Hadronic Weak Interaction Theory

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Outline

1. Introduction
   - The Standard Model
   - Why Difficult?
   - Why Important?
   - The Search Program
2. *S*–*P* Amps.
   - S-P Amplitudes
   - General Structure of *S*–*P* Amplitudes
3. Meson Exchange
   - Meson-Exchange Model
   - PV Meson-Nucleon Couplings
   - Current Status
4. EFT
   - EFT Formulation
   - Analysis
5. Outlook and Summary
   - Outlook
   - Summary
   - Further Reading

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Outline

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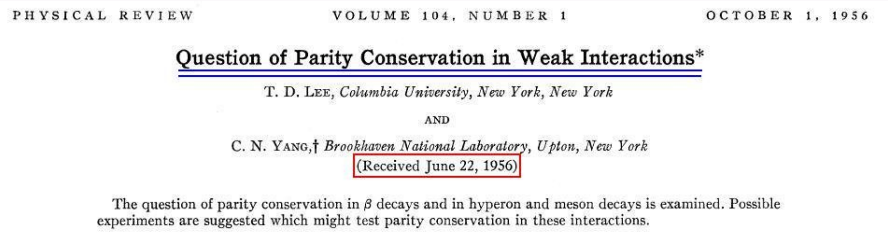
The Story Begins With...



PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

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(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

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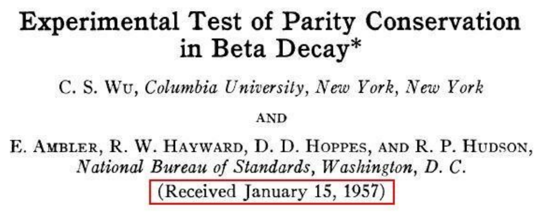

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

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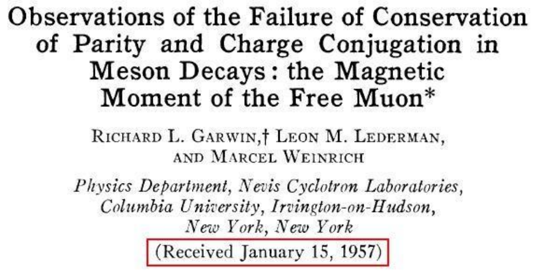

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

RICHARD L. GARWIN,† LEON M. LEDERMAN,
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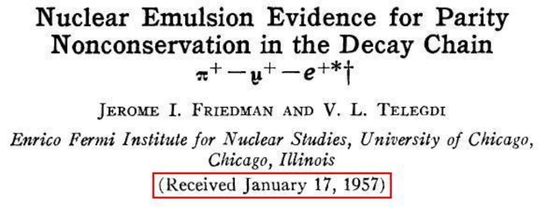
Physics Department, Nevis Cyclotron Laboratories,
Columbia University, Irvington-on-Hudson,
New York, New York

$\boxed{\text{(Received January 15, 1957)}}$

The Story Begins With...

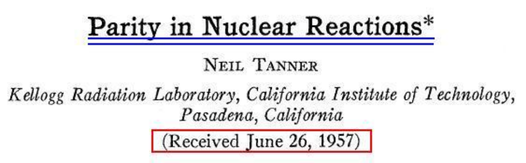


Nuclear Emulsion Evidence for Parity Nonconservation in the Decay Chain $\pi^{+}-\mu^{+}-e^{+}$[*][†]

JEROME I. FRIEDMAN AND V. L. TELEGDI
Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received January 17, 1957)

The Story Begins With...



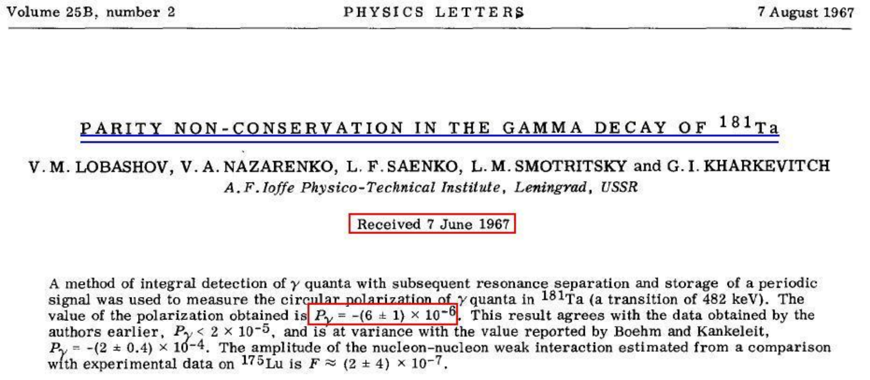
Parity in Nuclear Reactions*

NEIL TANNER

Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California

(Received June 26, 1957)

The Story Begins With...



Volume 25B, number 2 PHYSICS LETTERS 7 August 1967

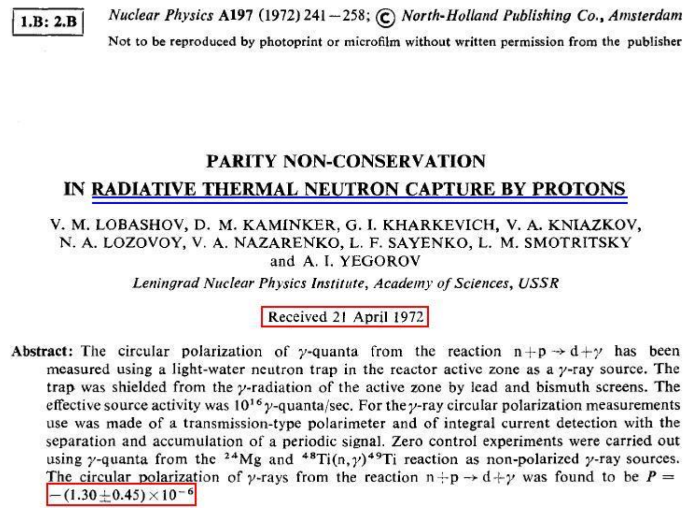
PARITY NON-CONSERVATION IN THE GAMMA DECAY OF ^{181}Ta

V. M. LOBASHOV, V. A. NAZARENKO, L. F. SAENKO, L. M. SMOTRITSKY and G. I. KHARKEVITCH
A. F. Ioffe Physico-Technical Institute, Leningrad, USSR

Received 7 June 1967

A method of integral detection of γ quanta with subsequent resonance separation and storage of a periodic signal was used to measure the circular polarization of γ quanta in ^{181}Ta (a transition of 482 keV). The value of the polarization obtained is $\boxed{P_\gamma = -(6 \pm 1) \times 10^{-6}}$. This result agrees with the data obtained by the authors earlier, $P_\gamma < 2 \times 10^{-5}$, and is at variance with the value reported by Boehm and Kankeleit, $P_\gamma = -(2 \pm 0.4) \times 10^{-4}$. The amplitude of the nucleon-nucleon weak interaction estimated from a comparison with experimental data on ^{175}Lu is $F \approx (2 \pm 4) \times 10^{-7}$.

