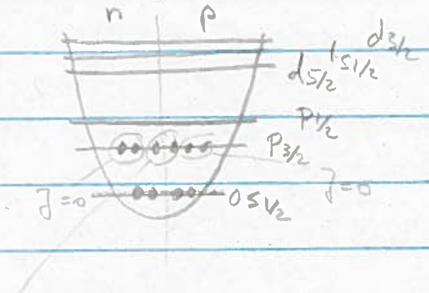
Lecture F26: Nuclear forces and electroweak interactions

(1) Review of nuclear structure: simple shell model

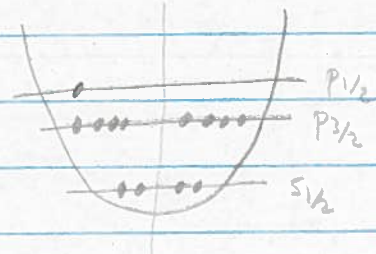
^{10}B



np for N=Z nucleus T=0 (deuteron like) → J=1 or $(p_{3/2})^2$ with J=3 aligned

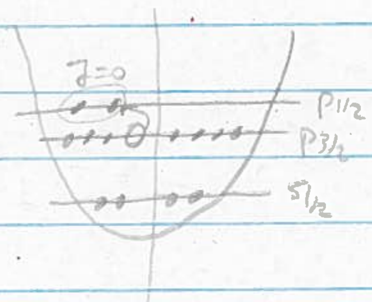
⇒ 3^+, 1^+ lowest states

^{13}C



→ $\frac{1}{2}^-$ ground state

excited state



→ $3/2^-$

(2) Electroweak currents

(3) Example: axial-vector weak current → neutral current interactions e.g. ν scattering

(4) Electromagnetic currents → charged current interactions e.g. β decay

(5) 3N forces and oxygen anomaly

next week

Electroweak interactions

→ astrophysical reactions: stellar evolution, reactions in sun, supernovae, nucleosynthesis

→ fundamental symmetries: superallowed Fermi β-decay → V_{ud} and CKM unitarity

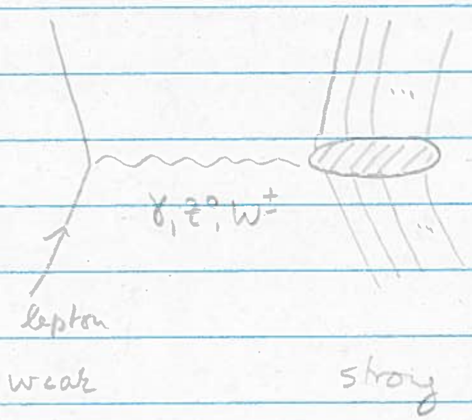
^3H β decay → neutrino mass

neutrinoless $\beta\beta$ decay → Majorana nature of ν
+ lepton number violation

→ nuclear structure and electroweak transitions, resonances

systematic calculations with theoretical uncertainties needed

→ chiral EFT: coupling to electroweak probes → minimal substitution for e.m.

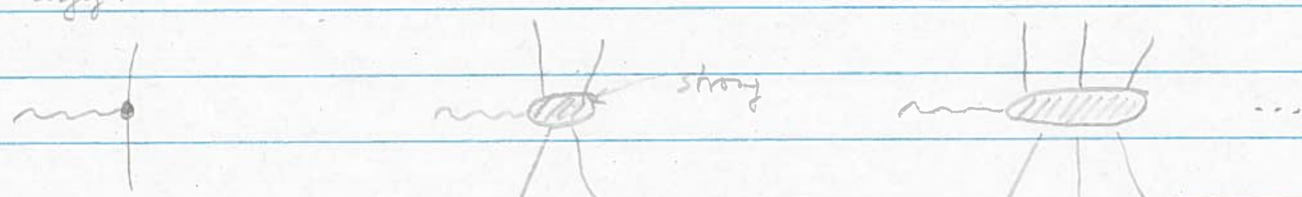


write as current-current interaction at low energies, e.g. in case of weak interactions

$$\mathcal{L}_{int} = \frac{G_F}{\sqrt{2}} \int d^3r \; j^\mu(\vec{r}) \, J_\mu(\vec{r})$$

leptonic   nucleonic current

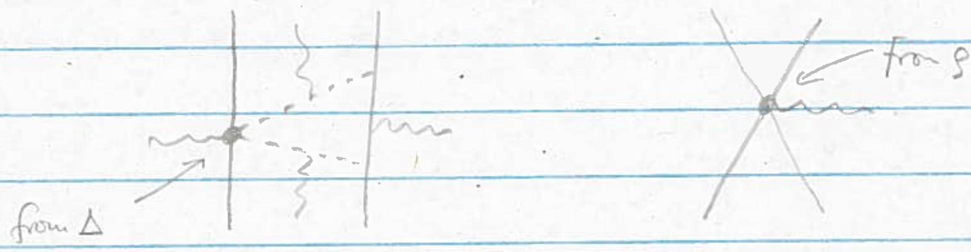
terminology:



one-body current   two-body currents (corrections)   three-body currents (very small)

also called meson-exchange currents (MEC) expand currents consistently in chiral EFT to Q^4

Why do 2- (and higher-body) currents occur? take generic strong interaction process and consider electromagnetic coupling



intermediate states involve charged N, π, γ can couple to these!

