Title: 13/14 PSI - Explorations in Particle Theory - Lecture 12

Date: Apr 23, 2014 09:00 AM

URL: http://pirsa.org/14040069

Abstract:

Last time:

Pseudo-Goldstone field oscillation could give DM if

- vacuum at $t \gg t_{osc}$ $\neq$ vacuum at $t \sim t_{osc}$
- osc starts relatively late ($T_{osc} \lesssim T_{\text{w}} \ll f$)

Correction: $\rho_{osc}(t_{osc}) = \frac{1}{2} f_a^2 m_a^2(t_{osc}) \times \mathcal{O}(1)$

Yesterday, took $t_{osc} = t(\Lambda_G)$

↳ but actually, can start a bit earlier

$$m_a(t_{osc})\, t_{osc} = 1$$

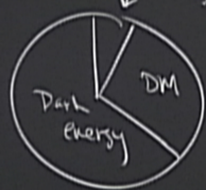
QCD: $m_a(T) \approx 4 \times 10^{-18}\,\text{GeV} \left(\frac{10^{12}\,\text{GeV}}{f_a}\right)\left(\frac{\text{GeV}}{T}\right)^4$ for $T \gtrsim \Lambda_{QCD}$

$$\Omega_{DM} \approx 0.25 \left(\frac{f_{QCD}}{10^{11}\,\text{GeV}}\right)^{7/6}$$

XII Intro to Baryogenesis

10^{11} GeV

XII Intro to Baryogenesis



$\Omega_b \approx 0.05$

$e^{i\theta} \to e^{i\alpha/3}$

$Y_B = \frac{n_B}{s} \sim 10^{-10} = \frac{n_B - n_{\bar{B}}}{s}$

What are baryons?

$U(1)_B$: all quarks have charge $+\frac{1}{3}$

($\bar{q}$ have $B = -\frac{1}{3}$)

$\mathcal{L}_{quark} = \bar{Q}\gamma^\mu D_\mu Q + H\bar{Q}_L Q_R$

Bound states of q: $p, n \Rightarrow B = 1$
uud udd

Have only baryons (cosmologically) and not antibaryons.

$B_{tot} = 3(n_q - n_{\bar{q}}) \neq 0$

We have inflation $\xrightarrow[\text{universe}]{\text{"resets"}}$ $B_{tot} = 0$ at T_{RH}

Baryogenesis: physical process that allows

$B_{tot} = 0 \longrightarrow B_{tot} \neq 0$

Roadmap

① Evidence for baryon asymmetry

② Sakharov conditions for baryogenesis

① Evidence

a) Obvious → we exist → we only observe matter

True astrophysically, $\Phi_{\bar{p}} \ll \Phi_p$

b) What if we are in a domain of baryons?

→ no evidence for large-scale $p\bar{p}$ ann. astrophysically

c) Domains $> H^{-1}$

- current Hubble patch comes from many causally disconnected region

→ inflation : dilutes the n_B/s before inflation

*possible

Roadmap

① Evidence for baryon asymmetry

② Sakharov conditions for baryogenesis

① Evidence

a) Obvious → we exist → we only observe matter

True astrophysically, $\Phi_{\bar p}$ vs Φ_p $\ll$

b) What if we are in a domain of baryons?

→ no evidence for large-scale $p\bar p$ ann. astrophysically

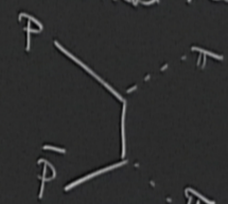
c) Domains $> H^{-1}$

• current Hubble patch comes from many causally disconnected region

→ inflation: dilutes the n_B/s before inflation

* possible

d) Thermal freeze-out



• huge $\langle \sigma v \rangle$

$\Omega_B \sim 10^{-12}$

* something kicks in @ $T \gtrsim 25$ MeV

② Sakharov Conditions for Baryogenesis

1) Violation of $U(1)_B$

2) CP violation
   - CP transformation maps particles $\longrightarrow$ antiparticles

3) Departure from thermal equilibrium

$$\frac{dx}{dt} = 0$$

1) $\cancel{B}$:

$$B_{tot} = 3(n_q - n_{\bar{q}})$$
$$= \text{constant}$$
if $U(1)_B$ is exact

we need

0 baryon #

n baryon #

2) $\cancel{CP}$:

2) $\cancel{CP}$:

CP : particles $\longleftrightarrow$ antiparticles.

