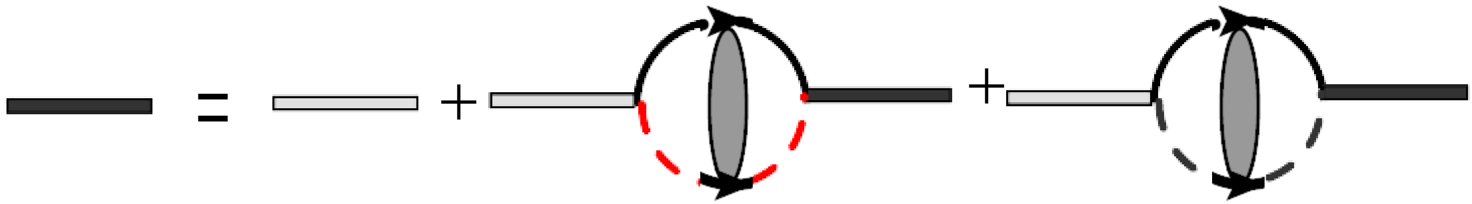


$$\frac{-6\pi M_{\rm R}}{h_t^2\, D} = -\frac{1}{a_1} + \frac{r_1}{2}k^2 - 2k_C(k^2 + k_C^2)H(k_C/k) - 2k_C\frac{h^2_{(^3P_2^*)}}{h_t^2}(k_*^2 + k_C^2)H(k_C/k_*)$$

$$\frac{6\pi}{Z} + h_t^2\, r_1 = 2\frac{k_C}{\gamma}\left\{\frac{h_t^2}{\gamma^2}\left[2\gamma^3\tilde{H}\left(\frac{k_C}{\gamma}\right) + (k_C^3 - k_C\gamma^2)\tilde{H}'\left(\frac{k_C}{\gamma}\right)\right]\right.$$
$$\left. + \frac{h^2_{(^3P_2^*)}}{\gamma^{*2}}\left[2\gamma^{*3}\tilde{H}\left(\frac{k_C}{\gamma^*}\right) + (k_C^3 - k_C\gamma^{*2})\tilde{H}'\left(\frac{k_C}{\gamma_*}\right)\right]\right\}$$

$$\frac{C_Y^2}{h_Y^2\gamma^2\Gamma^2(2 + k_C/\gamma)} = \frac{C^2_{(^3P_2^*)}}{h^2_{(^3P_2^*)}\gamma^{*2}\Gamma^2(2 + k_C/\gamma^*)} = \frac{Z}{3\pi} \qquad Y = {}^3P_2 \text{ and } {}^5P_2$$

P-wave



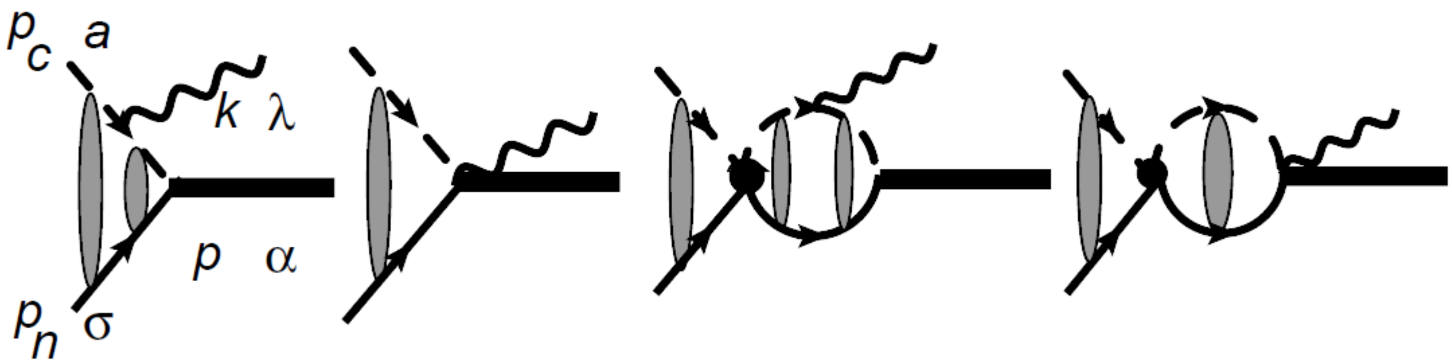
$$\frac{-6\pi M_{\rm R}}{h_t^2\, D} = -\frac{1}{a_1} + \frac{r_1}{2}k^2 - 2k_C(k^2+k_C^2)H(k_C/k) - 2k_C\frac{h^2_{(^3P_2^*)}}{h_t^2}(k_*^2+k_C^2)H(k_C/k_*)$$

$$\frac{6\pi}{Z} + h_t^2\, r_1 = 2\frac{k_C}{\gamma}\left\{\frac{h_t^2}{\gamma^2}\left[2\gamma^3\tilde{H}\left(\frac{k_C}{\gamma}\right) + (k_C^3 - k_C\gamma^2)\tilde{H}'\left(\frac{k_C}{\gamma}\right)\right]\right.$$
$$\left. + \frac{h^2_{(^3P_2^*)}}{\gamma^{*2}}\left[2\gamma^{*3}\tilde{H}\left(\frac{k_C}{\gamma^*}\right) + (k_C^3 - k_C\gamma^{*2})\tilde{H}'\left(\frac{k_C}{\gamma_*}\right)\right]\right\}$$

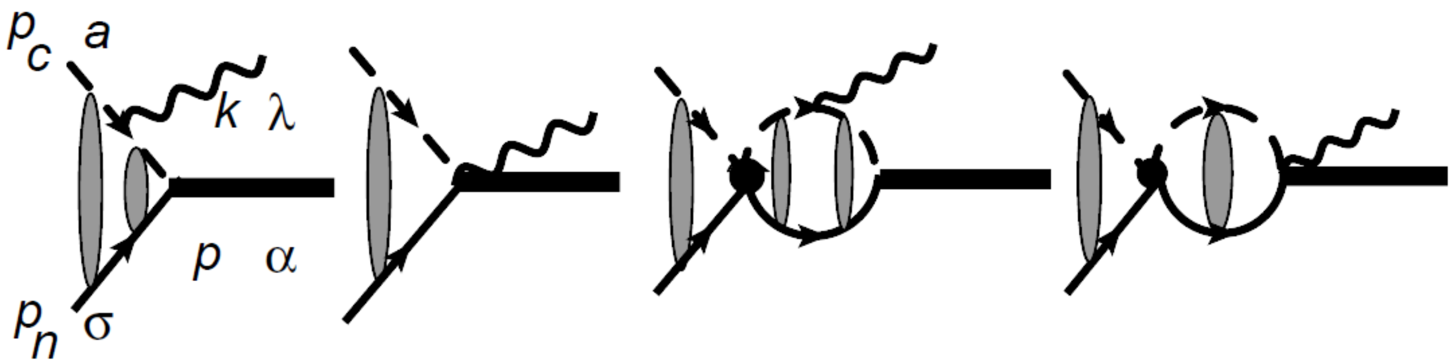
$$\frac{C_Y^2}{h_Y^2\gamma^2\Gamma^2(2+k_C/\gamma)} = \frac{C^2_{(^3P_2^*)}}{h^2_{(^3P_2^*)}\gamma^{*2}\Gamma^2(2+k_C/\gamma^*)} = \frac{Z}{3\pi} \qquad Y = {}^3P_2 \text{ and } {}^5P_2$$

4 parameters: 3 h + 1 Delta, or 3 C + gamma

Radiative captures: LO



Radiative captures: LO

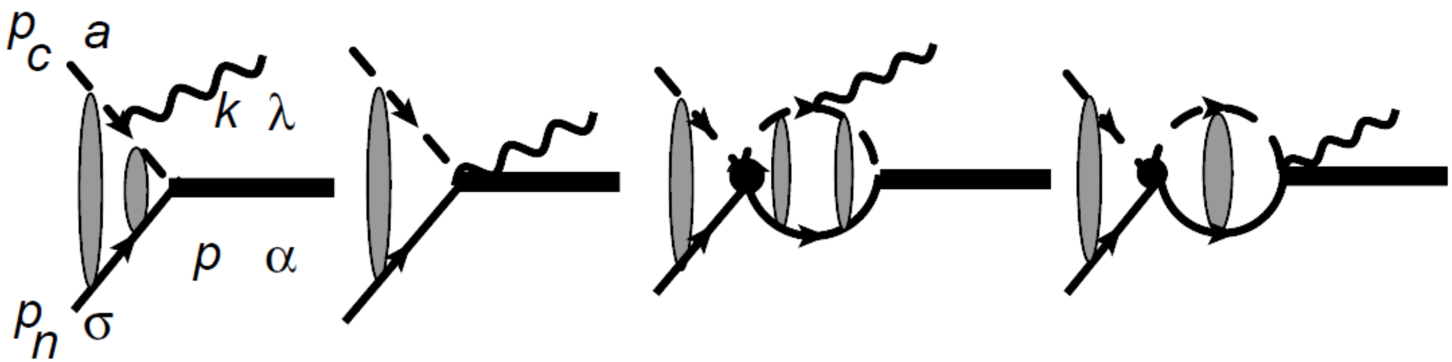


$$\langle \pi^\alpha | L_{EM} | \chi_{\boldsymbol{p}}^{(+)}, \delta, a \rangle \equiv T_i^{\delta a} T_\alpha^{ij} \mathcal{M}_j$$

