Application of Isospin Non-Conserving Hamiltonian to Isospin-Mixing Correction in Superallowed β Decay

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Shell Model as a Unified View of Nuclear Structure

Institut Pluridisciplinaire Hubert Curien (IPHC),
IN2P3-CNRS/Université Louis Pasteur,
BP 28, F-67037 Strasbourg Cedex, France.
8-10 October 2012.

Outline

1. **Test of CKM Matrix**
   - CKM matrix
   - Superallowed Transition
2. **Isospin-Mixing Correction δ_{IM}**
   - δ_{IM} for Superallowed Transitions
   - δ_{IM} for Non-Analogue States
3. **Summary and Perspective**

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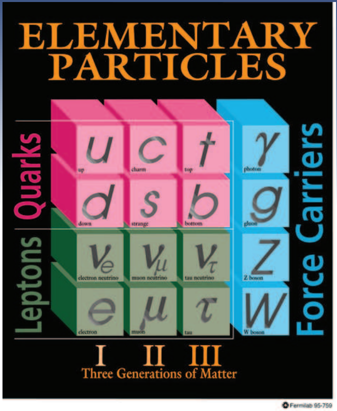
Outline

Cabibbo-Kobayashi-Maskawa (CKM) matrix

- Elementary Particles of Standard Model,



Cabibbo-Kobayashi-Maskawa (CKM) matrix

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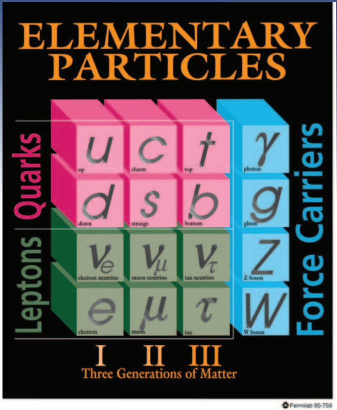
  - *up*-type quarks,
    $u_h^j = \sum_k \left(U_h^u\right)_{jk} u_h'^k$,



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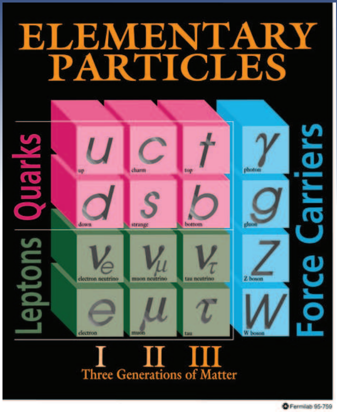

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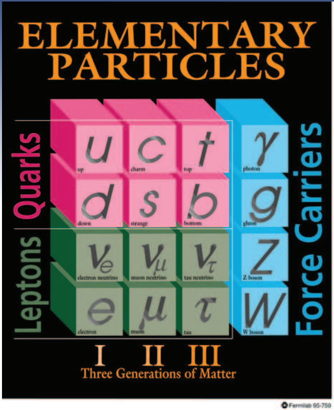
- Lagrangian for a charge-current weak interaction,

$$\mathscr{L}_W = -\frac{g}{\sqrt{2}} \sum_j \left(\overline{u}_L'^j \gamma_\mu d_L'^j + \overline{\nu}_L^j \gamma_\mu l_L^j \right) W_+^\mu + h.c.$$



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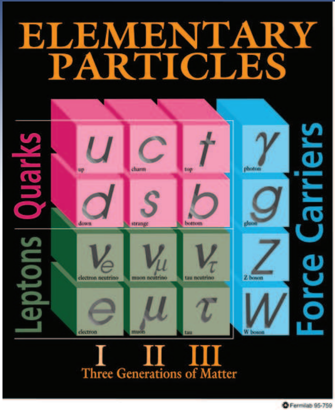