The Story Begins With...



1.B: 2.B

Nuclear Physics **A197** (1972) 241—258; © *North-Holland Publishing Co., Amsterdam*

PARITY NON-CONSERVATION IN RADIATIVE THERMAL NEUTRON CAPTURE BY PROTONS

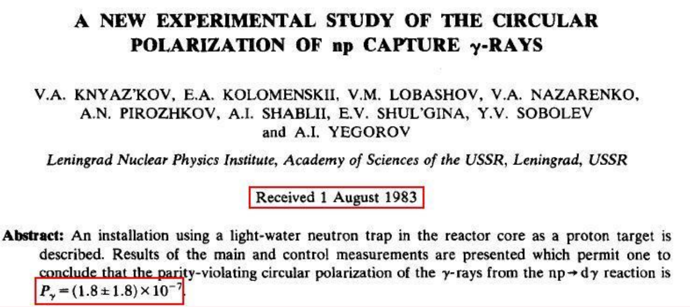
V. M. LOBASHOV, D. M. KAMINKER, G. I. KHARKEVICH, V. A. KNIAZKOV,
N. A. LOZOVOY, V. A. NAZARENKO, L. F. SAYENKO, L. M. SMOTRITSKY
and A. I. YEGOROV

Leningrad Nuclear Physics Institute, Academy of Sciences, USSR

Received 21 April 1972

Abstract: The circular polarization of γ-quanta from the reaction $n+p \rightarrow d+\gamma$ has been measured using a light-water neutron trap in the reactor active zone as a γ-ray source. The trap was shielded from the γ-radiation of the active zone by lead and bismuth screens. The effective source activity was 10^{16} γ-quanta/sec. For the γ-ray circular polarization measurements use was made of a transmission-type polarimeter and of integral current detection with the separation and accumulation of a periodic signal. Zero control experiments were carried out using γ-quanta from the ^{24}Mg and ^{48}Ti$(n,\gamma)^{49}$Ti reaction as non-polarized γ-ray sources. The circular polarization of γ-rays from the reaction $n+p \rightarrow d+\gamma$ was found to be $P = -(1.30 \pm 0.45) \times 10^{-6}$

The Story Begins With...



A NEW EXPERIMENTAL STUDY OF THE CIRCULAR POLARIZATION OF np CAPTURE γ-RAYS

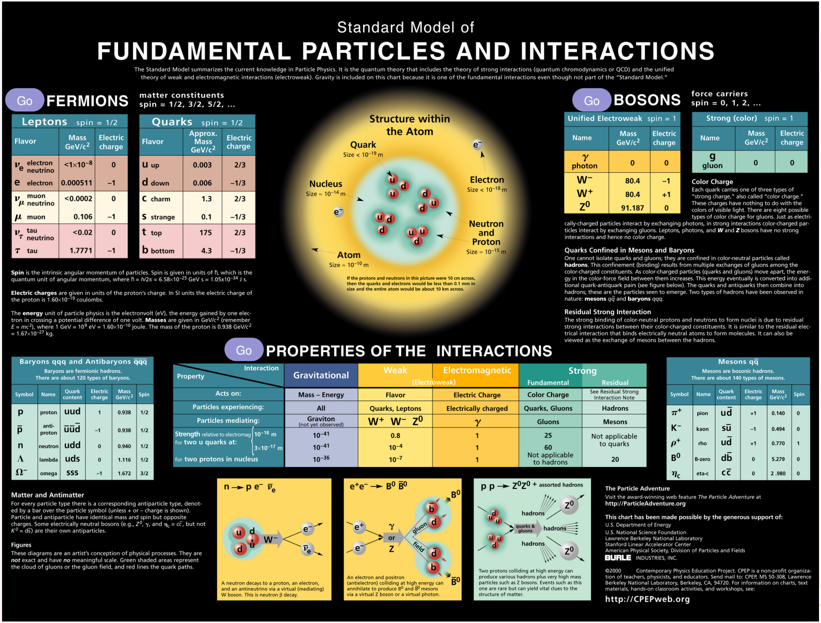
V.A. KNYAZ'KOV, E.A. KOLOMENSKII, V.M. LOBASHOV, V.A. NAZARENKO,
A.N. PIROZHKOV, A.I. SHABLII, E.V. SHUL'GINA, Y.V. SOBOLEV
and A.I. YEGOROV

Leningrad Nuclear Physics Institute, Academy of Sciences of the USSR, Leningrad, USSR

Received 1 August 1983

Abstract: An installation using a light-water neutron trap in the reactor core as a proton target is described. Results of the main and control measurements are presented which permit one to conclude that the parity-violating circular polarization of the γ-rays from the $np \to d\gamma$ reaction is $\boxed{P_\gamma = (1.8 \pm 1.8) \times 10^{-7}}$

Outline



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

Go

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

Structure within the Atom

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Go

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Go

PROPERTIES OF THE INTERACTIONS

Interaction / Property	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)	(Electroweak)	Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$

A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$

An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\, p \rightarrow Z^0 Z^0$ + assorted hadrons

Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
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Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
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Classification of Weak Interactions

Interaction	Charged		Neutral		Charged+Neutral	
Leptonic						
	(1)	$\mu \to e\nu\nu$ (2×10^{-5})	(4)	$\nu_\mu e \to \nu_\mu e$	(7)	$\nu_e e \to \nu_e e$ (10%)
	(2)	$\nu_\mu e \to \mu\nu_e$	(5)	$\bar{\nu}_\mu e \to \bar{\nu}_\mu e$	(8)	$\bar{\nu}_e e \to \bar{\nu}_e e$
	(3)	$\tau \to l\nu\nu$	(6)	$e^+e^- \to l^+l^-$	(9)	$e^+e^- \to \nu_e\bar{\nu}_e$
Semileptonic						
Meson	(10)	$\pi^+ \to \mu\nu,\ e\nu$ (2×10^{-4})				
		$K^+ \to \mu\nu,\ e\nu$				
		$F^+ \to \tau^+\nu$				
	(11)	$\pi^+ \to \pi^0 e\nu$				
	(12)	$K^+ \to \pi^0 l\nu$				
		$K^0_L \to \pi^\pm l\nu$				
	(13)	$D \to \begin{pmatrix}\pi \\ K \\ K^*\end{pmatrix} l\nu$				
Baryon	(14)	$\mu^- B \to B'\nu$	(17)	$\nu N \to \nu N,\ \nu N\pi,\ \nu X$		
	(15)	$B \to B' l\nu$	(18)	$\bar{\nu}_e + D \to n + p + \bar{\nu}_e$		
	(16)	$\nu B \to B' l$	(19)	$eN \to eN,\ eX$ (10%)		
Hadronic						
Meson	(20)	$K \to \pi\pi$ (1×10^{-3})				
	(21)	$K \to 3\pi$ (8×10^{-3})				
	(22)	$D \to KK,\ K\pi,\ K2\pi,\ K3\pi$				
	(23)	$B^{0,\pm} \to D\pi,\ DK$				
Baryon	(24)	$\Lambda \to N\pi$			(26)	$NN \to NN$ (10%)
		$\Sigma \to N\pi$				
		$\Xi \to N\pi$				
	(25)	$\Lambda_c^- \to pK^-\pi^+$				

Outline

Fact

Strong (and EM, too) interaction is omnipresent!