Initial total spin Si=1

$$\mathcal{M}_j = (-i) C_{\eta,0} C^{\mathrm{LO}}_{(^3P_2)} \frac{Z_{eff}}{M_{\mathrm{R}}} \frac{2\pi}{\sqrt{3}} \left(\gamma^2 + k^2\right) \left[e^{i\sigma_0} \epsilon_j^* Y_{00}(\hat{p}) \mathcal{S}(^3S_1) + e^{i\sigma_2} \epsilon_k^* \sqrt{2} T_j^{ka} Y_{2a}(\hat{p}) \mathcal{D} \right]$$

Radiative captures: LO



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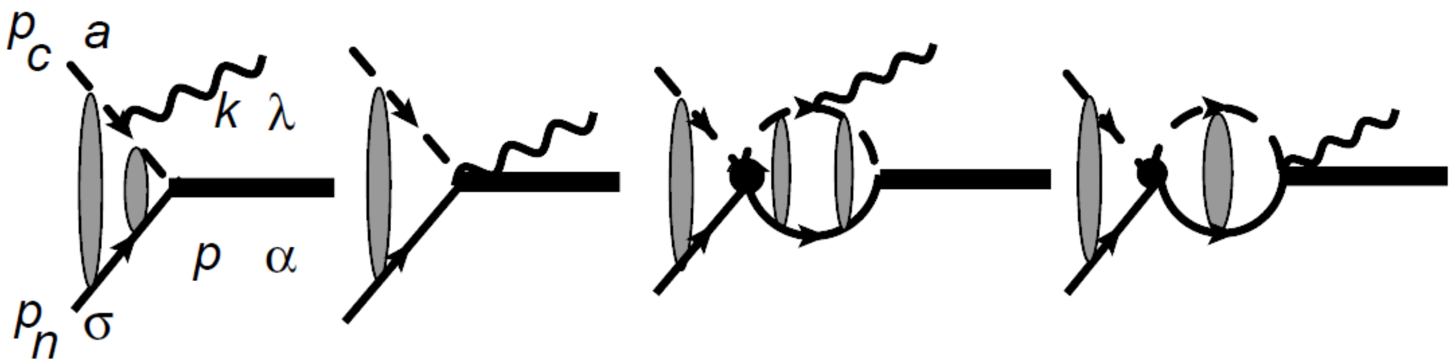
$$\mathcal{S}(X) \equiv \int_0^{+\infty} dr W_{-\eta_B, \frac{3}{2}}(2\gamma r) r \left[\frac{C_{\eta,0} G_0(k,r)}{-a^{-1}_{(X)} - 2k_C H(\eta)} + \frac{F_0(k,r)}{C_{\eta,0} k} \frac{-a^{-1}_{(X)} - 2k_C \mathrm{Re}\left[H(\eta)\right]}{-a^{-1}_{(X)} - 2k_C H(\eta)} \right]$$

$$\mathcal{D} \equiv \int_0^{+\infty} dr W_{-\eta_B, \frac{3}{2}}(2\gamma r) r \frac{F_2(k,r)}{C_{\eta,0} k}$$

Radiative captures: LO



$$\langle \pi^\alpha | L_{EM} | \chi_{\boldsymbol{p}}^{(+)}, \delta, a \rangle \equiv T_i^{\delta a} T_\alpha^{ij} \mathcal{M}_j$$

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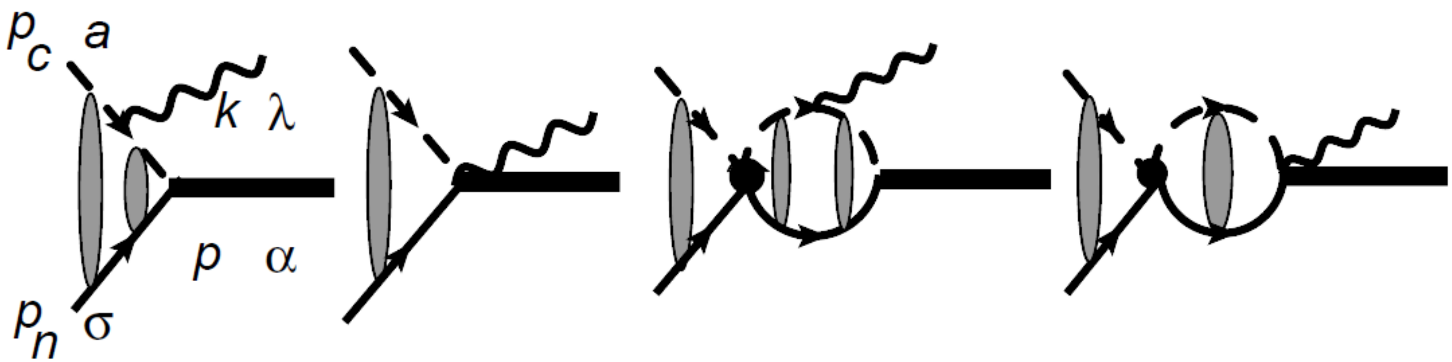
$$\mathcal{D} \equiv \int_0^{+\infty} dr W_{-\eta_B, \frac{3}{2}}(2\gamma r) r \frac{F_2(k,r)}{C_{\eta,0} k}$$

$$F \to j$$
$$G \to n$$
$$W \to h$$

Radiative captures: LO



$$S(E) = \frac{e^{2\pi\eta}}{e^{2\pi\eta}-1}\frac{Z_{eff}^2}{M_{\rm R}^2}\frac{\pi}{24}\omega k_C\left(\gamma^2+k^2\right)^2 \, \frac{5}{3} \times$$

$$\left[{C^{\rm LO}_{(^3P_2)}}^2\left(|\, \mathcal{S}(^3S_1)\,|^2 + 2\,|\,\mathcal{D}\,|^2\right) + {C^{\rm LO}_{(^5P_2)}}^2\left(|\, \mathcal{S}(^5S_2)\,|^2 + 2\,|\,\mathcal{D}\,|^2\right)\right]$$

