CP Violation, Baryon Oscillations, and Baryogenesis

work with David McKeen, arXiv:1512.05359
and in progress with Kyle Aitken, David McKeen, Thomas Neder
See also Seyda Ipek, David McKeen, A.E.N., arXiv:1407.8193
Akshay Ghalsasi, David McKeen, A.E.N., arXiv:1508.05392

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CPV beyond the Standard Model

• Needed to produce early universe asymmetry of $10^{-8}$ between quarks and anti-quarks? (baryogenesis)

• Effects of CKM phase in early universe highly suppressed by small mixing angles and mass differences.

• non standard CPV

or

• non standard enhancement of standard CPV
Particle Oscillations

- Quantum interference due to coherent superposition of particles with slightly different masses
- Production conserves some *approximate* symmetry
- Observed in neutrinos (lepton flavor oscillations), neutral K, D, B mesons (particle-anti-particle oscillations)
- Masses must be near degenerate-
  - Wave packet propagation must be similar enough so spatial separation does not occur over an oscillation time
  - Oscillation time must not be too fast or too slow or oscillations not observable
CPV in Oscillations

- CP Violation: amplitude depends on CP odd phase in Hamiltonian and CP even phase in propagation

- \[ |A(i \rightarrow f)|^2 \neq |A(i_{CP} \rightarrow f_{CP})|^2 \]

- **without decays**, CPV in oscillations requires oscillations between 3 states
  - (this kind of CPV has not yet been observed)

- increasing hints of CPV in \( \nu \) flavor oscillations
Oscillations among 2 states can only violate CP when they are unstable.

CPT: \[ \text{Prob}(A \rightarrow A) = \text{Prob}(\bar{A} \rightarrow \bar{A}) \]

Unitarity: \[ \text{Prob}(A \rightarrow A) + \text{Prob}(A \rightarrow \bar{A}) = 1 \]
\[ \text{Prob}(\bar{A} \rightarrow \bar{A}) + \text{Prob}(\bar{A} \rightarrow A) = 1 \]

So \[ \text{Prob}(\bar{A} \rightarrow A) = \text{Prob}(A \rightarrow \bar{A}) \]
CPV in oscillations of unstable states

- Only requires 2 oscillating states
- Observed in neutral kaon anti-kaon and neutral B meson-anti-B meson oscillations
- Large effect possible when oscillation and decay rates comparable

$O(1)!$
Pseudo-Dirac Fermion Oscillation: Two state system, similar to neutral mesons

- pseudo-Dirac fermions have 4 states, but mix in 2 x 2 blocks:
  - Charge+, spin ↑ can oscillate into Charge -, spin ↑
  - Charge+, spin ↓ can oscillate into Charge -, spin ↓
  - Rotational invariance (in rest frame) guarantees that these 2 x 2 blocks have same effective Hamiltonian
CPT and rotation constraints

- CPT: exchanges spin $\uparrow$ particle in initial state with spin $\downarrow$ anti particle in final state
- can rotate spin
- $H_{\text{eff}}$ must have form:
  $\begin{pmatrix}
  m_D - i\Gamma/2 & m_{12} - i\Gamma_{12}/2 \\
  m^*_{12} - i\Gamma^{*}_{12}/2 & m_D - i\Gamma/2
  \end{pmatrix}$
- Can work in basis with $m_{12}$ real
- looks exactly like neutral meson $H_{\text{eff}}$
- CPV phase difference between $m_{12}$ and $\Gamma_{12}$
CPV in Fermion particle—anti-particle oscillations

• Requires a *Pseudo Dirac Fermion*: massive, carries *approximately* conserved charge, can *oscillate* into own anti-particle as well as decay, requires common final state in decays of particle and anti-particle

• fermion particle-anti-particle oscillations have never been observed

• SM candidates: neutron, other neutral baryons

• BSM candidates: Mesino, pseudo-Dirac gluino, neutralino
Neutron Oscillations

• Dim 9 $\Delta B=2$ operator $\frac{1}{\Lambda^5} uddudd$

• Oscillations between equal energy states at rate which is linear in operator

• free neutron oscillation rate bound: $\tau > 10^8$ s

• Bound neutrons, or neutrons in an external field: split in $n$ $\bar{n}$ energies $\rightarrow$ rate is quadratic in operator. $10^8$ s $\rightarrow 10^{40}$ s

• comparable (marginally stronger) bounds on operator from dinucleon decay (SuperKamiondande)

• $\Lambda \sim PeV$ $\langle \bar{n} | \frac{1}{\Lambda^5} uddudd | n \rangle < 10^{-25} eV$
CPV in neutron oscillations?

\[ H = \begin{pmatrix} m_n - \frac{i}{2} \Gamma_n & M_{12} - \frac{i}{2} \Gamma_{12} \\ M_{12}^* - \frac{i}{2} \Gamma_{12}^* & m_n - \frac{i}{2} \Gamma_n \end{pmatrix} \]

\[
\frac{P_{|n\rangle \rightarrow |\bar{n}\rangle}}{P_{|\bar{n}\rangle \rightarrow |n\rangle}} - 1 = \frac{2 \Im (M_{12} \Gamma_{12}^*)}{|M_{12}|^2 - |\Gamma_{12}|^2 / 4 - \Re (M_{12} \Gamma_{12}^*)}
\]

Origin of \( M_{12} \):
\[
\frac{1}{\Lambda^5} uddudd
\]

Origin of \( \Gamma_{12} \):
\[
\frac{1}{\Lambda^8} udduud\tilde{\nu}
\]
or new fermion(s) \( \chi \)
938 MeV Neutral Majorana Fermion?