- Experimentally:
  - The signal-to-noise ratio $S/N \sim \frac{g_W^2}{M_W^2} \Big/ \frac{g_s^2}{m_\pi^2} \sim G_F\, m_\pi^2 \approx 10^{-7}$

$$\begin{aligned}
A_L^{\vec{p}+p}(45\,\mathrm{MeV}) &= (-1.57 \pm 0.23) \times 10^{-7} \\
A_L^{\vec{p}+\alpha}(46\,\mathrm{MeV}) &= (-3.34 \pm 0.93) \times 10^{-7} \\
P_\gamma^{^{18}\mathrm{F}}(1081\,\mathrm{keV}) &= (12 \pm 38) \times 10^{-5} \\
A_\gamma^{^{19}\mathrm{F}}(110\,\mathrm{keV}) &= (-7.4 \pm 1.9) \times 10^{-5} \\
A_L^{\vec{n}+^{137}\mathrm{La}}(0.734\,\mathrm{eV}) &= (9.8 \pm 0.3) \times 10^{-2} \\
A_\gamma^{^{180}\mathrm{Hf}}(501\,\mathrm{keV}) &= (-1.66 \pm 0.18) \times 10^{-2}
\end{aligned}$$

- Theoretically:
  - The non-perturbative QCD at low energies ▸ Go
  - The difficult nuclear many-body problems ▸ Go

Outline

Fundamental Weak Current in Flavor $SU(3)$

$$J_W = \cos\theta_C\, \bar{u}\gamma_\mu(1-\gamma_5)\,d + \sin\theta_C\, \bar{u}\gamma_\mu(1-\gamma_5)\,s$$

$$J_Z = \bar{u}\gamma_\mu(1-\gamma_5)\,u - \bar{d}\gamma_\mu(1-\gamma_5)\,d - \bar{s}\gamma_\mu(1-\gamma_5)\,s$$

Fundamental $\Delta S = 0$ q–q Interaction in Flavor $SU(3)$

$$\frac{G_F}{\sqrt{2}}\left[\cos^2\theta_C\, J_W^{I=1\,\dagger} J_W^{I=1} + \sin^2\theta_C\, J_W^{I=1/2\,\dagger} J_W^{I=1/2} + J_Z^{I=0,1\,\dagger} J_Z^{I=0,1}\right] + \text{H.c.}$$

1. $\Delta I = 0$: from $J_W^{1\,\dagger} J_W^{1}$, $J_Z^{I0\dagger} J_Z^{0}$ and $J_Z^{I1\dagger} J_Z^{1}$
2. $\Delta I = 1$: from $J_W^{1/2\,\dagger} J_W^{1/2}$, $J_Z^{I0\dagger} J_Z^{1}$ and $J_Z^{I1\dagger} J_Z^{0}$
3. $\Delta I = 2$: from $J_W^{1\,\dagger} J_W^{1}$ and $J_Z^{I1\dagger} J_Z^{1}$

Charged $\Delta I = 1$ is suppress by $\sin^2\theta \sim 1/25$, therefore $\Delta I = 1$ is dominated by NC (may not be the case for dressed quarks)

The Importance of $\Delta S = 0$ Hadronic Weak Interaction

- The only viable venue to observe the hadronic neutral current effect: FCNC is GIM suppressed ▸ Go
- Provide other touchstones for strong dynamics: How the strong interaction modify the above interaction? ▸ Go
- Complementary to the $\Delta S = 1$ sector: Any similar thing to the $\Delta I = 1/2$ rule? ▸ Go

Outline

The Search Program

1. Experiments: $O_{1\ldots N}$
   - Find nuclear PV observables, such as $A_L(\vec{x}, x)$, $\phi_{spin}(\vec{x}, \vec{x}')$, $P_\gamma(X, \vec{\gamma})$, $A_\gamma(\vec{X}, \gamma)$, or P-odd nuclear moments, such as anapole (measured in atomic PV) ▸ Go
2. Nuclear Theory: $O_{1\ldots N} = O_{1\ldots N}(C_{1\ldots M}) \rightarrow C_{1\ldots M} = C_{1\ldots M}(O_{1\ldots N})$
   - Identify the parameters (model-dep. or model-indep.) which determine the P-odd NN interaction
   - Need good nuclear structure and reaction calculations (few- and many-body) to interpret the experimental data
3. Hadronic Theory: $C_{1\ldots M} = C_{1\ldots M}(G_F)$
   - Link the nuclear parameters to the fundamental P-odd q–q interaction
   - Need good non-perturbative calculations (quark model, QCD sum rules, lattice QCD) to get theoretical predictions

If $C_{i\ldots M}(O_{1\ldots N})\big|_{phenomenology} \cong C_{i\ldots M}(G_F)\big|_{theory}$

Consistency is reached and the SM gains further success in $\Delta S = 0$ sector!

Outline

S-P Amplitudes: $\langle P|H_{\not{P}}|S\rangle$ (1st-order Born Approx.)

- **Basic idea:** At low energies, only S-wave and its P-wave admixture substantially contribute to observables (Danilov 65, 71), and there are 5 independent ones:

Transition	$I \leftrightarrow I'$	ΔI	n-n	n-p	p-p	Amp.	$E \longrightarrow 0$
${}^3S_1 \leftrightarrow {}^1P_1$	$0 \leftrightarrow 0$	0		$\surd$		u	λ_t
${}^1S_0 \leftrightarrow {}^3P_0$	$1 \leftrightarrow 1$	0	$\surd$	$\surd$	$\surd$	v^0	λ_s^0
		1	$\surd$		$\surd$	v^1	λ_s^1
		2	$\surd$	$\surd$	$\surd$	v^2	λ_s^2
${}^3S_1 \leftrightarrow {}^3P_1$	$0 \leftrightarrow 1$	1		$\surd$		w	ρ_t

- **Note:** The energy dependence is determined by strong phase shifts
- **Generalization:** Approximate finite nuclei as nuclear matter, and applying the Bethe-Goldstone eqn. to obtain an effective PV interaction for many-body problems (Desplanques and Missimer 78, 80)

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General Structure of *S*-*P* Amplitudes

$$
\begin{aligned}
f_{pp,nn}(\vec{Q},\vec{q}) &\propto v_{pp,nn}\,[R^{v}_{pp,nn}\,\vec{\sigma}_{-}\cdot\vec{Q}+\vec{\sigma}_{\times}\cdot\vec{q}]\\
f_{np}(\vec{Q},\vec{q}) &\propto v_{np}\,[R^{v}_{np}\,\vec{\sigma}_{-}\cdot\vec{Q}+\vec{\sigma}_{\times}\cdot\vec{q}]+u\,[R^{u}\,\vec{\sigma}_{-}\cdot\vec{Q}-\vec{\sigma}_{\times}\cdot\vec{q}]+w\,[R^{w}\,\vec{\sigma}_{+}\cdot\vec{Q}-\mathrm{P}^{\tau}_{12}\,\vec{\sigma}_{+}\cdot\vec{q}]
\end{aligned}
$$