C: charge conj, P: parity

Consider a Weyl fermion

$$\psi_\alpha \xrightarrow[\text{complex conj.}]{\text{antiparticle}} \psi^\dagger_{\dot{a}}$$

$$e^{i\theta} \qquad\qquad e^{-i\theta}$$

$$\Psi = \begin{pmatrix} \psi \\ \chi^\dagger \end{pmatrix}$$

$C: \psi \to \chi$

$P: \psi \to \chi^\dagger$

$CP: \psi \to \psi^\dagger$

Break CP:

$$\sigma_{prod}(\psi) \neq \sigma_{prod}(\psi^\dagger)$$

$\Rightarrow B = 1$

ud udd

CP: related Hermitian conjugation of fields

→ need complex parameters in Lagrangian

Processes in Feynman rules for $\chi^\dagger$ are just complex conjugate of Feynman rules for χ

It's a bit subtle

→ write Lag. in a particular basis

vs.

σ_{phys} are basis-independent

ex. Scalar field (complex)
real

$$V(\Phi) = \underset{\text{real}}{m^2} |\Phi|^2 + \lambda |\Phi|^4 + g\Phi^4 + h.c.$$

→ no evidence for large-scale $p\bar{p}$ ann. astrophysically

$\bar{p}$ ... π

$\Omega_B \sim 10^{-12}$

- Any coeff of a "real" field term

$\bar{\psi}\psi$, $|\Phi|^2$

→ no phase

General case: $g = |g| e^{i\theta}$

BUT: Re-define $\Phi \to e^{-i\theta/4} \Phi$

$V(\Phi) = \text{real} + \ldots |g| \Phi^4$

$\equiv$ Purely real

$$V(\Phi) = m^2 |\Phi|^2 + \lambda |\Phi|^4 + g \Phi^4 + \mu \Phi^2 + h.c.$$

→ 2 complex params: g, μ

→ 1 possible field re-def.

$|\mu| e^{i\alpha} e^{-i\theta/2} \Phi^2$

α is a physical phase

$\alpha - \frac{\theta}{2}$

$\Phi = \phi_1 + i\phi_2$

${}^4 + h.c.$

Now, assume we have some CP phases

$\longrightarrow$ how does this give $\sigma_\psi - \sigma_{\psi^+} \neq 0$

Define $M \equiv M(\psi\ \text{prod})$ CP conj processes

$\tilde{M} = M(\psi^+_{\text{prod}})$

Conjecture that $M = \tilde{M}^*$ wrong

Define $M = M_1 e^{i\phi}$

1 process : 1 matrix element

$|M|^2 = |M_1 e^{i\phi}|^2 = \text{real}\ M_1^2$

$|\tilde{M}|^2 = |M_1 e^{-i\phi}|^2 = M_1^2$

$\sigma_\psi = \sigma_{\psi^+}$ $\times$

lesson #1 : need $\gtrsim 2$ terms in matrix element

1 process : 1 matrix element

$$|M|^2 = |M_1 e^{i\phi}|^2 = \text{real} \; M_1^2$$

$$|\tilde{M}|^2 = |M_1 e^{-i\phi}|^2 = M_1^2$$

$$\bar{\sigma}_\gamma = \sigma_\gamma + X$$

Lesson #1: need $\gtrsim 2$ terms in matrix element

$$M = M_1 e^{i\phi_1} + M_2 e^{i\phi_2} + \dots$$

$$|M|^2 = M_1^2 + M_2^2 + 2\,\mathrm{Re}\left(M_1 M_2 e^{i(\phi_1-\phi_2)}\right)$$

$$= \text{ind} + 2 M_1 M_2 \cos(\phi_1-\phi_2)$$

$$\tilde{M} = M_1 e^{-i\phi_1} + M_2 e^{-i\phi_2}$$

$$|\tilde{M}|^2 = M_1^2 + M_2^2 + 2 M_1 M_2 \cos(\phi_1-\phi_2)$$

$$\bar{\sigma}_\gamma = \sigma_\gamma + X$$ NO CPV

$$M(\text{1st proc}) \neq \tilde{M}$$

$$M = M_1 e^{i\phi_1} + M_2 e^{i\phi_2} + \ldots\ldots$$

$$|M|^2 = M_1^2 + M_2^2 + 2\,\mathrm{Re}\left(M_1 M_2 e^{i(\phi_1-\phi_2)}\right)$$

$$= \phi\ \text{ind} + 2 M_1 M_2 \cos(\phi_1-\phi_2)$$

$$\tilde{M} = M_1 e^{-i\phi_1} + M_2 e^{-i\phi_2}$$

$$|\tilde{M}|^2 = M_1^2 + M_2^2 + 2 M_1 M_2 \cos(\phi_1-\phi_2)$$

$$\sigma_\gamma = \sigma_\gamma^+ \quad \otimes$$ NO CPV

$$M(\gamma\ \text{prod}) \neq \tilde{M}(\gamma^+\ \text{prod})^*$$

Answer: couplings, etc in Feynman diagram are complex conj.