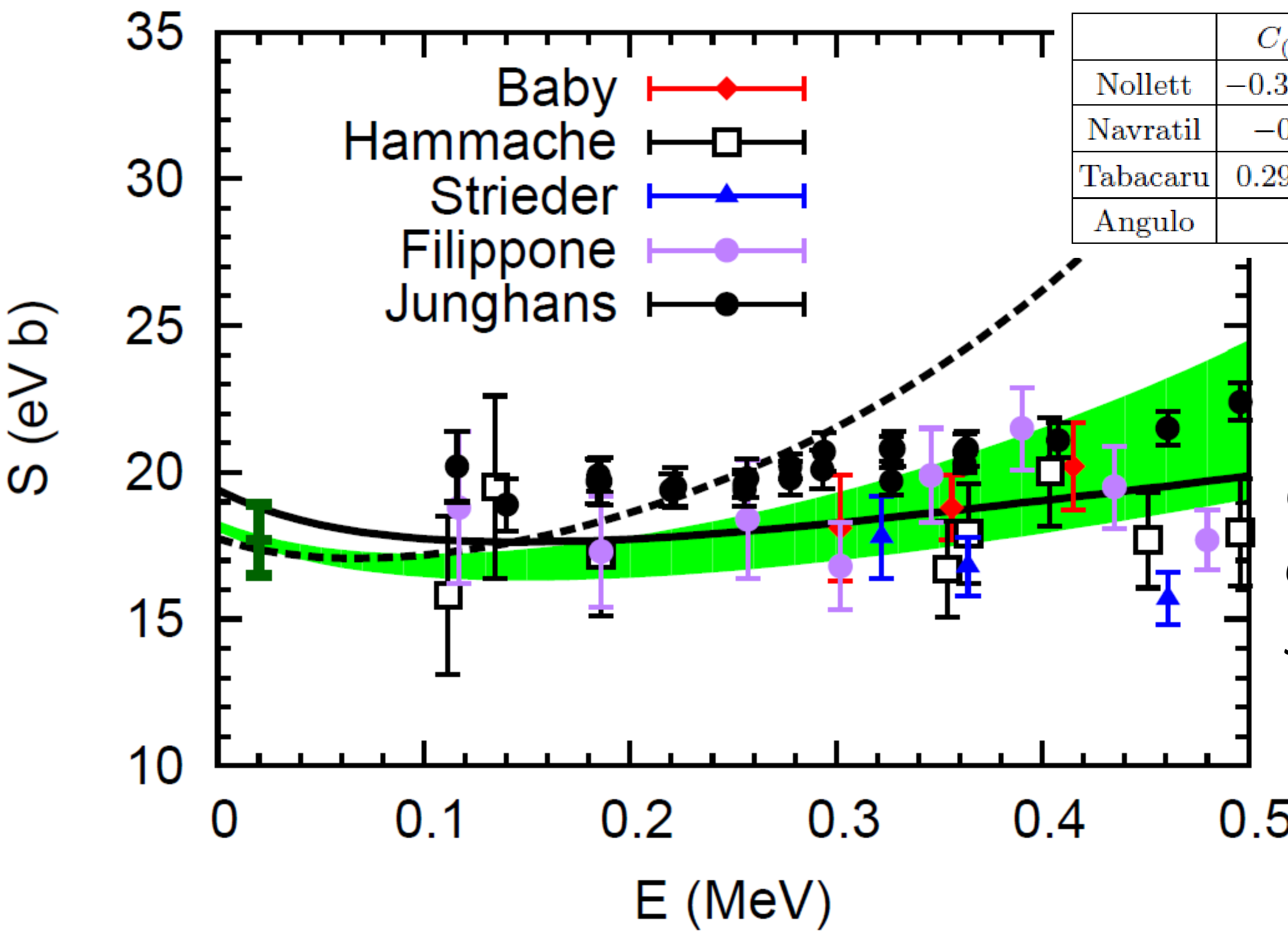
LO results on Be7(p,gamma)B8

	$C_{(^3P_2)}$	$C_{(^5P_2)}$	$a_{(^3S_1)}$	$a_{(^5S_2)}$
Nollett	$-0.315(19)$	$-0.662(19)$		
Navratil	-0.294	-0.650	-5.2	-15.3
Tabacaru	$0.294(45)$	$0.615(45)$		
Angulo			$25(9)$	$-7(3)$

$$C_{(^3P_2^*)} = -0.3485(51)$$

P. Navratil, R. Roth and S. Quaglioni, *Phys. Lett. B* 704, 379 (2011);
C. Angulo *et. al., Nucl. Phys. A* 716, 211 (2003);
G. Tabacaru, *et. al., Phys. Rev. C 73,* 025808 (2006)

LO results on Be7(p,gamma)B8



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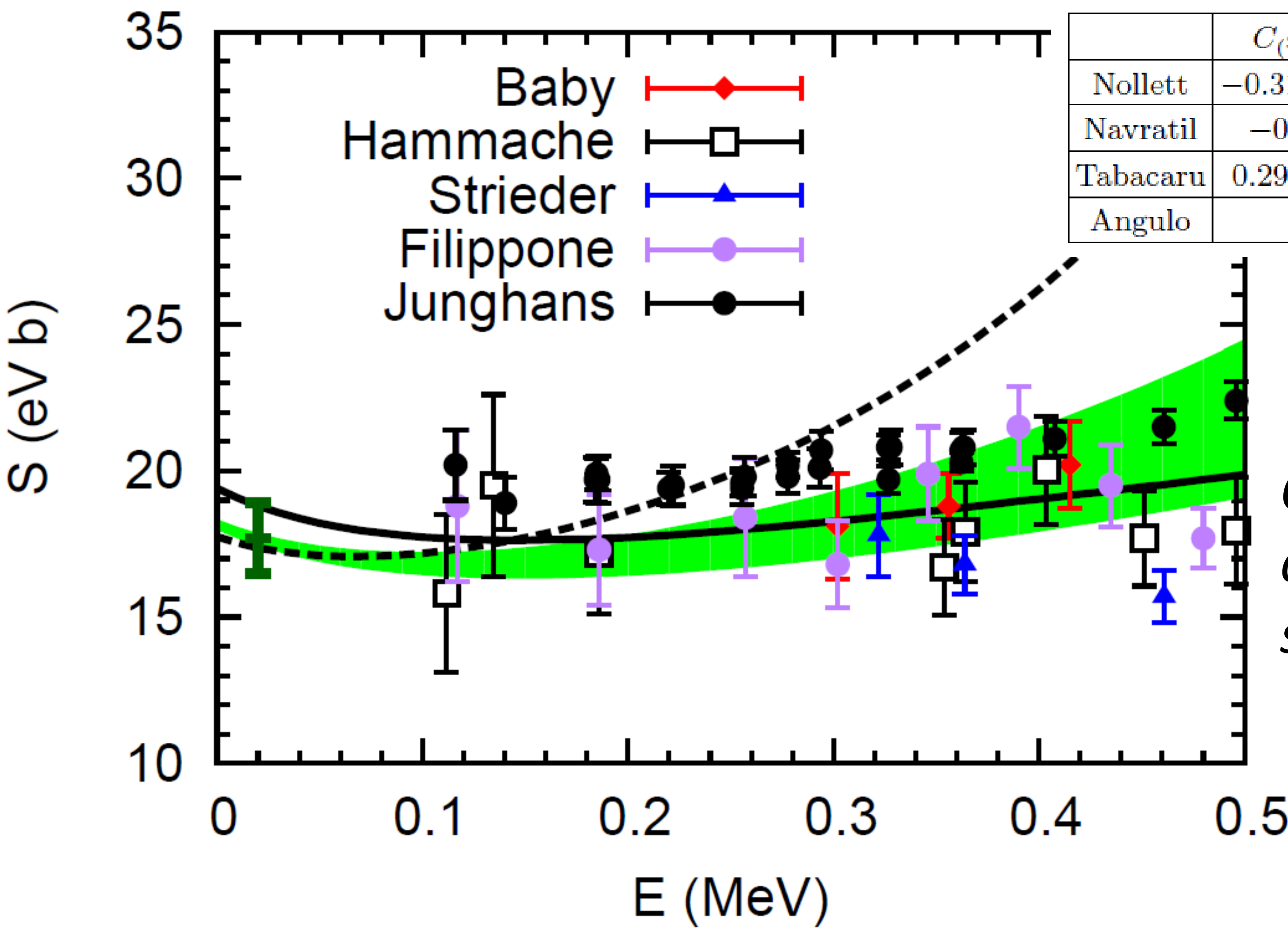
One standard deviation in S-wave scattering lengths

P. Navratil, R. Roth and S. Quaglioni, *Phys. Lett. B* 704, 379 (2011)

LO results on Be7(p,gamma)B8



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Angulo			$25(9)$	$-7(3$

$$C_{(^3P_2^*)} = -0.3485(51)$$

One standard deviation in S-wave scattering lengths

Need better measurement of S-wave scattering lengths and/or effective ranges to extrapolate data to zero energy

P. Navratil, R. Roth and S. Quaglioni, *Phys. Lett. B* 704, 379 (2011)

LO results on Be7(p,gamma)B8

$$S(E) = S(0)(1 + d_1 E + d_2 E^2)$$ *Fit to 0<E<50 keV*

	$S(0)$ (eV b)	$S_{(^3S_1)}(0)$	$d_1(\text{MeV}^{-1})$	d_2 (MeV^{-2})
No+A	18.2(12)	3.1(4)	-1.62	10.3
Na	17.8	3.0	-1.26	10.8
T+A	15.7(27)	2.7(8)	-1.62	10.3
	20.8(16)		$-1.5(1)$	6.5(2.0)