The building blocks:

- Isospin: 1, $\vec{\tau}_1\cdot\vec{\tau}_2$, $\tau^z_+=(\tau^z_1+\tau^z_2)/2$, $\tau^z_-=(\tau^z_1-\tau^z_2)/2$, $\tau^z_\times=i(\vec{\tau}_1\times\vec{\tau}_2)^z$, and $\tau^{zz}=(3\tau^z_1\tau^z_2-\vec{\tau}_1\cdot\vec{\tau}_2)/2\sqrt{6}$
- Spin: $\vec{\sigma}_+=\vec{\sigma}_1+\vec{\sigma}_2$, $\vec{\sigma}_-=\vec{\sigma}_1-\vec{\sigma}_2$, $\vec{\sigma}_\times=i(\vec{\sigma}_1\times\vec{\sigma}_2)$
- Spatial: $\vec{p}_{1,2}$ and $\vec{p}\,'_{1,2}$

The symmetry considerations:

- Pseudoscalar: $\vec{\sigma}\cdot\vec{k}$ form (Hermitian, PV, ignore higher order in k)
- Permutation symmetry: $f(1,2)=f(2,1)$
- Translational invariance: out of three independent momenta from $\vec{p}_{1,2}$ and $\vec{p}\,'_{1,2}$, only $\vec{q}\equiv\vec{p}\,'_1-\vec{p}_1=\vec{p}_2-\vec{p}\,'_2$ and $\vec{Q}=(\vec{p}\,'_1+\vec{p}_1-\vec{p}\,'_2-\vec{p}_2)/2$ are allowed
- Time-reversal invariance: $\vec{q}\rightarrow\vec{q}$, $\vec{Q}\rightarrow-\vec{Q}$; $\langle\vec{\sigma}_{+,\times}\rangle\rightarrow\langle\vec{\sigma}_{+,\times}\rangle$, $\langle\vec{\sigma}_-\rangle\rightarrow-\langle\vec{\sigma}_-\rangle$

Note

5 amplitudes, each one has 2 independent structures ($5\times2=10$)

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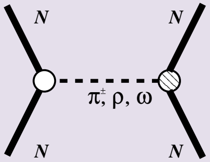
   - Analysis
5. Outlook and Summary
   - Outlook
   - Summary
   - Further Reading

Meson Exchange Picture

- **Building blocks**: nucleon, mesons (pseudo-scalar and vector), and their couplings
- **Basic assumption**: the $\not{P}$ physics, which is short-ranged, is buried inside the $\not{P}$ meson-nucleon couplings
- **Low-Energy**: light mesons with $m_x < 1$ GeV
- **Barton's Thm.**: *CP* conservation excludes scalar coupling to neutral pseudoscalar mesons (*C*-even *P*-odd)

OME with $\pi^{\pm}$, ρ, and ω



$2\, m_N \times H_{\not{P}}$ based on OME

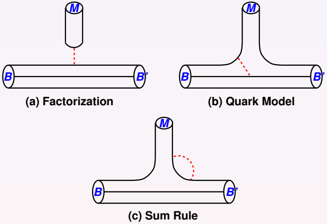
$$
\begin{aligned}
& g_\pi\, h^1_\pi/(2\sqrt{2})\, \tau^z_\times\, \vec{\sigma}_+ \cdot \vec{y}_{\pi-}(\vec{r}) \\
& - g_\rho\, (h^0_\rho\, \vec{\tau}_1 \cdot \vec{\tau}_2 + h^1_\rho\, \tau^z_+ + h^2_\rho \tau^{zz})\, (\vec{\sigma}_- \cdot \vec{y}_{\rho+} + \mu_\rho\, \vec{\sigma}_\times \cdot \vec{y}_{\rho-}) \\
& - g_\omega\, (h^0_\omega\, 1 + h^1_\omega\, \tau^z_+)\, (\vec{\sigma}_- \cdot \vec{y}_{\rho+} + \mu_\omega\, \vec{\sigma}_\times \cdot \vec{y}_{\rho-}) \\
& - (g_\omega\, h^1_\omega - g_\rho\, h^1_\rho)\, \tau^z_-\, \vec{\sigma}_+ \cdot \vec{y}_{\rho+} - g_\rho\, h'^1_\rho\, \vec{\sigma}_+ \cdot \vec{y}_{\rho-}
\end{aligned}
$$

with $\vec{y}_{x\pm}(\vec{r}) \equiv [\vec{p}_1 - \vec{p}_2\, , \mathrm{e}^{-m_x r}/(4\pi r)]_\pm$

Outline

Predictions for $\not{P}$ Meson-Nucleon Couplings

$\times 10^7$	DDH Range	Best	DZ	FCDH	KM
h_π^1	0.0↔ 11.4	4.6	1.1	2.7	0.2
h_ρ^0	-30.8↔ 11.4	-11.4	-8.4	-3.8	-3.7
h_ρ^1	-0.4↔ 0.0	-0.2	0.4	-0.4	-0.1
h_ρ^2	-11.0↔ 7.6	-9.5	-6.8	-6.8	-3.3
h_ω^0	-10.3↔ 5.7	-1.9	-3.8	-4.9	-6.2
h_ω^1	-1.9↔ 0.8	-1.1	-2.3	-2.3	-1.0
$h_\rho^{\prime 1}$		0.0			-2.2



(a) Factorization **(b) Quark Model**

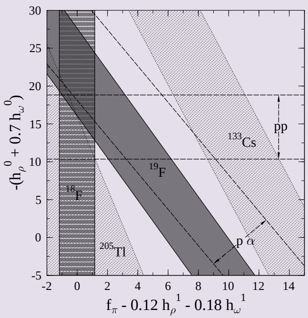
(c) Sum Rule

- Calculations by DDH, DZ, FCDH are based on quark models, KM used the chiral soliton model
- $h_\rho^{\prime 1}$ term is usually ignored, so leaving 6 $\not{P}$ couplings to be checked by exps.
- QCD sum rule calculations of h_π^1 give 3 $\times 10^{-7}$ (HHK 98, formerly 2×10^{-8}) and 3.4 $\times 10^{-7}$ (Lobov 02)
- Lattice QCD calculations of h_π^1 (should be similar to g_π but with a shorter range) are proposed (e.g. Beane and Savage: matching PQQCD to PQChPT)

Outline

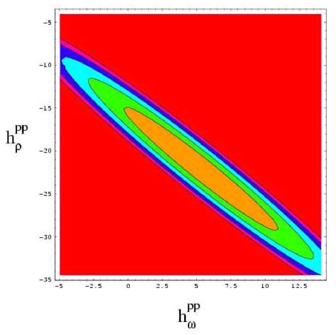
Two Major Puzzles

Is h_π^1 small?