* extra phase that is SAME for $M, \tilde{M}$

$$M = M_1 e^{i\phi_1 + i\theta} + M_2$$

$$\tilde{M} = M_1 e^{-i\phi_1 + \theta_1} + M_2$$

$$\boxed{\sigma_\gamma - \sigma_{\gamma}^+ = -2 M_1 M_2 \sin\theta_1 \sin\phi_1}$$

$$= \cancel{\phi}\text{ ind} + 2M_1M_2\cos(\phi_1-\phi_2)$$

$$\tilde{M} = M_1e^{-i\phi_1} + M_2e^{-i\phi_2}$$

$$|\tilde{M}|^2 = M_1^2 + M_2^2 + 2M_1M_2\cos(\phi_1-\phi_2)$$

$$\sigma_\gamma = \sigma_\gamma^+ \quad \otimes \text{ NO CPV}$$

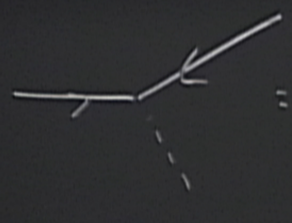
$\ast$ extra phase that is $\underline{\underline{\text{SAME}}}$ for $M, \tilde{M}$

$$M = M_1e^{i\phi_1+i\theta_1} + M_2$$

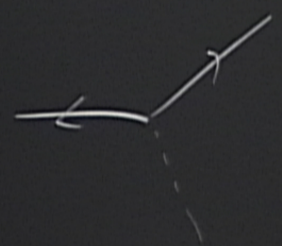
$$\tilde{M} = M_1 \underbrace{e^{-i\phi_1+\theta_1}}_{\text{CP-odd}} + \underbrace{M_2}_{\text{CP-even}}$$

$$\boxed{\sigma_\gamma - \sigma_\gamma^+ = -2M_1M_2\sin\theta_1\sin\phi_1}$$

couplings are CP-odd phases

 $= \lambda$

CP
trans
conjugate
coupling

 $= \lambda^*$

How do we get CP-even phase?