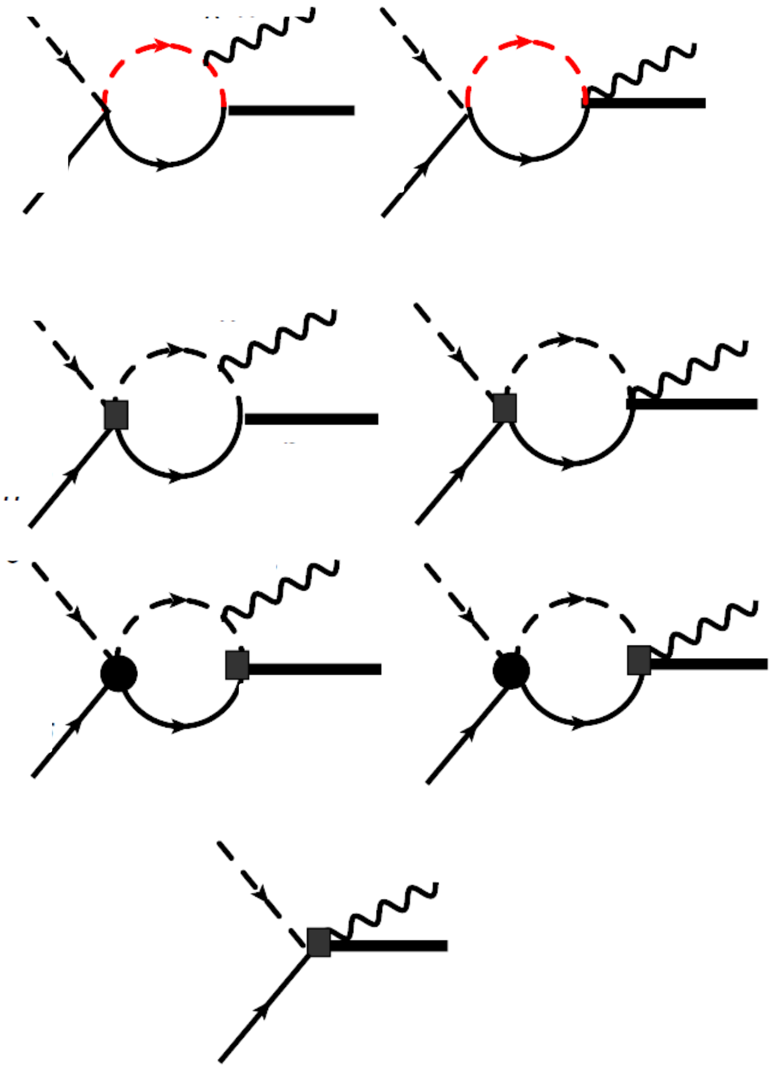
E. G. Adelberger, *et al., Rev. Mod. Phys.* 83, 195 (2011)

L. T. Baby, *et. al.,* [ISOLDE Collaboration], *Phys. Rev.*Lett. 90, 022501 (2003);
F. Hammache, *et. al., Phys. Rev. Lett*. 86, 3985 (2001);
F. Strieder, *et. al., Nucl. Phys. A* 696, 219 (2001);
B. W. Filippone, *et. al., Phys. Rev. C* 28, 2222 (1983);
A. R. Junghans, *et. al., Phys. Rev. C* 68, 065803 (2003);
A. R. Junghans, *et. al., Phys. Rev. C* 81, 012801 (2010).

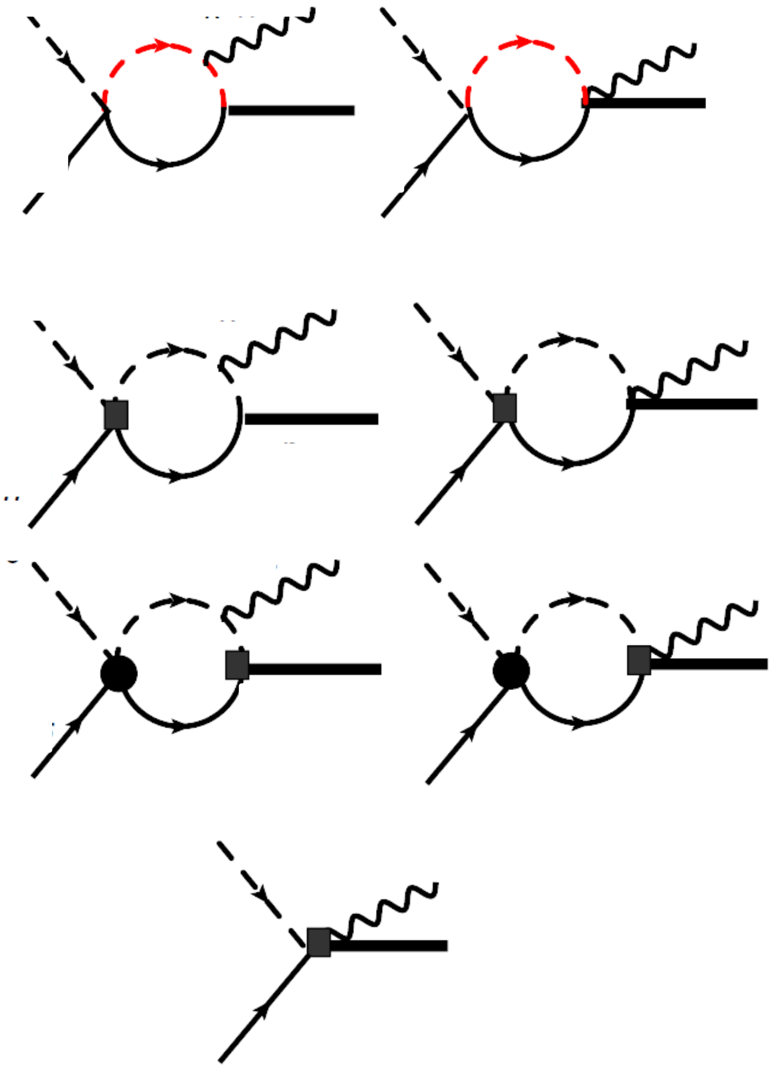
Summary

- EFT (power counting)+ab initio works as expected at LO
- LO need s-wave scattering length, p-wave ANCs, and binding momentum
- The p-wave is a coupled-channel problem
- For Be7 capture, improving s-wave measurement is important for extrapolating data to stellar energies.

Outlook: NLO

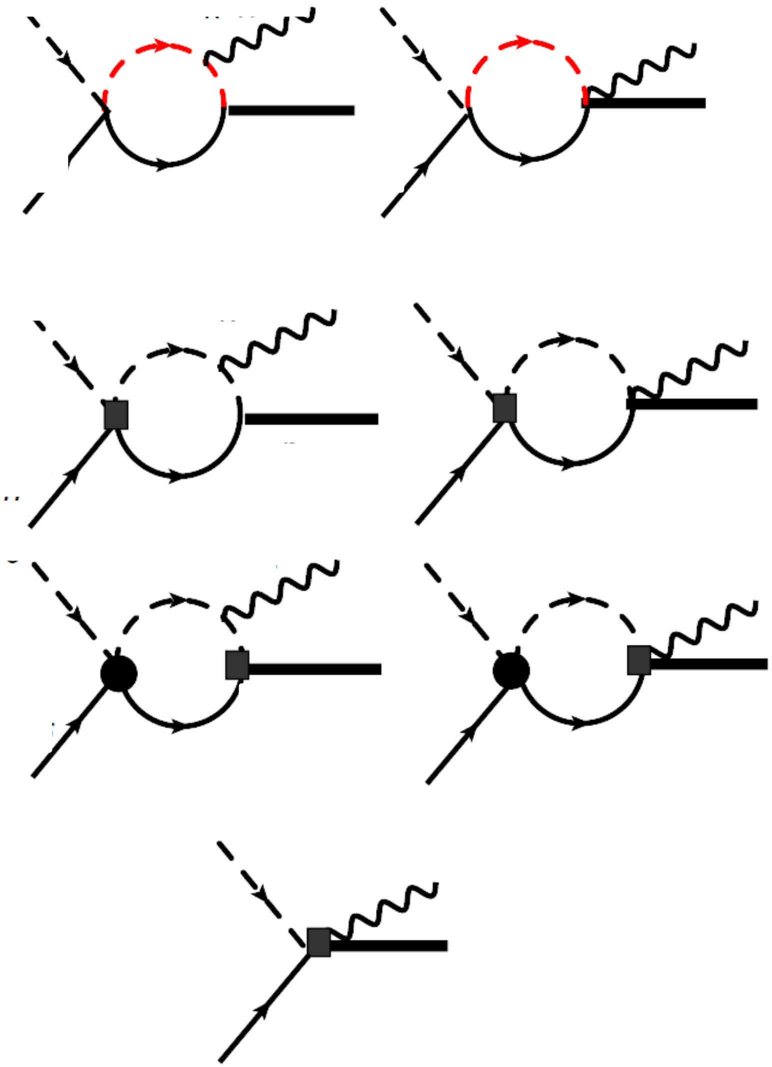


Outlook: NLO



- Need to fix higher order couplings, i.e., need more “observables”.
- Extract from ab initio calculations?
- Change the boundary conditions?
- Change the background fields?

Outlook: NLO



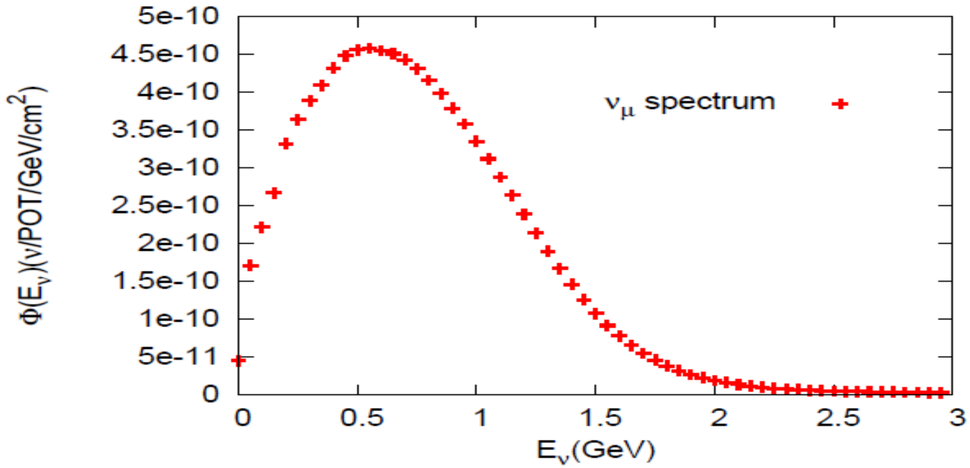
- Need to fix higher order couplings, i.e., need more “observables”.
- Extract from ab initio calculations?
- Change the boundary conditions?
- Change the background fields?
- Another approach by using data?