The ^{18}F is performed by five different groups, the theoretical calculation (Haxton 85) is thought to be reliable(?)

Is $h_\omega \equiv h_\omega^0 + h_\omega^1$ positive?



$\vec{p}p$ scattering @ 13.6, 45, and 221 MeV where A_L depends on a linear combination of h_ρ and h_ω (Carlson et al. 02)

Outline

$H_{\not p}$ in EFT

In parallel to the success in the PC sector, the ChPT is extended to the PV sector at $O(Q)$ (Zhu et al. 04)
The benefits over or cure to the meson-exchange version include:

1. It's model-independent
2. It's completely general and exhibits the underlying symmetries
3. It has a systematic expansion scheme (power counting) and improvable

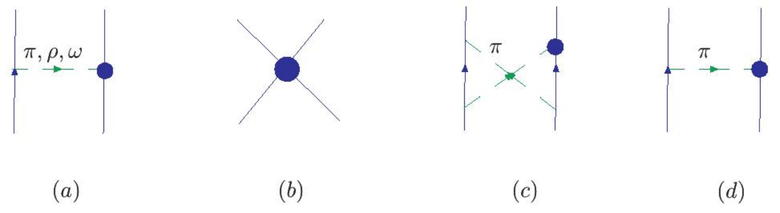
Basic ingredients:

- **Chiral symmetry**: $SU(2)_L \times SU(2)_R$ (massless quarks)
- **SSB**: $SU(2)_L \times SU(2)_R \to SU(2)_V$ (eight massless Goldstone bosons: π, K, and η)
- **Scales**: $\Lambda_{\chi SB} \sim m_N \sim m_\rho \sim 1\,\mathrm{GeV}$, $m_\pi \sim f_\pi \sim 100\,\mathrm{MeV}$, so expansions in terms of $Q/\Lambda_{\chi SB}$ and m_π/m_N converges well

Two Versions

The proposed form has two versions:

Pionless:	pions are integrated out, i.e. only (b) Good for low energies, interaction is short-ranged Has 10 LECs
Pionful:	pions are dynamical OPE provides some long-ranged interaction, (b)+(c)+(d)+... Introduces additional 3 couplings



$H_{\not{p}}$ in Pionless EFT

$$
\begin{aligned}
V_{\not{\pi}}^{\mathrm{PV}} = V_{1,\mathrm{SR}}^{\mathrm{PV}} &= 2/\Lambda_\chi^3 \\
&\times \Big\{ \left[C_1 + (C_2 + C_4)\,\tau_+^z + C_3\,\vec{\tau}_1\cdot\vec{\tau}_2 + C_5\,\tau^{zz} \right] \vec{\sigma}_-\cdot\vec{y}_{m+} \\
&+ \left[\widetilde{C}_1 + (\widetilde{C}_2 + \widetilde{C}_4)\,\tau_+^z + \widetilde{C}_3\,\vec{\tau}_1\cdot\vec{\tau}_2 + \widetilde{C}_5\,\tau^{zz} \right] \vec{\sigma}_\times\cdot\vec{y}_{m-} \\
&+ (C_2 - C_4)\,\tau_-^z\,\vec{\sigma}_+\cdot\vec{y}_{m+} + \widetilde{C}_6\,\tau_\times^z\,\vec{\sigma}_+\cdot\vec{y}_{m-} \Big\}
\end{aligned}
$$

- Overall, there are 10 LECs (too many!)
    - In ZRA, $\langle\vec{y}_{m+}\rangle = \langle\vec{y}_{m-}\rangle$, the 10 LECs can be effectively reduced into 5
    - If $\langle\vec{y}_{m+}\rangle/\langle\vec{y}_{m-}\rangle \equiv R(E) \approx R$, the 10-to-5 reduction can still be valid
- When $m \to \infty$, $\vec{y}_{m\pm} \to [\vec{p}_1 - \vec{p}_2\,,\, \delta(r)/r^2]_\pm$: the contact form
    - For calculations using realistic w.fs., $\delta(r)$ is softened (hybrid EFT, EFT*)
    - Taking $m = m_\rho$ and $\widetilde{C}_{1,2/3,4,5}/C_{1,2/3,4,5} = \mu_{\omega/\rho}$, $V_{1,\mathrm{SR}}^{\mathrm{PV}} \equiv V_{\rho+\omega}^{\mathrm{OME}}$, both have 6 independent parameters

$H_{\not{p}}$ in Pionful EFT

$$V^{\mathrm{PV}}_{\pi-\mathrm{ful}} = V^{\mathrm{PV}}_{-1,\mathrm{LR}} + V^{\mathrm{PV}}_{1,\mathrm{LR}} + V^{\mathrm{PV}}_{1,\mathrm{MR}} + V^{\mathrm{PV}}_{1,\mathrm{SR}}$$

- $V^{\mathrm{PV}}_{-1,\mathrm{LR}}$: the normal OPE one, depends on h^1_π
- $V^{\mathrm{PV}}_{1,\mathrm{LR}}$: from vertex corrections in both PC and PV parts with one new coupling k^{1a}_π [1] ▸ Go
- $V^{\mathrm{PV}}_{1,\mathrm{MR}}$: from TPE, depends on h^1_π, has non-analytic $\ln q/m_\pi$ terms ▸ Go
- $V^{\mathrm{PV}}_{1,\mathrm{SR}}$: similar structure to the pionless version, but LECs bear different meaning ▸ Go
- $V^{\mathrm{PV}}_{\pi-\mathrm{ful}}$ depends on the regularization scheme which shuffles some pion-exchange contributions into $V^{\mathrm{PV}}_{1,\mathrm{SR}}$.
- Most MECs are constrained by gauging the potential, with a transverse piece depending one a new coupling constant $\bar{c}_\pi$ [2] ▸ Go

---

[1] Redundant (Liu and Ramsey-Musolf)

[2] Suppressed by k/m_N (Liu)

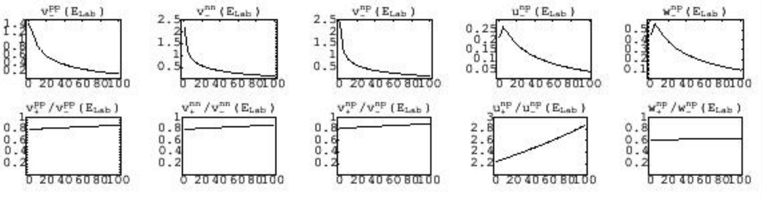
Outline

Reduction of 10-to-5 LECs

Fact

The condition $\langle \vec{y}_{m+} \rangle / \langle \vec{y}_{m-} \rangle \equiv R(E) \approx R$ has to be satisfied.