<u>Example: axial-vector weak interactions</u> $\vec{j}^{\,i} = g_A \vec{\sigma} \tau^i$ $i=3 \rightarrow$ neutral, $i=\pm \rightarrow$ charged

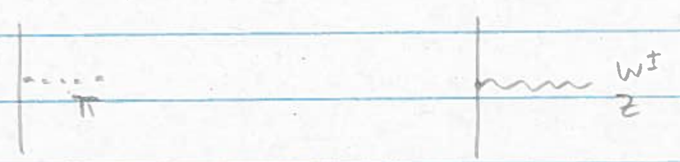
axial-vector currents based on same symmetry as Chiral symmetry currents $\rightarrow$ pions

see this e.g. at the level of one-pion-exchange

<u>Goldberger-Treiman relation</u> $g_{\pi NN} f_\pi = g_A m_N$

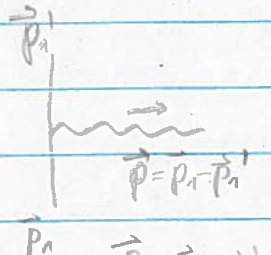
πN coupling $\longleftrightarrow$ axial coupling from weak interactions

diagrammatically



$$\sim \frac{g_A}{2f_\pi} \vec{\sigma}\cdot\vec{q}\, \tau^i \longleftrightarrow g_A \vec{\sigma} \tau^i$$

Single-nucleon current to order Q^2



$\vec{P} = \vec{p}_1 + \vec{p}_1'$

$E = E_1 - E_1'$

Gamow-Teller operator

pseudoscalar

$$\vec{J}^{(0+2),i} = \tau^i \Big(g_A(\vec{p}^2)\,\vec{\sigma} - g_P(p^2)\,\frac{\vec{p}(\vec{p}\cdot\vec{\sigma})}{2m}$$

$$+\, i\,(g_M + g_V)\,\frac{\vec{\sigma}\times\vec{p}}{2m} - g_V\,\frac{\vec{P}}{2m} \Big)$$

magnetic coupling

vector coupling see temporal component

$$J^{(0+2),i}_{\mu=0} = \tau^i \Big(g_V(p^2) - g_A\,\frac{\vec{P}\cdot\vec{\sigma}}{2m} + g_P(p^2)\,\frac{E(\vec{p}\cdot\vec{\sigma})}{2m} \Big)$$

Fermi operator

p-dependence of couplings due to loop corrections and pion propagators, to Q^2

$$g_{V,A}(p^2) = g_{V,A}\left(1 - 2\,\frac{p^2}{\Lambda^2_{V,A}}\right)$$

$g_V = 1, \quad g_A = 1.27$

$\Lambda_V = 850\,\text{MeV}, \quad \Lambda_A = 1040\,\text{MeV}$

$$g_P(p^2) = \frac{2 g_{\pi NN} f_\pi}{\vec{p}^2 + m_\pi^2} - 4 g_A(p^2)\,\frac{m}{\Lambda_A^2}$$

$g_{\pi NN} = 13.05$

$g_M = \mu_p - \mu_n = 3.70$

Example: nuclear β decays $\rightarrow$ very low momentum transfers (low Q-values!)

$$ft = \frac{2\pi^3 \ln 2}{m_e^3 G_F^2 V_{ud}^2 \left[(1+\Delta_R^V)\, g_V^2 |M_V|^2 + (1+\Delta_R^A)\, g_A^2 |M_A|^2 \right]}$$

comparative half-life
includes dependence on Z of daughter
and max electron energy in f

$$|M_V|^2 \sim \left| \langle i \| \sum_{n=1}^{A} \tau_n^{\pm} \| f \rangle \right|^2$$

$$|M_A|^2 \sim \left| \langle i \| \sum_{n=1}^{A} \vec{\sigma}_n \tau_n^{\pm} \| f \rangle \right|^2$$

Two-body axial-vector weak currents

derive with diagrammatic rule 

enter at $Q^3 \rightarrow$ 3N forces 

long-range short range

$\Longrightarrow$ 

given by c_i by c_D

$\rightarrow$ c_i relate πN, NN, 3N, axial-vector weak currents

$\rightarrow$ c_D relates 3N, axial-vector weak currents, and π-production 

can use this to fit 3N forces to ^{3}H β-decay!

$$\vec{j}^{(3)i} = \sum_{m<n=1}^{A} \vec{j}^{\,i}_{mn}$$ with many structures, for details see Park et al. PRC $\underline{67}$, 055206 (2003)