Other works

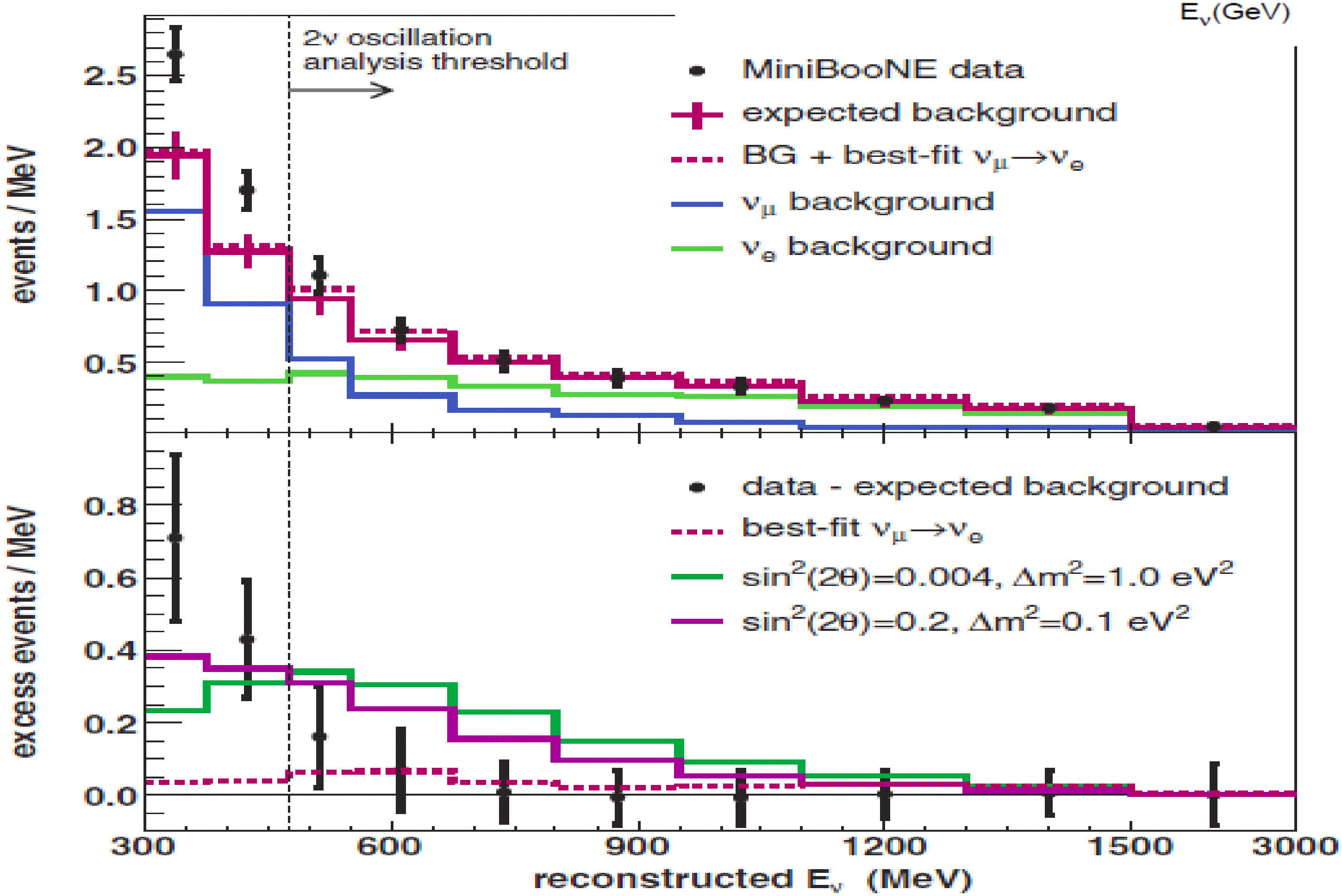
- Neutrino-nucleus interactions (GeV): neutral-current induced photon (motivated by MiniBooNE low energy excess), pion productions, nuclear effects [with Brian Serot]
- Jet quenching in heavy ion collisions: initial state fluctuation, different phenomenological jet energy loss models, possible near-Tc enhancement [with Jinfeng Liao]
- Two-loop contributions: nuclear matter, neutron matter, finite temperature [With Madappa Prakash]

https://sites.google.com/site/xilinzhangphysics/

MiniBooNE

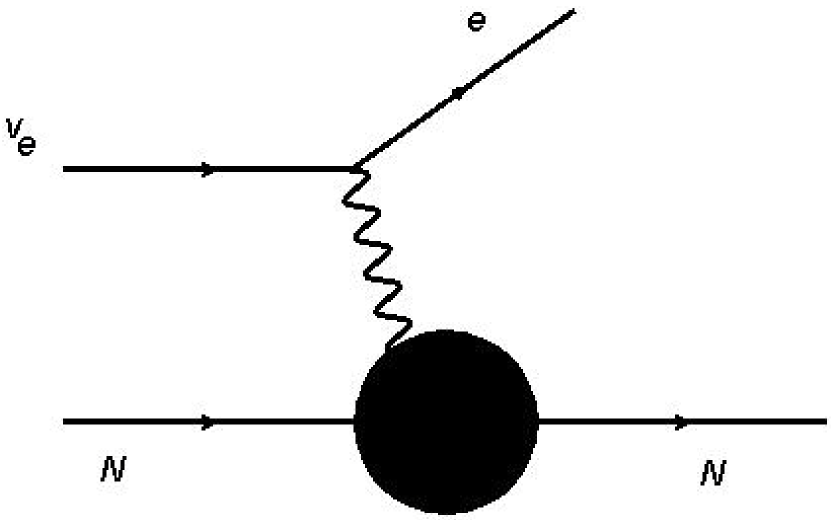


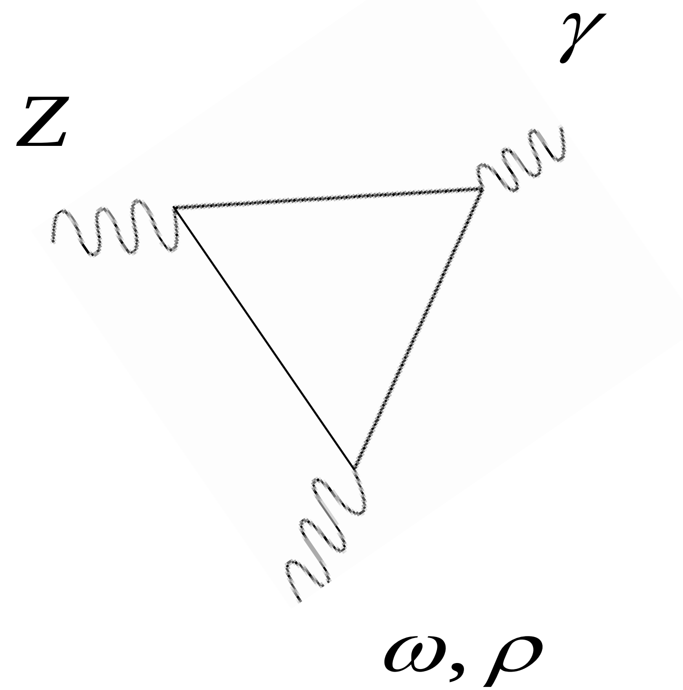
Φ(E_ν)(ν/POT/GeV/cm²)
E_ν(GeV)
ν_μ spectrum

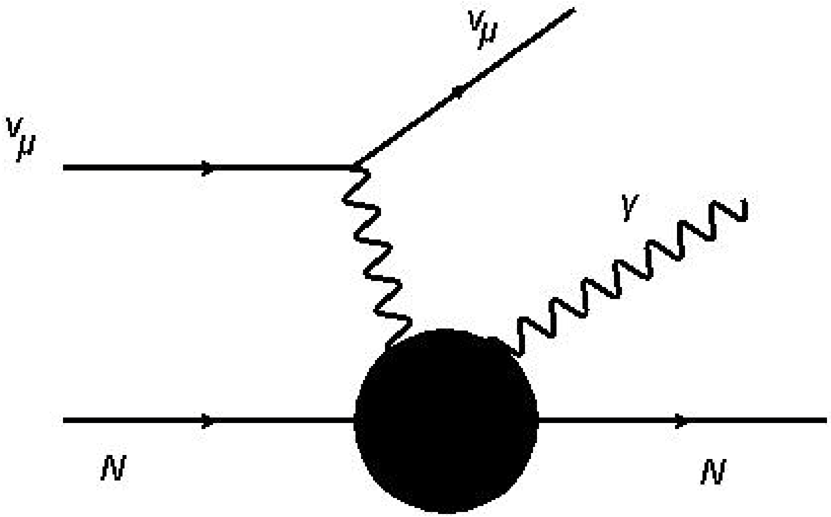


2ν oscillation
analysis threshold
MiniBooNE data
expected background
BG + best-fit ν_μ→ν_e
ν_μ background
ν_e background
events / MeV
data - expected background
best-fit ν_μ→ν_e
sin²(2θ)=0.004, Δm²=1.0 eV²
sin²(2θ)=0.2, Δm²=0.1 eV²
excess events / MeV
reconstructed E_ν (MeV)

New hadronic interactions?