The results are (PRELIMINARY!):



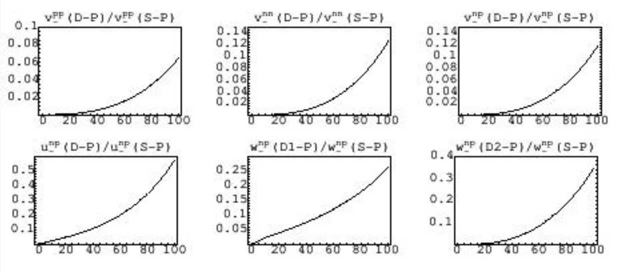
- For all v's and w, the constancy is excellent
- For u, if constrained to $E_{\text{Lab}} \lesssim 40\,\text{MeV}$, the variation is about 10% (acceptable)

Limit of 10-to-5 Reduction

Fact

At low energies, S-P amplitudes dominate which makes the reduction valid. But when D-P and F-P ones come into play, this will no longer be the case.

The results are (PRELIMINARY!):



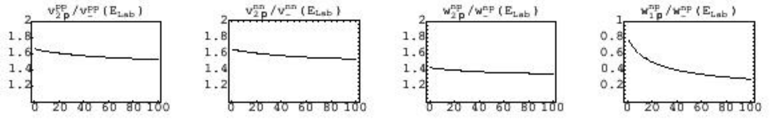
- For v's, the 10% correction enters at $E_{\text{Lab}} \approx 90\,\text{MeV}$ for np and nn, and even higher for pp (Coulomb barrier)
- The 10% correction enters at $E_{\text{Lab}} \approx 40, 60\,\text{MeV}$ for u and w respectively

Does Pionless EFT Really Make Sense?

Fact

It depends on whether pion contributions have roughly similar energy-dependence to the short-ranged interaction

The results are (PRELIMINARY!):



Conclusion

- While TPE tracks with the SR interaction very well, OPE does not.
- The OPE part has to be singled out independently.
- Overall, six parameters are needed for low energies.
- As long as *S*-*P* amps. dominate, EFT$\doteq$OME?

Outline

Few-body PV Observables

Goal

Have at least 6 low-energy measurements which are linearly-independent enough, and apply the analysis in the EFT framework

Observables	Theory (PRELIMINARY!) ★	Experiment ($\times 10^7$)
$A_L^{\vec{p}p}(13.6\,\mathrm{MeV})$	$-2.48\,\bar{\lambda}_s^{pp}$	-0.93 ± 0.21
$A_L^{\vec{p}p}(45\,\mathrm{MeV})$	$-4.48\,\bar{\lambda}_s^{pp}$	-1.57 ± 0.23
$\frac{d}{dz}\phi_n^{\vec{n}p}(\mathrm{th.})$	$1.44\,\bar{\lambda}_s^{np} + 0.08\,\bar{\lambda}_t + 0.36\,\bar{\rho}_t + 0.57\,C^{1\pi}$	SNS
$P_\gamma^{np}(\mathrm{th.})$	$-0.93\,\bar{\lambda}_s^{np} - 0.98\,\bar{\lambda}_t$	(1.8 ± 1.8), SNS?
$A_L^{\vec{\gamma}d}(1.32\,\mathrm{keV})$	Same as above	HIGS? IASA? Spring-8?
$A_\gamma^{\vec{n}p}(\mathrm{th.})$ ***	$-0.29\,\bar{\rho}_t - 0.57\,C^{1\pi}$	LANSCE, SNS
$A_\gamma^{\vec{n}d}(\mathrm{th.})$	To be improved	(0.6 ± 2.1), SNS?
$A_L^{\vec{p}\alpha}(46\,\mathrm{MeV})$	To be improved	-3.3 ± 0.9
$\frac{d}{dz}\phi_n^{\vec{n}\alpha}(\mathrm{th.})$	To be improved	(8 ± 14), NIST, SNS

*** Will be a unique determination of h_π^1!?

★ All LECs are not in usual convention!

Outline

In Conclusion:

- The strangeness-conserving hadronic weak interaction is the last piece of the jigsaw for a complete test of the standard electroweak theory; at the same time, it provides another window for examining strong interaction dynamics which is complementary to purely PC observables or its strangeness-non-conserving counterpart.
- An EFT formulation of PV nucleon-nucleon interaction anticipates six independent parameters for the low-energy processes in which S-P amplitudes dominate the observables.
- Theory and experiment of nuclear few-body physics are mature enough to make new progress, and one will see if a more consistent picture will result from these efforts.

Outline

For More Details and References:

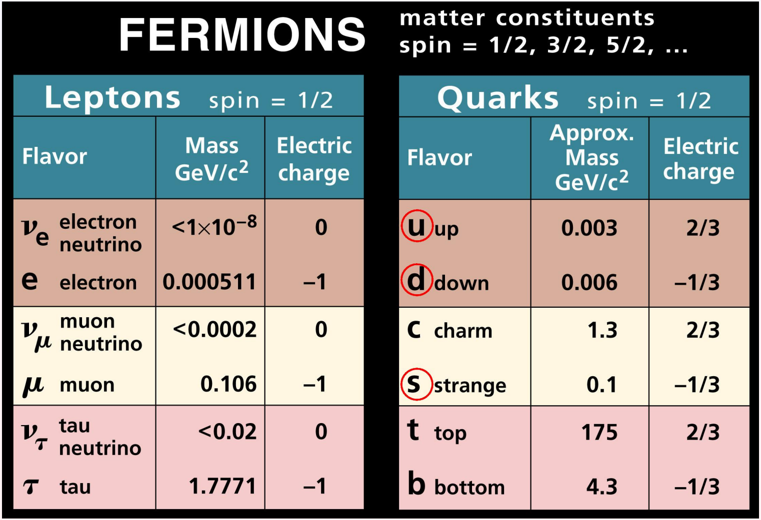
E.G. Adelberger and W.C. Haxton
Ann. Rev. Nucl. Part. Sci. 35, 501–558 (1985).

W. Haeberli and B.R. Holstein
in *Symmetries and Fundamental Interactions in Nuclei* (eds. W.C. Haxton and E.M. Henley), World Scientific, Singapore (1995), pp. 17–66.

B. Desplanques
Phys. Rep. 297, 1–61 (1998).

M.J. Ramsey-Musolf and S.A. Page
hep-ph/0601127.

B.R. Holstein
Weak Interactions in Nuclei, Princeton Univ. Press, Princeton (1989).



FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	−1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	−1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	−1

Quarks spin = 1/2

Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	−1/3
c	charm	1.3	2/3
s	strange	0.1	−1/3
t	top	175	2/3
b	bottom	4.3	−1/3

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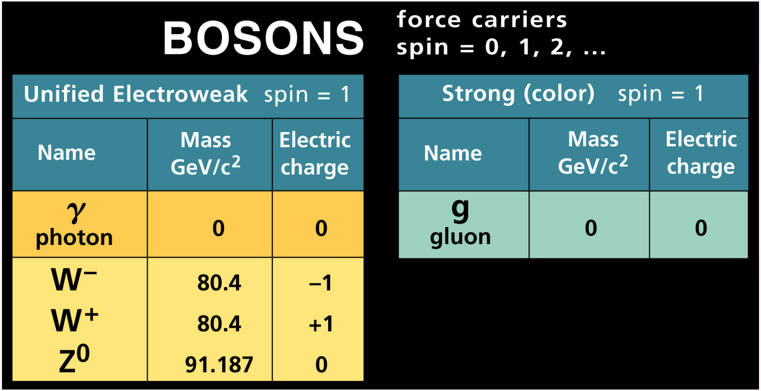

BOSONS

force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1		
Name	**Mass GeV/c^2**	**Electric charge**
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	**Mass GeV/c^2**	**Electric charge**
g gluon	0	0

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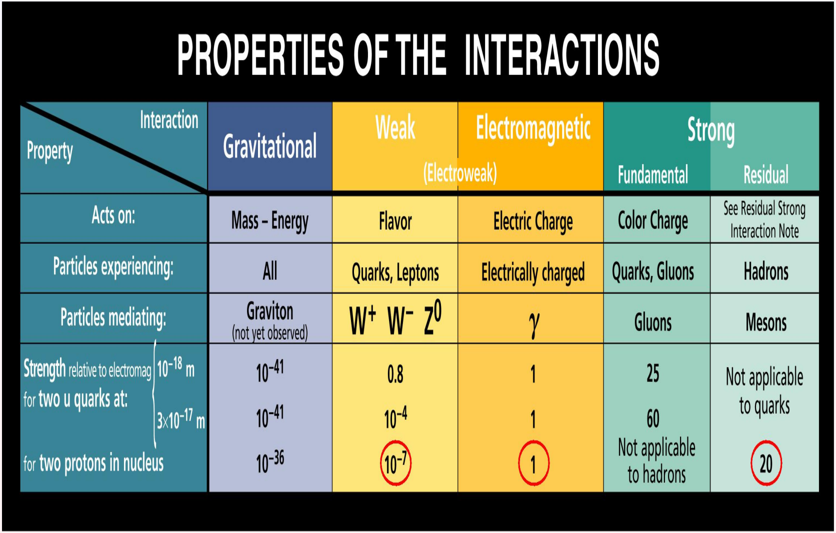


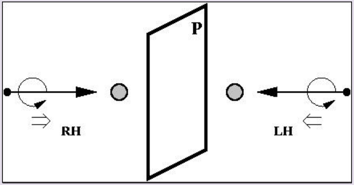
PROPERTIES OF THE INTERACTIONS

Interaction Property	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
$3{\times}10^{-17}$ m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

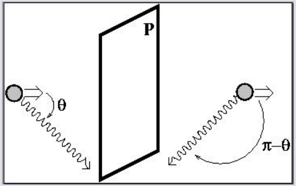
Return

Generic Parity-Violating Observables

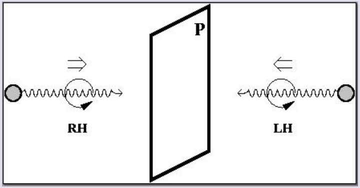
Longitudinal Asymmety



Photon Asymmetry



Circular Polarization



EM Moments

J	CJ	EJ	MJ
0	PT		
1	$\not{P}\not{T}$	$\not{P}T$	PT
2	PT	$P\not{T}$	$\not{P}\not{T}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$

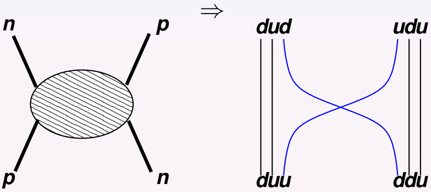
* $C1$: EDM, $M2$: MQM

* $E1$: Anapole

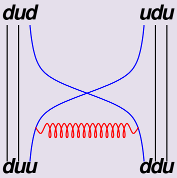
Return

N–*N* Interactions in Terms of *q*–*q* Interactions

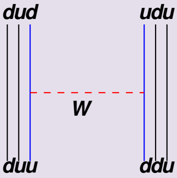
How to calculate $\langle n,p|V_{NN}|p,n\rangle = \langle n,p|(\bar{q}'_1\,\Gamma_1\,q_1)\,G(q)\,(\bar{q}'_2\,\Gamma_2\,q_2)|n,p\rangle$?



Parity-Conserving

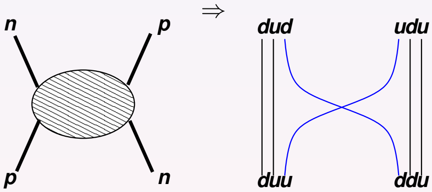


Parity-Violating

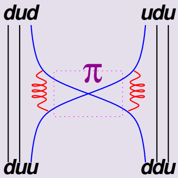


N–N Interactions in Terms of q–q Interactions

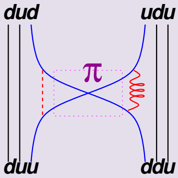
How to calculate $\langle n,p|V_{NN}|p,n\rangle = \langle n,p|(\bar{q}_1'\,\Gamma_1 q_1)\,G(q)\,(\bar{q}_2'\,\Gamma_2 q_2)|n,p\rangle$?



Parity-Conserving



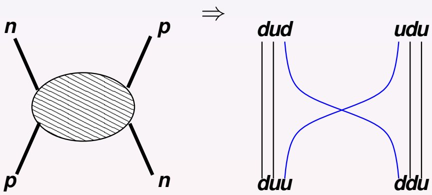
Parity-Violating



Return

N–N Interactions in Terms of q–q Interactions

How to calculate $\langle n,p|V_{NN}|p,n\rangle = \langle n,p|(\bar{q}'_1\,\Gamma_1\,q_1)\,G(q)\,(\bar{q}'_2\,\Gamma_2\,q_2)|n,p\rangle$?



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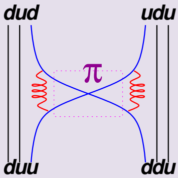
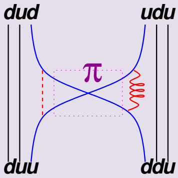


Parity-Violating



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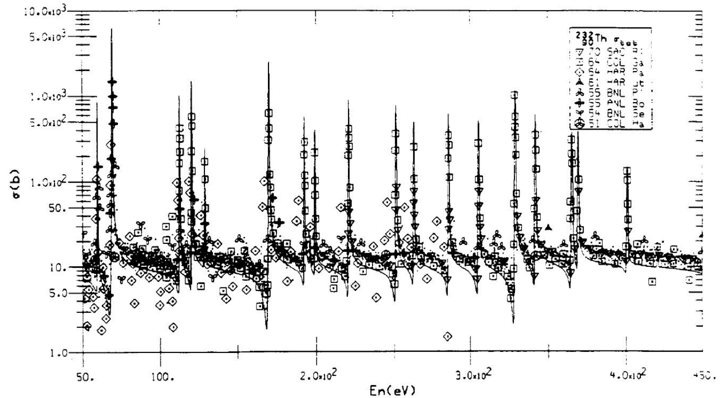
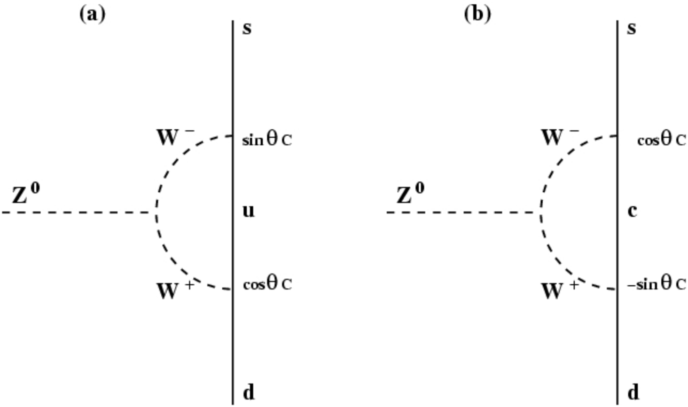


Figure 2 Total cross section of ^{232}Th + n as a function of neutron energy (8a).