- Lagrangian for a charge-current weak interaction,

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- Lagrangian rewritten in terms of mass eigenstates,

$$\mathscr{L}_W = -\frac{g}{\sqrt{2}} \sum_{jkm} (\overline{u}_L^k \gamma_\mu \underbrace{(U_L^u)_{kj} (U_L^d)_{jm}^\dagger}_{V_{km} = \sum_j (U_L^u)_{kj} (U_L^d)_{jm}^\dagger} d_L^m + \overline{\nu}_L^j \gamma_\mu l_L^j) W_+^\mu + h.c.$$

Cabibbo-Kobayashi-Maskawa (CKM) matrix

- For $n = 2$ flavors,

$$\mathscr{L}_W = -\frac{g}{\sqrt{2}}(\overline{u}_L \overline{c}_L)\gamma_\mu \underbrace{\begin{pmatrix} cos\theta_c & sin\theta_c \\ -sin\theta_c & cos\theta_c \end{pmatrix}}_{\text{Cabibbo-mixing angle, } \theta_c} \begin{pmatrix} d_L \\ s_L \end{pmatrix} W_+^\mu + h.c.$$

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. Cabibbo-mixing angle, θ_c

- For $n = 3$ flavors,

$$\mathscr{L}_W = -\frac{g}{\sqrt{2}}(\overline{u}_L \overline{c}_L \overline{t}_L)\gamma_\mu \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W_+^\mu + h.c.$$

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- . Cabibbo-Kobayashi-Maskawa (CKM) matrix

Symmetry Test

Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

[1] L. Wolfenstein, Phys. Rev. Lett. 51 (1983) 1945.

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Wolfenstein's CKM matrix[1]

$$V = \begin{pmatrix} 1 - \frac{\lambda^2}{2} - \frac{\lambda^4}{8} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + \frac{A^2\lambda^5}{2}[1 - 2(\rho + i\eta)] & 1 - \frac{\lambda^2}{2} - \frac{\lambda^4}{8}(1 + 4A^2) & A\lambda^2 \\ A\lambda^3\left\{1 - \left[1 - \frac{\lambda^2}{2}\right](\rho + i\eta)\right\} & -A\lambda^2 + \frac{A\lambda^4}{2}[1 - 2(\rho + i\eta)] & 1 - \frac{A\lambda^4}{2} \end{pmatrix}$$

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Symmetry Test

- Why it's so important ?

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  - Normalization test on rows and columns, Unitarity Test,
    $\sum_k V_{ik} V_{ki}^\dagger = \sum_k |V_{ik}|^2 = \sum_k V_{ki}^\dagger V_{ik} = \sum_i |V_{ik}|^2 = 1.$

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    - The best precision is achieved in the top row:
      $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

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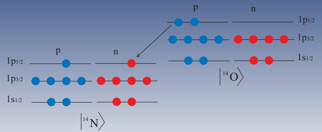
Superallowed $0^+ \rightarrow 0^+$ Transition

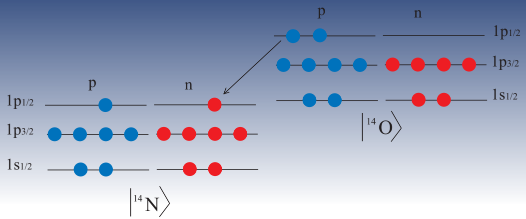
β-Decay Rate, Γ

$$\Gamma = \frac{1}{\tau} = \frac{\ln 2}{t} = \frac{G_F^2 g_V^2 m_e^5}{2\pi^3} V_{ud}^2 \left(f_V |M_F^0|^2 + f_A \lambda^2 |M_{GT}^0|^2 \right)$$



- τ = mean life time,
- G_F = fundamental weak interaction coupling constant
- g_V = vector coupling constant, ($g_V = 1$ if the CVC holds),
- m_e = electron mass
- V_{ud} = upper-left CKM matrix elements
- f_V = phase-space integral for Fermi transitions
- f_A = phase-space integral for Gamow-Teller transitions
- M_F and M_{GT} are the Fermi and Gamow-Teller matrix elements, respectively.
- The superallowed $0^+ \rightarrow 0^+$ β-decay
  $\rightarrow$ purely vector, $\left(\left| M_{GT}^0 \right|^2 = 0 \right)$