J.A. Harvey, C.T. Hill, R.J. Hill, Phys. Rev. Lett. ***99****, 261601 (2007), Phys. Rev. D* ***77****, 085017(2008). R.J. Hill, Phys. Rev. D* ***81,*** *013008 (2010),* ***84*** *017501(2011).*

Production of single photons in the exclusive neutrino process $\nu N \to \nu\gamma N$

S. S. Gershteĭn, Yu. Ya. Komachenko, and M. Yu. Khlopov

Institute of High Energy Physics, Serpukhov
(Submitted 16 January 1981)
Yad. Fiz. 33, 1597–1604 (June 1981)

It is shown that the experimentally observed production of single photons in neutrino interactions involving neutral currents without visible accompaniment of other particles can be explained by the scattering of the neutrino by a virtual ω meson with small momentum transfer to a nucleon and subsequent coherent enhancement of the process in the nucleus.

PACS numbers: 13.15. + g, 14.80.Kx

1. INTRODUCTION

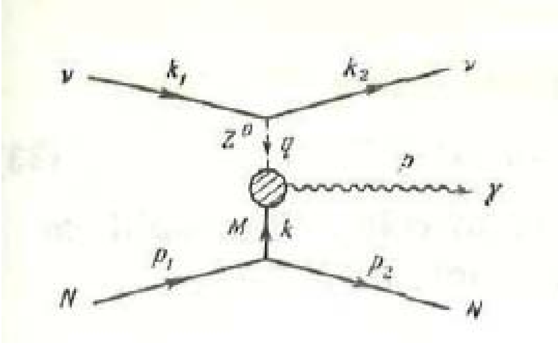
In neutrino experiments performed at CERN using the chamber Gargamelle, more than ten events were detected in which it was observed that single photons with energy 1–10 GeV were produced without visible tracks of any other particles.[1] It can be assumed that the observed events correspond to the weak–electromagnetic process of single-photon production in the reaction

$$\nu N \to \nu\gamma N, \qquad (1)$$

$$H_{\mu\nu} = \sum_M T^{(M)} P^{(M)} J_{\mu\nu}^{(M)}, \qquad (3)$$

in which $T^{(M)}$ is the vertex for emission of a virtual meson (M) by the target nucleon, $P^{(M)}$ is the meson propagator, and $J_{\mu\nu}^{(M)} = \int \langle 0| T(J_\mu^W(x), J_\nu^{EM}(y))| M\rangle e^{iqx+ipy} d^4x d^4y$ is the weak-electromagnetic $Z^0 M\gamma$ vertex. The notation for the particle momenta is given in Fig. 2.

In accordance with the estimates of Ref. 3, we shall take into account the contributions to the diagram of Fig.

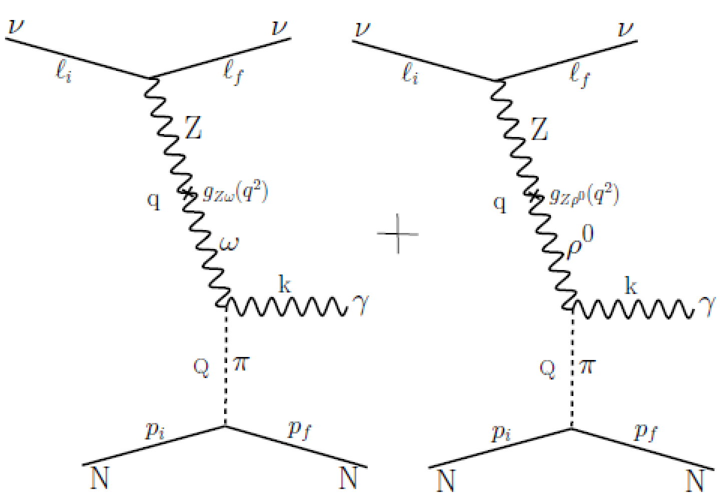


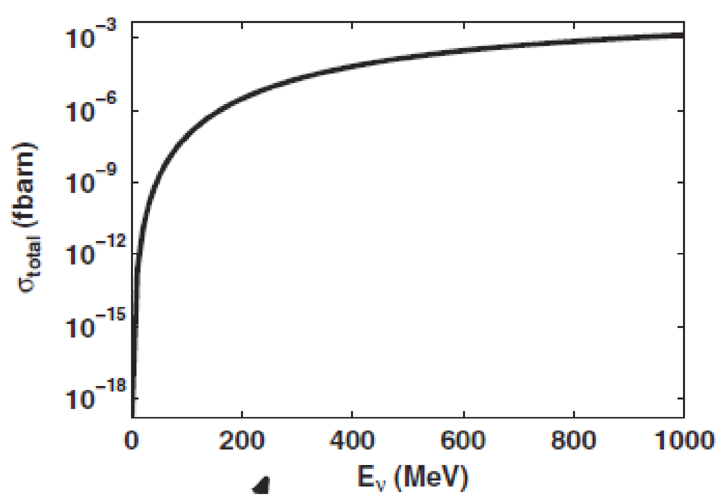
Proceedings of the DPF-2009 Conference, Detroit, MI, July 27-31, 2009

A phenomenological study of photon production in low energy neutrino nucleon scattering

James Jenkins and T. Goldman
Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545

Low energy photon production is an important background to many current and future precision neutrino experiments. We present a phenomenological study of t-channel radiative corrections to neutral current neutrino nucleus scattering. After introducing the relevant processes and phenomenological coupling constants, we will explore the derived energy and angular distributions as well as total cross-section predictions along their estimated uncertainties. This is supplemented throughout with comments on possible experimental signatures and implications. We conclude with a general discussion of the analysis in the context of complimentary methodologies.





Physics Letters B 706 (2012) 268–275

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NOMAD exp.

A search for single photon events in neutrino interactions

C.T. Kullenberg [s], S.R. Mishra [s,*], D. Dimmery [s], X.C. Tian [s], D. Autiero [h], S. Gninenko [h,l], A. Rubbia [h,x], S. Alekhin [y], P. Astier [n], A. Baldisseri [r], M. Baldo-Ceolin [m], M. Banner [n], G. Bassompierre [a], K. Benslama [i], N. Besson [r], I. Bird [h,i], B. Blumenfeld [b], F. Bobisut [m], J. Bouchez [r], S. Boyd [t,1], A. Bueno [c,x], S. Bunyatov [f], L. Camilleri [h], A. Cardini [j], P.W. Cattaneo [o], V. Cavasinni [p], A. Cervera-Villanueva [h,v], R. Challis [k],

Letter of Intent: A new investigation of $\nu_\mu \to \nu_e$ oscillations with improved sensitivity in an enhanced MiniBooNE experiment