- Proton stability: $m_p - m_e < M_\chi$
- $M_\chi < m_n \rightarrow \Gamma_{12} > 0$
- $Z_2$ subgroup of baryon number $\rightarrow$ stable dark matter candidate if $M_\chi < m_p + m_e$

$$\Gamma_{12} = \frac{\mu^2 m_n^2 m_\chi}{16\pi} \left(1 - \frac{m_\chi^2}{m_n^2}\right)^3$$

$$M_{12} \sim \left(\frac{\kappa g y}{m_\phi^2}\right)^2 \frac{m_\chi}{m_n^2 - m_\chi^2}$$
Do not expect to see CPV in $n\bar{n}$ oscillations

- Restrictive Kinematics: $\Delta M = M_n - M_\chi < \text{MeV}$ (proton stability)

$$\frac{P_{\langle n \rangle \rightarrow \langle \bar{n} \rangle}}{P_{\langle \bar{n} \rangle \rightarrow \langle n \rangle}} - 1 \propto \frac{|\Gamma_{12}|}{|M_{12}|} \lesssim 10^{-14} \left( \frac{\Delta M}{1 \text{ MeV}} \right)^4$$
Other neutral baryons?

• What constraints on baryon violating operators containing heavy flavors?

• For $\Delta B=2, \Delta s=1,2,3$ operators dinucleon decay into 1,2,3 kaons is almost as constraining as neutron oscillations.

• $\Delta B=2, \Delta s=4$: $\Xi^0-\Xi^0$ oscillations? $\Omega \rightarrow \bar{p} K$? Not looked for.

• $\Delta B=2, \Delta c=2, \Delta b=2$: heavy flavor baryon oscillations $bcd \rightarrow \bar{b} \bar{c} \bar{d}$
  • not looked for

• Conceivable to look for oscillations of neutral charmed baryons at Belle II
Constraints from weak flavor violation

- Do constraints from $n \bar{n}$ make other flavors of $\Delta B=2$ unobservable?

- Operators involving right-handed (SU(2) singlet) quarks much less constrained

- Kuzmin (1996) $bsu \rightarrow \bar{b}SU$ baryon oscillations from RPV could be as fast as decay!
Di-nucleon decay constraints

\[
\frac{1}{\Lambda^5} \text{bus} \rightarrow \left( \frac{g^2 V_{ub} V_{ud} m_b \Lambda_{QCD}}{16\pi^2 M_W^2} \right)^2 \left( \frac{1}{\Lambda^5} \text{dus} \right)
\]

- dinucleon → kaons constraints similar to neutron oscillation constraints
- bus baryon allowed to oscillate at \( \sim 10^{18} \) faster rate than neutron: \( 10^{-10} \) s
Model for CPV in heavy flavor baryon oscillation

- same model as in “mesino oscillation” model arXiv:1508.05392, different parameters ($\chi$ lighter than heavy flavor baryon)

- “RPV SUSY-lite”

- New particles:
  - Neutral Majorana fermions $\chi_i$, $i=1,2,\ldots$, mass~few GeV
  - charge $-1/3$ colored scalar $\phi$, mass $>\sim 650$ GeV
  - low energy effective theory: \[ \frac{\alpha_{ij}y_{k\ell}}{m_{\phi}^2} \bar{d}_i \bar{u}_j \bar{d}_k \chi_\ell \]

Dinucleon decay constraints on combinations of $\alpha_{11}, \alpha_{21}, y_{1k}, y_{2k}$
CPV in heavy flavor oscillations

• oscillation rate in neutral heavy flavor baryons could be $10^{-2} - 10^{-3}$ times decay rate, when 2 weak interactions required to convert operator to one producing dinucleon decay

• $\Gamma_{12}$ not kinematically suppressed, could be $\sim 10^{-1} M_{12}$

• could this be CPV be observable, and directly related to baryogenesis?
Baryogenesis?

• CPV in Baryon oscillations fulfills 2/3 Sakharov conditions

• Heavy flavor baryons out of equilibrium in early universe via long lived $\chi$ decay when early universe has temperature between $\sim 1$ and 200 MeV

• Some of the baryons will undergo CPV oscillations before they decay.
Summary

\[ \frac{\alpha_{ij} y_{k \ell}}{m^2_{\phi}} \bar{d}_i \bar{u}_j \bar{d}_k \chi_{\ell} \]

- Low energy effective theory with neutral Majorana fermions $\chi$ with baryon violating couplings for heavy flavored quarks
- Stability of matter $\rightarrow$ lightest $\chi$ satisfies $m_p - m_e < M_{\chi}$
- Stable dark matter candidate if lightest $\chi$ satisfies $M_{\chi} < m_p + m_e$
- $n \, \bar{n}$ oscillations consistent with heavy flavor baryon oscillations with $\tau \sim 10^{-10}$ s
- CPV in heavy flavor baryon oscillations (requires at least one $\chi$ to be lighter than the heavy flavor baryon (need $\Gamma_{12}$))
- Low energy baryogenesis? (requires 1 long lived $\chi$)