Superallowed $0^+ \to 0^+$ Transition



- Transition dependent part of radiative correction:

$$\mathscr{F}t = f_{exp}t(1+\delta_R')(1+\delta_{NS}-\delta_{IM}-\delta_{RO}) = \frac{K}{|M_{F0}|^2 G_F^2 g_v^2 V_{ud}^2 (1+\Delta_R^v)}$$

Superallowed $0^+ \to 0^+$ Transition

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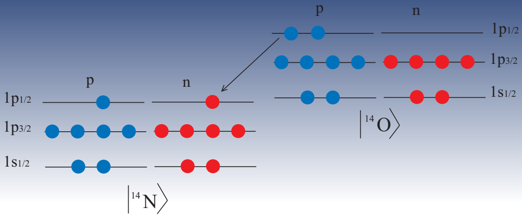

- Transition dependent part of radiative correction:
  - δ_{NS},

$$\mathscr{F}t = f_{exp}t(1 + \delta'_R)(1 + \delta_{NS} - \delta_{IM} - \delta_{RO}) = \frac{K}{|M_{F0}|^2 G_F^2 g_v^2 V_{ud}^2 (1 + \Delta_R^v)}$$

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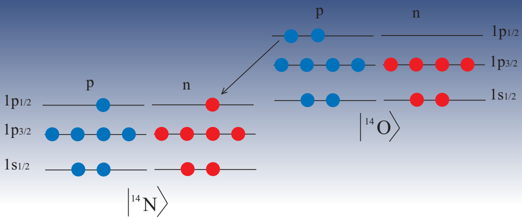

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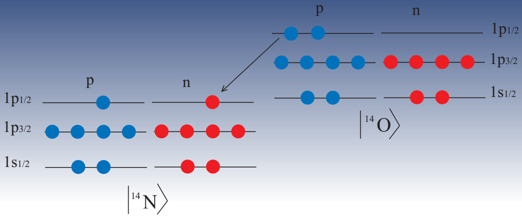

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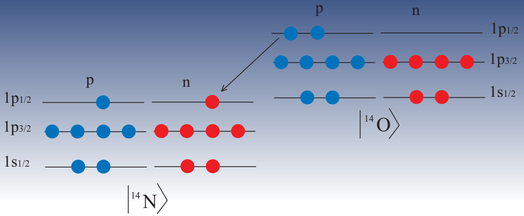
- Isospin symmetry breaking correction:

Superallowed $0^+ \rightarrow 0^+$ Transition



- Transition dependent part of radiative correction:
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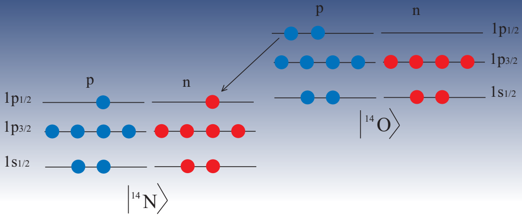
- Isospin symmetry breaking correction:
  - Isospin mixing correction, δ_{IM},

Superallowed $0^+ \to 0^+$ Transition



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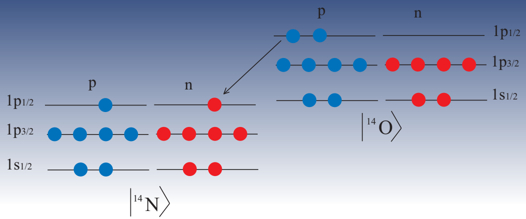

- Transition dependent part of radiative correction:
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$\delta_{Isospin\ Mixing}$ (δ_{IM}) Correction

Isospin Non-Conserving Nuclear Hamiltonian:

Isovector : Coulomb + Nucl. Hamil. (USD) + Isovector Single Particle Energies
Isotensor : Coulomb + Nucl. Hamil. (USD)
Isovector : Coulomb + Nucl. Hamil. (KB3G) + Isovector Single Particle Energies
Isotensor : Coulomb + Nucl. Hamil. (KB3G)