MiniBooNE Collaboration

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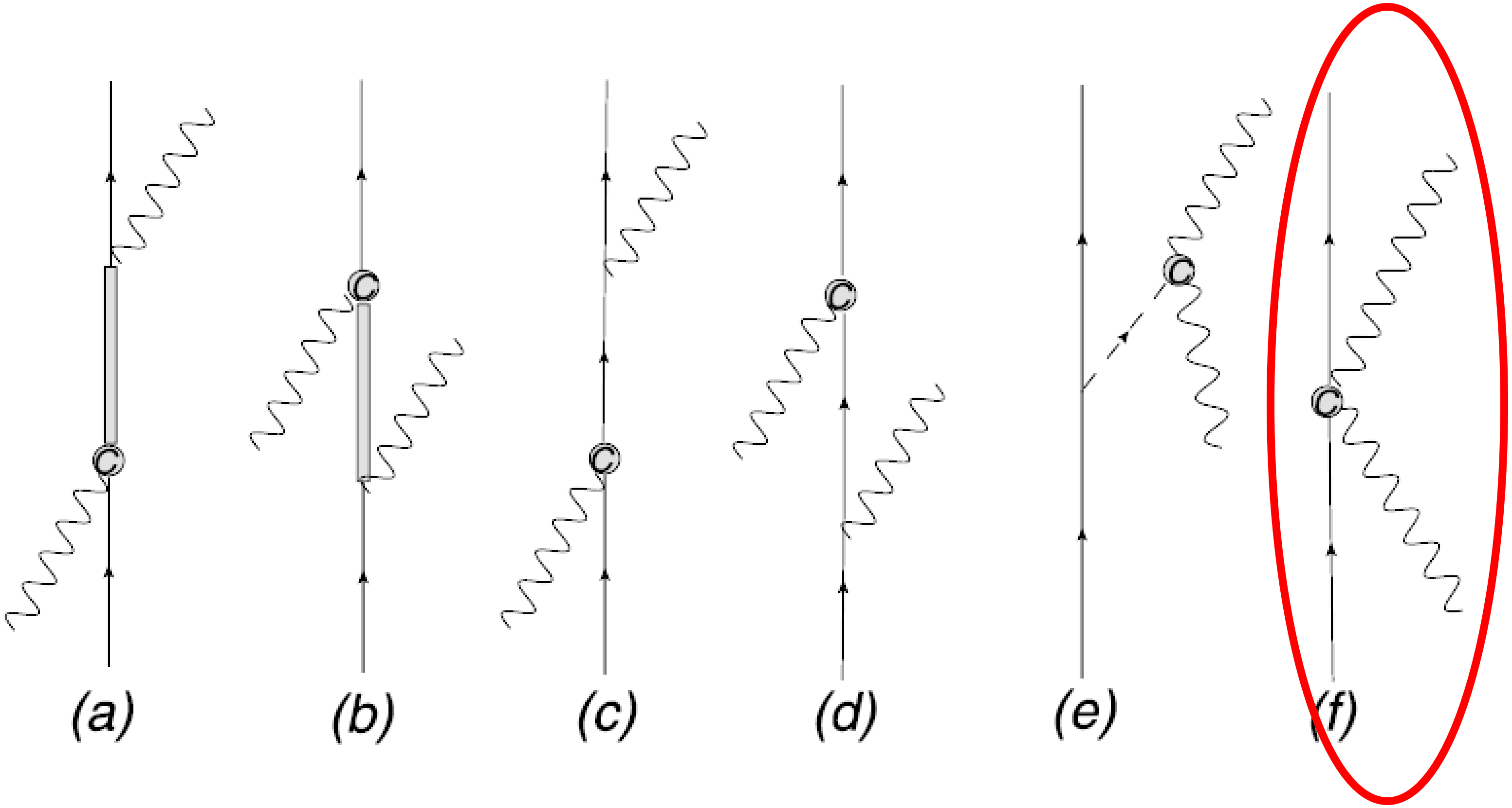
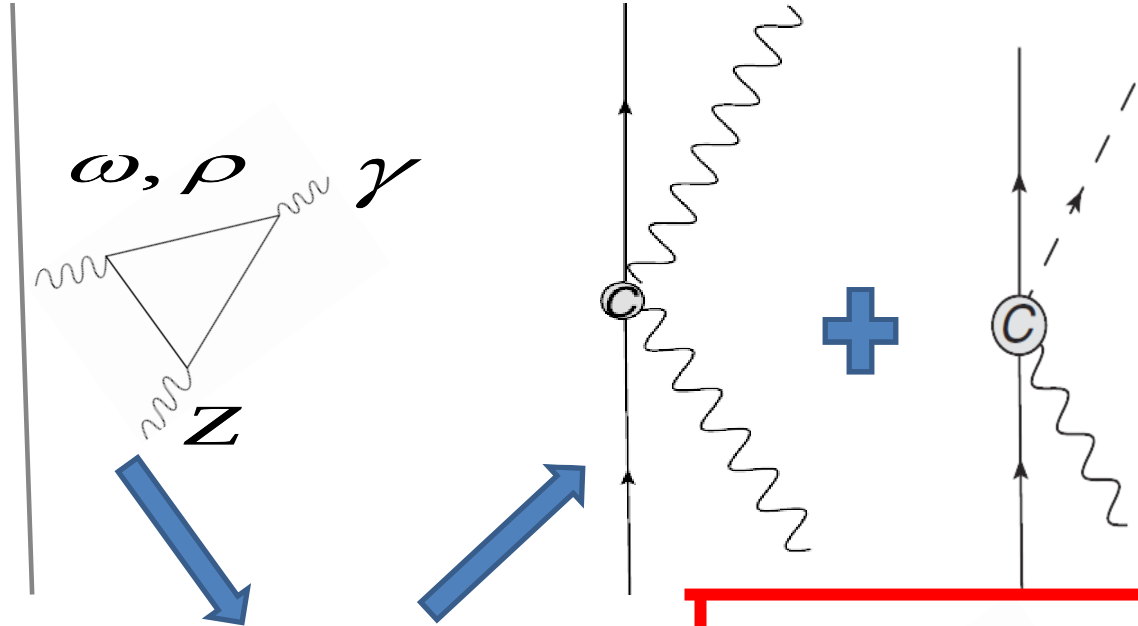
B. C. Brown, F.G. Garcia, R. Ford, W. Marsh, C. D. Moore, D. Perevalov, & C. C. Polly
Fermi National Accelerator Laboratory, Batavia, IL 60510

J. Grange, J. Mousseau, B. Osmanov, & H. Ray

NC photon production off the nucleon



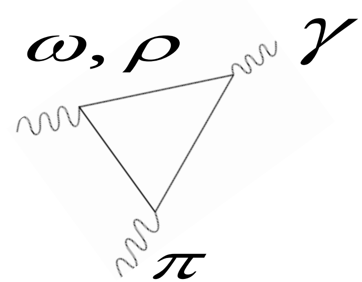


$$\frac{c_1}{M^2}\overline{N}\gamma^\mu N\,\mathrm{Tr}(\tilde{a}^\nu \overline{F}^{(+)}_{\mu\nu}), \qquad \frac{e_1}{M^2}\overline{N}\gamma^\mu \tilde{a}^\nu N \overline{f}_{s\mu\nu}$$

$$F^{(+)}_{\mu\nu} \approx 2\partial_{[\mu}\mathrm{v}_{\nu]} + 2\epsilon^{ijk}\frac{\pi_j}{f_\pi}\frac{\tau_k}{2}\partial_{[\mu}\mathrm{a}_{i\nu]}$$

$$\tilde{a}_\mu \approx \frac{1}{f_\pi}\partial_\mu \pi^i \frac{\tau_i}{2} + \mathrm{a}_{i\mu}\frac{\tau^i}{2} + \epsilon^{ijk}\frac{\pi_j}{f_\pi}\frac{\tau_k}{2}\mathrm{v}_{i\mu}$$

*R. J. Hill, Phys. Rev. D **81**, 013008 (2010)*
W. Peters l, H. Lenske, U. Mosel,
Nucl. Phy. A640,89 (1998)



$c_1 = 1.5$

$e_1 = 0.8$

$$\langle J^\mu_{NC}\rangle_\gamma = \delta^A_B \frac{-iec_1}{M^2}\epsilon^{\mu\nu\alpha\beta}\,\overline{u}_f\gamma_\nu k_\alpha \epsilon^*_\beta(k)u_i + \delta^A_B \frac{-iec_1 q^\mu}{M^2(q^2-m_\pi^2)}\epsilon^{\lambda\nu\alpha\beta}\,\overline{u}_f\gamma_\lambda q_\nu k_\alpha \epsilon^*_\beta(k)u_i$$

N intermediate state $\sim \dfrac{1}{M}$

These terms are small

MiniBooNE NC photon events

E_{QE}(GeV)	[0.2, 0.3]	[0.3, 0.475]	[0.475, 1.25]
coh	1.5 (2.9)	6.0 (9.2)	2.1 (8.0)
inc	12.0 (14.1)	25.5 (31.1)	12.6 (23.2)
H	4.1 (4.4)	10.6 (11.6)	4.6 (6.3)
Total	17.6 (21.4)	42.1 (51.9)	19.3 (37.5)
MiniBN	19.5	47.3	19.4
Excess	42.6 ± 25.3	82.2 ± 23.3	21.5 ± 34.9

E_{QE}(GeV)	[0.2, 0.3]	[0.3, 0.475]	[0.475, 1.25]
coh	1.0 (2.2)	3.1 (5.5)	0.87 (5.4)
inc	4.5 (5.3)	10.0 (12.2)	4.0 (10.2)
H	1.3 (1.6)	3.6 (4.3)	1.1 (2.4)
Total	6.8 (9.1)	16.7 (22.0)	6.0 (18.0)
MiniBN	8.8	16.9	6.8
Excess	34.6 ± 13.6	23.5 ± 13.4	20.2 ± 22.8

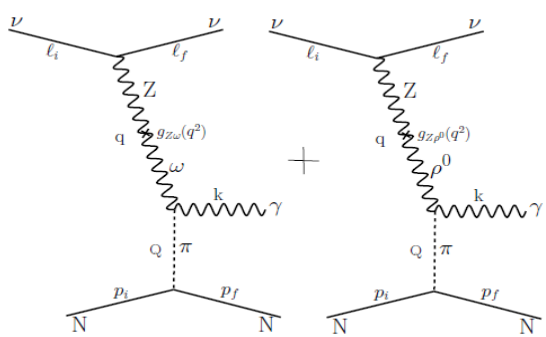
Xection needs to be doubled at least.