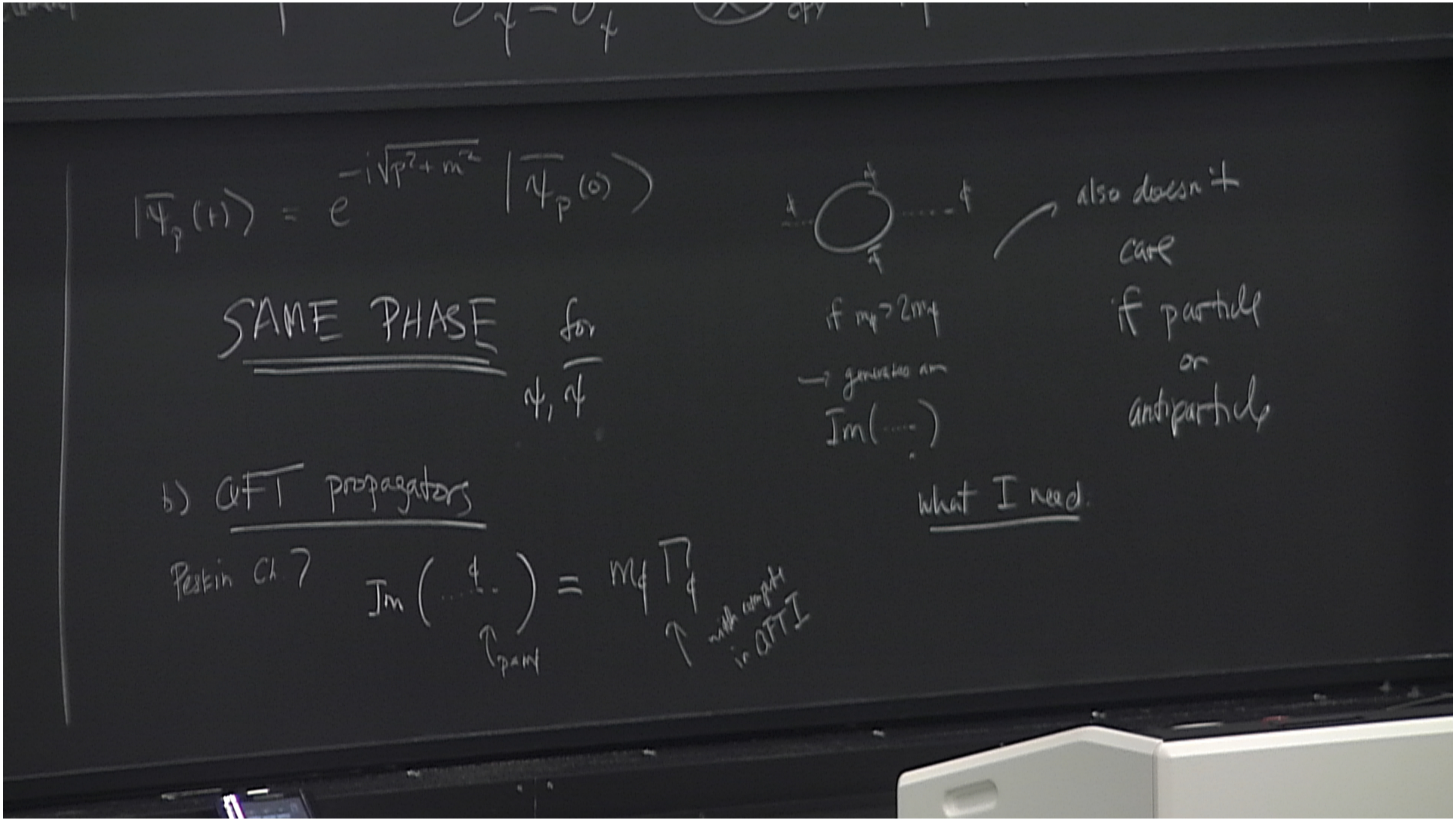
→ quantum mechanics

$$\frac{d}{dt}|\psi\rangle = -iH|\psi\rangle$$

a) Time evolution operator
of mass m, momentum p

$$|\psi_p(t)\rangle = e^{-i\sqrt{p^2+m^2}\,t}\,|\psi_p(0)\rangle$$

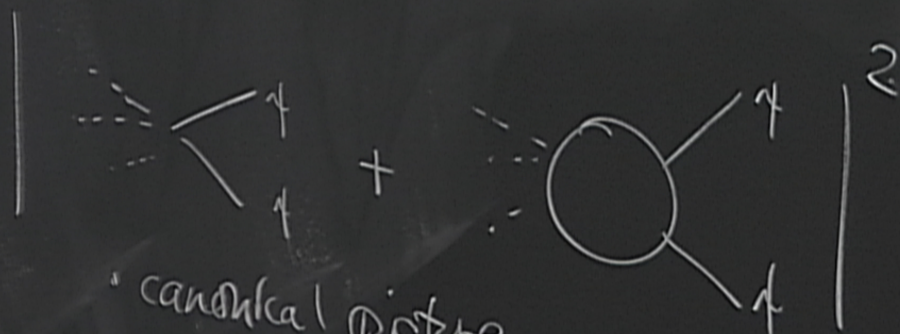
$|\bar{\psi}_p(t)\rangle =$


$|\Psi_p(t)\rangle = e^{-i\sqrt{p^2+m^2}}\,|\Psi_p(0)\rangle$
SAME PHASE for $\psi, \bar{\psi}$
b) QFT propagators
Peskin Ch 7
$\mathrm{Im}(\ldots) = m_\phi \Gamma_\phi$
pair
with complete in QFT I
if $m_\phi > 2m_\psi$
→ generates an $\mathrm{Im}(\ldots)$
what I need.
also doesn't care if particle or antiparticle

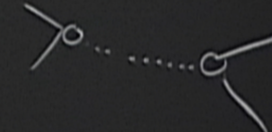
I need for $C\cancel{P}$:

1) Interference of 2 terms $\quad \frac{1}{p^2 - m_{\phi_1}^2 + i m_{\phi_1}\Gamma_1} \quad \frac{1}{p^2 - m_{\phi_2}^2 + i m_{\phi_2}\Gamma_2}$

2) CP-even phase → loop, time evolution, ...



$\sim C\cancel{P}$



"canonical picture"