	δ_{IM} (%)						
	Present Works[1]					Previous Works	
Parent	UCOM	Jastrow type SRC function			without SRC	Ormand &	Towner &
Nucleus		Argonne V18[2]	CD-Bonn[2]	Miller-Spencer		Brown	Hardy[5]
^{22}Mg	0.022	0.021	0.021	0.023	0.021	0.017[4]	0.010 (10)
$^{26}Al^{m}$	0.012	0.012	0.011	0.013	0.011	0.01[3]	0.025 (10)
^{26}Si	0.046	0.046	0.046	0.046	0.046	0.028[4]	0.022 (10)
^{30}S	0.028	0.027	0.025	0.030	0.026	0.056[4]	0.137 (20)
^{34}Cl	0.037	0.036	0.036	0.036	0.037	0.06[3]	0.091 (10)
^{34}Ar	0.006	0.006	0.006	0.007	0.005	0.008[4]	0.023 (10)
^{46}V	0.036	0.035	0.035	0.032	0.032	0.09[3]	0.040 (30)
^{50}Mn	0.033	0.032	0.031	0.030	0.030	0.02[3]	0.057 (20)

[1] Lam, Smirnova, Caurier, 2012 submitted to PRC.
[2] Proposed parameters for Jastrow-type function on the basis of coupled-cluster calculation with Argonne V18 or CD-Bonn.
[3] Ormand W. E. & Brown B. A., Phys. Rev. Lett. 62 (1989) p.866.; Phys. Rev. C 52 (1995) p.2455.
[4] Calculated with strength parameters from Ormand & Brown NPA 491 '89 p.1
[5] Towner I. S. & Hardy J. C., Phys. Rev. C 77 (2008) 025501, Table III. unscaled δ_{C1}

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$\mathscr{F}t$ values of superallowed $0^+ \rightarrow 0^+$ transition

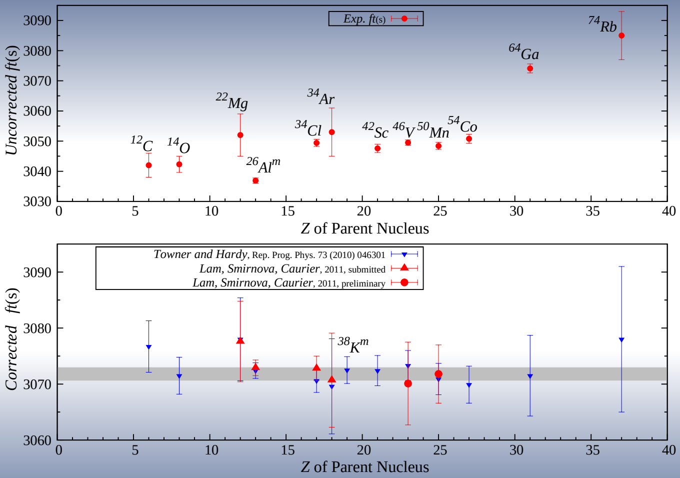
Parent Nucleus	Exp. ft[3]	Corrections (%) δ_{IM}[1]	δ_{RO}[2]	δ'_R[2]	δ_{NS}[2]	$\mathscr{F}t$ values: Present work[1]	Towner & Hardy[3]
^{22}Mg	3052 (7)	0.0216 (9)	0.370 (20)	1.466 (17)	-0.225 (20)	3077.6 (72)	3078.0 (74)
$^{26}Al^m$	3036.9 (9)	0.0120 (8)	0.280 (15)	1.478 (20)	0.005 (20)	3072.9 (13)	3072.4 (14)
^{34}Cl	3049.4 (12)	0.0363 (5)	0.550 (45)	1.443 (32)	-0.085 (15)	3072.6 (21)	3070.6 (21)
^{34}Ar	3053 (8)	0.0060 (4)	0.635 (55)	1.412 (35)	-0.180 (15)	3070.7 (84)	3069.6 (85)
^{46}V	3049.5 (9)	0.0034 (6)	0.075 (30)	1.445 (62)	-0.035 (10)	3070.1 (74)	3073.3 (27)
^{50}Mn	3048.4 (12)	0.0032 (5)	0.045 (20)	1.445 (54)	-0.040 (10)	3071.8 (52)	3070.9 (28)

[1] Lam, Smirnova, Caurier, 2012 submitted to PRC.