Return

Glashow–Iliopoulos–Maiani Mechanism



- (a)+(b) $\propto \sin\theta_C \cos\theta_C - \cos\theta_C \sin\theta_C = 0$, anticipate the charm quark!

Return

$\Delta I = 1/2$ Rule

Example ($\Lambda \longrightarrow N + \pi$ decay)

- $\Gamma(p+\pi^-)/\Gamma_{tot} = (63.9 \pm 0.5)\%, \quad \Gamma(n+\pi^0)/\Gamma_{tot} = (35.8 \pm 0.5)\%$
- $\langle(\frac{1}{2},\frac{1}{2}),(1,-1)|\frac{1}{2},-\frac{1}{2}\rangle^2/\langle(\frac{1}{2},-\frac{1}{2}),(1,0)|\frac{1}{2},-\frac{1}{2}\rangle^2 = 2$
- $\langle(\frac{1}{2},\frac{1}{2}),(1,-1)|\frac{3}{2},-\frac{1}{2}\rangle^2/\langle(\frac{1}{2},-\frac{1}{2}),(1,0)|\frac{3}{2},-\frac{1}{2}\rangle^2 = 1/2$

Therefore, $\Delta I = 1/2$ channel dominates the transition

Qualitatively understood, but not fully from the first principle

◂ Return

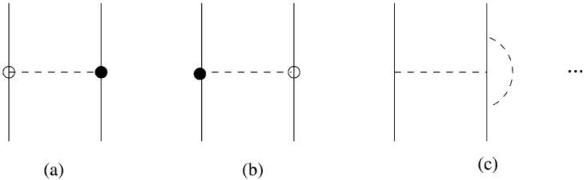


Fig. 4. Corrections to the long-range PV NN potential from insertions of (a), (b) higher-order PC πNN terms, which are denoted by the unfilled circle, and (c) loops.

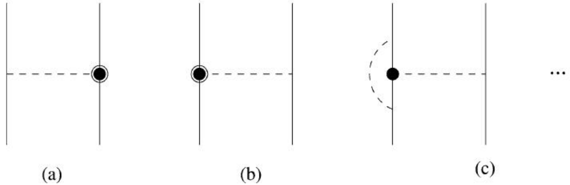


Fig. 5. Corrections to the long-range PV NN potential from insertions of (a), (b) higher-order PV πNN terms, which are denoted by the circled filled circle, and (c) loops.

Return

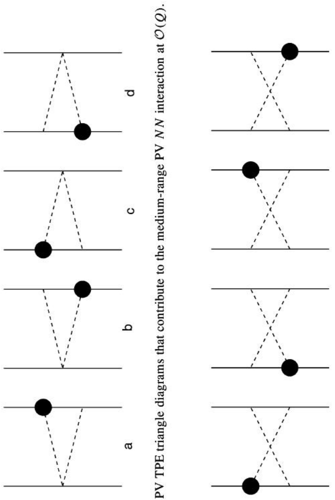


Fig. 8. PV TPE triangle diagrams that contribute to the medium-range PV NN interaction at $\mathcal{O}(Q)$.

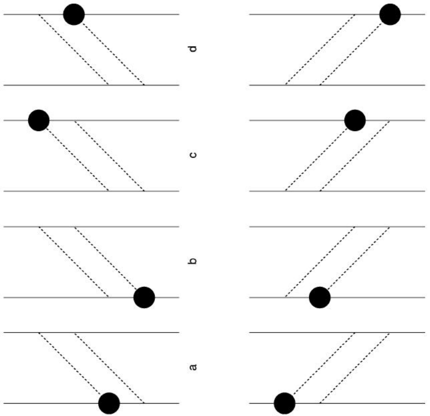


Fig. 9. PV TPE crossed diagrams that contribute to the medium-range PV NN interaction at $\mathcal{O}(Q)$.

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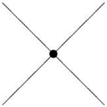

Fig. 6. PV NN contact interactions that contribute to the PV short-range potential.

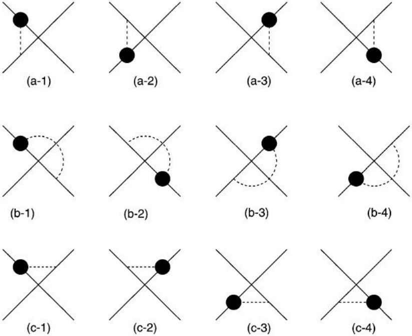

Fig. 7. Possible PV chiral corrections to PC NN couplings $C_{S,T}$.

Return

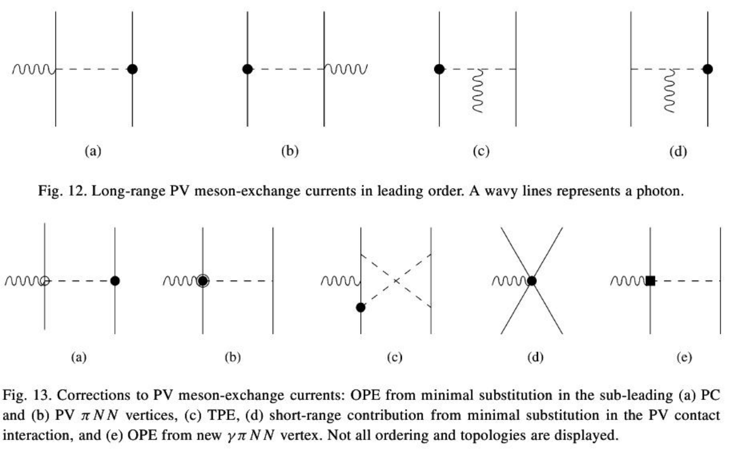

Fig. 12. Long-range PV meson-exchange currents in leading order. A wavy lines represents a photon.

Fig. 13. Corrections to PV meson-exchange currents: OPE from minimal substitution in the sub-leading (a) PC and (b) PV πNN vertices, (c) TPE, (d) short-range contribution from minimal substitution in the PV contact interaction, and (e) OPE from new $\gamma\pi NN$ vertex. Not all ordering and topologies are displayed.

Return