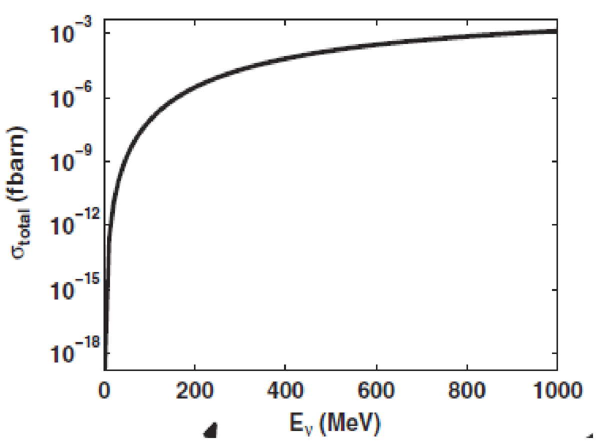
Proceedings of the DPF-2009 Conference, Detroit, MI, July 27-31, 2009

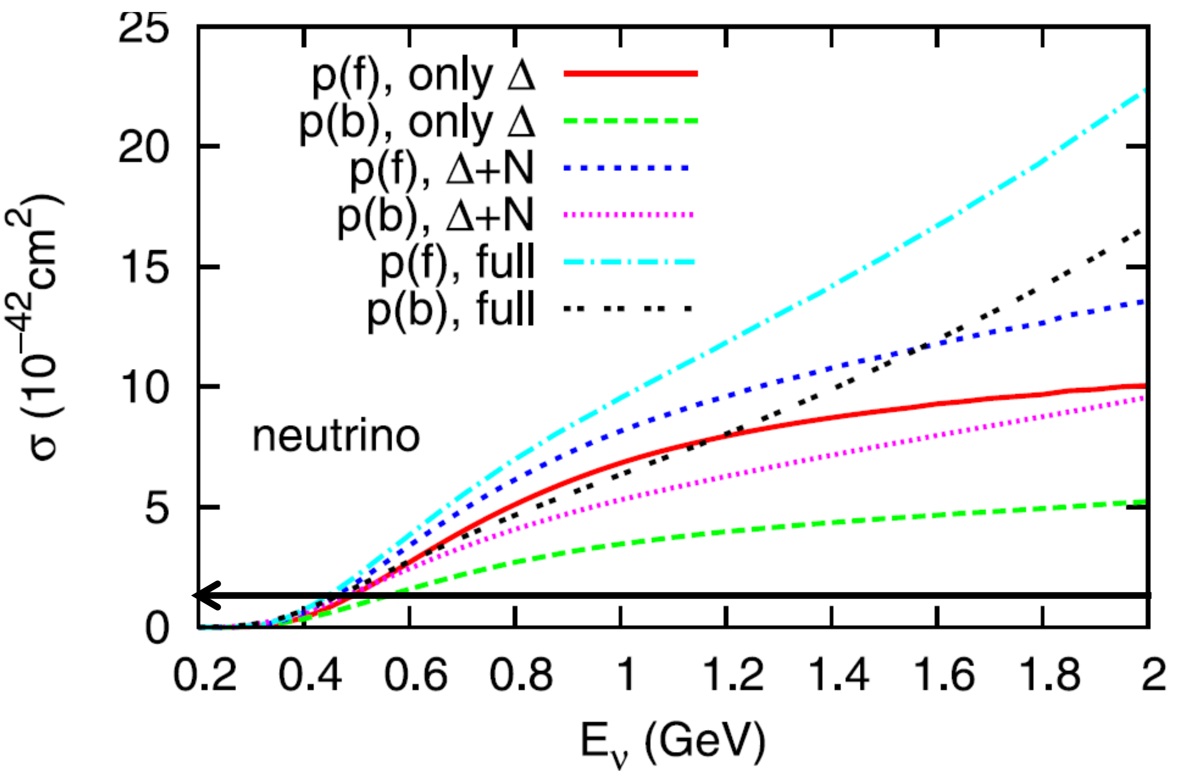
A phenomenological study of photon production in low energy neutrino nucleon scattering

James Jenkins and T. Goldman
Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545

- Incoherent one is small at Enu~ 1 GeV
- Coherent one is zero



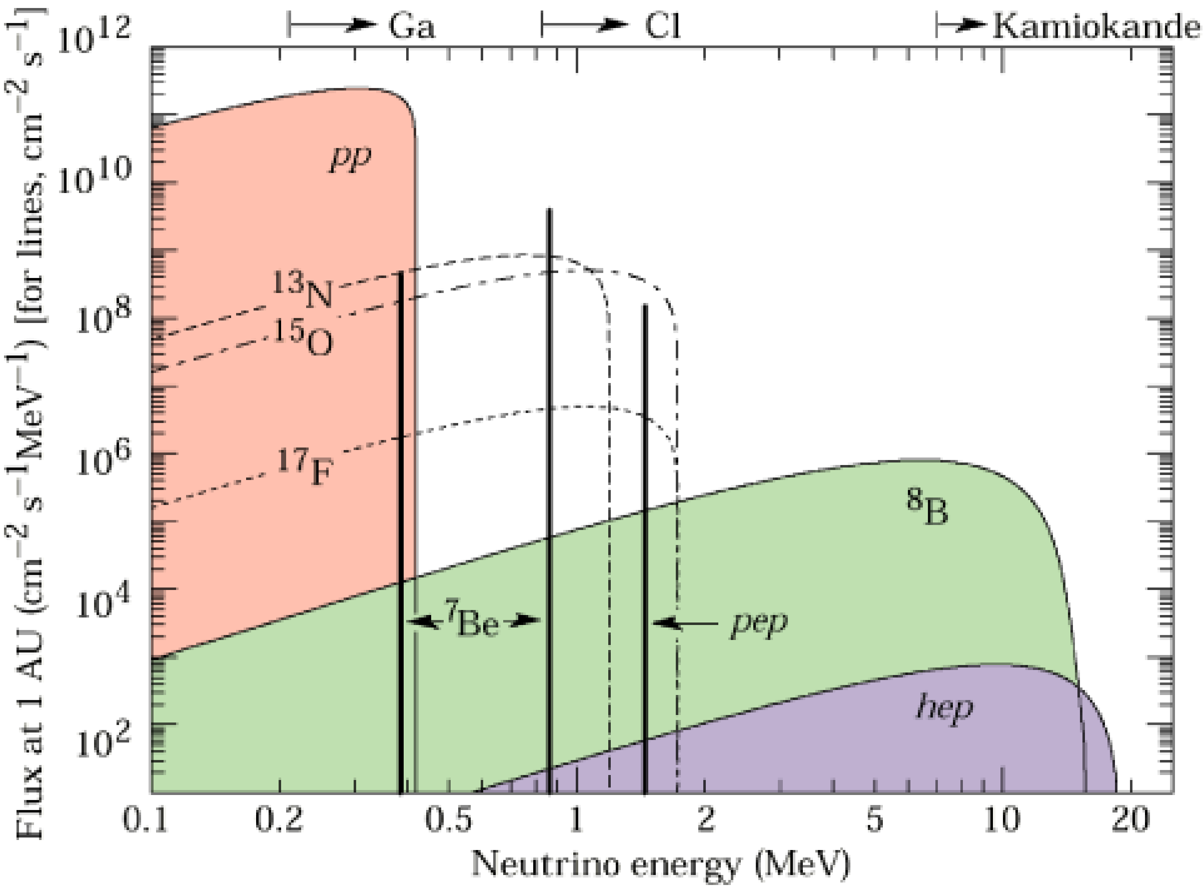




backup

- Capture cross section

- 20 keV ~ fb
- 1MeV ~mb



Ga
Cl
Kamiokande
pp
^{13}N
^{15}O
^{17}F
^{7}Be
pep
^{8}B
hep
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
0.1
0.2
0.5
1
2
5
10
20
Flux at 1 AU ($cm^{-2} s^{-1} MeV^{-1}$) [for lines, $cm^{-2} s^{-1}$]
Neutrino energy (MeV)