[2] Towner I. S. & Hardy J. C., Phys. Rev. C 77 (2008) 025501, Table II, V, VI.

[3] Towner I. S. & Hardy J. C., Rep. Prog. Phys. 73 (2010) 046301, Table 4.

V_{ud} and the Unitarity of CKM matrix



[1] Lam, Smirnova, Caurier (2012)

V_{ud} and the Unitarity of CKM matrix

V_{ud}

$$|V_{ud}|^2 = \frac{K}{2G_F^2(1+\Delta_R^V)\overline{\mathscr{F}t}} = \frac{2915.64 \pm 1.08^1}{\overline{\mathscr{F}t}}$$

$$\frac{K}{(\hbar c)^6} = \frac{2\pi^3 ln2}{(m_e c^2)^5}$$

$$G_V = G_F g_V V_{ud} = G_F V_{ud}$$

$$\overline{\mathscr{F}t} = 3073.12 \pm 0.78\ s$$

$$|V_{ud}|^2 = 0.94875 \pm 0.00041$$

$$|V_{ud}| = 0.97404 \pm 0.00021$$

[1] $\Delta_R^V = (2.361 \pm 0.038)\%$

[2] I. S. Towner & J. C. Hardy, Rep. Prog. Phys. 73 (2010) 046301

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V_{us}

$$|V_{us}| = 0.22521 \pm 0.00094^2$$

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$$|V_{us}| = 0.22521 \pm 0.00094^{2}$$

V_{ub}

$$|V_{ub}| = (3.38 \pm 0.36) \times 10^{-3} \Longleftarrow PDG\ (2010)$$

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V_{ud} and the Unitarity of CKM matrix

Finally...

Unitarity

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99949 \pm 0.00059$$

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Outline

$\delta_{Isospin\ Mixing}$ (δ_{IM}) for Non-Analog States

Isospin Non-Conserving Nuclear Hamiltonian:

Isovector : Coulomb + Nucl. Hamil. (USD) + Isovector Single Particle Energies
Isotensor : Coulomb + Nucl. Hamil. (USD)

	Nuclear Hamiltonian	Present Work[1]						Previous Work
		w/o SRC	UCOM	Jastrow type SRC function				
				Argonne V18	CD-Bonn	Miller Spencer	Strengths from OB (1989)	Ormand & Brown (1985)
$\delta_{IM}\ {}^{34}Ar \times 10^5$:								
	USD	−37.97	−8.843	−29.69	−48.19	−27.44	−361.2	−3.5
	USDA	−127.8	−101.2	−118.9	−140.2	−71.25	—	—
	USDB	−134.1	−120.8	−134.5	−142.9	−106.1	—	—
$\delta_{IM}\ {}^{34}Cl \times 10^2$:								
	USD	−3.103	−3.098	−3.061	−3.071	−3.061	−3.960	−2.7
	USDA	−2.734	−2.730	−2.697	−2.712	−2.695	—	—
	USDB	−3.120	−3.115	−3.076	−3.088	−3.071	—	—

[1] The δ_{IM} values of present work are given in 4 significant figures.

Summary and Perspective

- CKM unitarity test can be a check for isospin non-conserving Hamiltonian
- The unitarity of CKM matrix is tested,

$$\sum_i |V_{ij}|^2 = 0.99949 \pm 0.00059$$

However, more $\mathscr{F}t$ values of parent nuclei should be included.
For example, parent nuclei of *psd*, *sdpf*, *pf* shell spaces. δ_{RO} may be revisited.

- There is an indication of transition of isospin non-analog states in ^{34}Ar and ^{34}Cl.
- INC Hamiltonian can be used to describe isospin-forbidden proton emission.

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