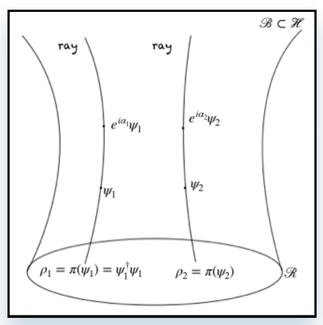
Expressing CP Violation in Terms of Bargmann Invariants and Geometric Phases in Kaon Decays and Baryogenesis

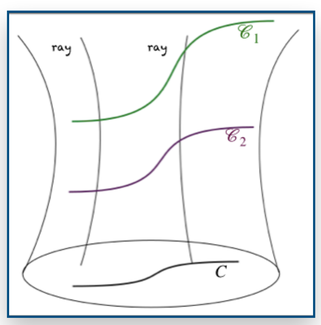
ID #711

Swarup Sangiri[1] , Utpal Sarkar[2]

1 Department of Physics, Indian Institute of Technology Kharagpur 2 Indian Institute of Science Education and Research Kolkata

Geometric Phase and Bargmann Invariant





Geometric Phase $\phi_g[C] = \phi_{tot}[\mathscr{C}] - \phi_{dyn}[\mathscr{C}]$

$$\phi_{tot}[\mathscr{C}] = arg(\psi(s_1), \psi(s_2)) \qquad \phi_{dyn}[\mathscr{C}] = Im\int_{s_1}^{s_2} ds(\psi(s), \frac{d}{ds}\psi(s))$$

$$\phi_g[free\ geodesic\ in\ \mathscr{R}] = 0$$

Bargmann Invariant

$$\Delta_3(\psi_1, \psi_2, \psi_3) = (\psi_1, \psi_2)(\psi_2, \psi_3)(\psi_3, \psi_1) = Tr(\rho_1\rho_2\rho_3)$$

$\phi_g[n - vertex\ polygon\ in\ \mathscr{R}\ connecting\ \rho_1\ to\ \rho_2,\ \rho_2\ to\ \rho_3, \ldots,$
$\rho_m\ to\ \rho_1\ by\ free\ geodesics] = -arg\Delta_m(\psi_1, \psi_2, \ldots, \psi_m)$

Connecting BIs to CP Violating Phase δ

$$|K_L\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}(|K_2\rangle + \epsilon|K_1\rangle) \qquad |K_S\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}(|K_1\rangle + \epsilon|K_2\rangle)$$

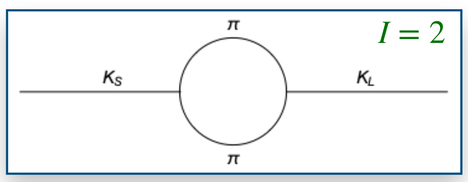
$$\Delta_3(K_L, K_S, K_1) + \Delta_3(K_L, K_S, K_2) = \frac{4(Re\{\epsilon\})^2}{(1+|\epsilon|^2)^2} = \delta^2$$

CP Violating Phase $\delta = \dfrac{2Re\{\epsilon\}}{1+|\epsilon|^2}$ $\quad \epsilon \neq 0 \Rightarrow$ ***CP violation***

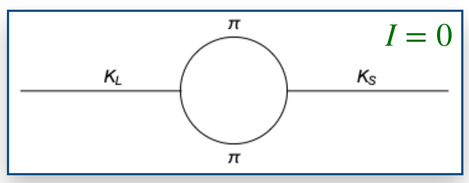
$\epsilon \approx 10^{-3}$

Bargmann Invariant for Kaon Decay

Mixing of K_S and K_L Through Pions



$K_S \to (\pi\pi)_2 \to K_L$



$K_L \to (\pi\pi)_0 \to K_S$

$$\Delta_4(K_a, (\pi\pi)_j, K_b, (\pi\pi)_i) = (K_a, (\pi\pi)_j)((\pi\pi)_j, K_b)(K_b, (\pi\pi)_i)((\pi\pi)_i, K_a)$$
$$= Tr[\rho(K_a)\rho((\pi\pi)_j)\rho(K_b)\rho((\pi\pi)_i)]$$
$$= f^*_{aj}f_{bj}f^*_{bi}f_{ai}$$

$J = Im(V_{22}V_{13}V^*_{23}V^*_{12})$
Quark level Jarlskog invariant

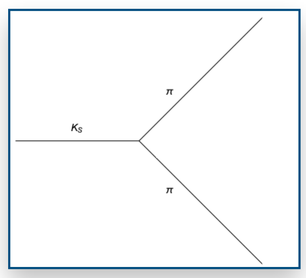
$f^*_{aj}f_{bj}f^*_{bi}f_{ai}I_{ab}$
Rephasing invariant

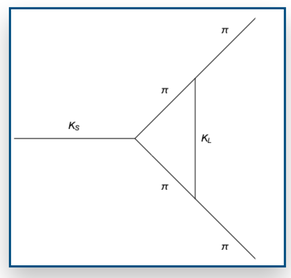
AIM

- To connect the CP violating parameters appearing in neutral kaon decay, oscillation and Baryogenesis to the Bargmann invariants and hence geometric phases in the effective field theory; establishing the *geometric origin of CP violation.*

Bargmann Invariant for Kaon Decay

One Loop Vertex Correction to the Tree Level



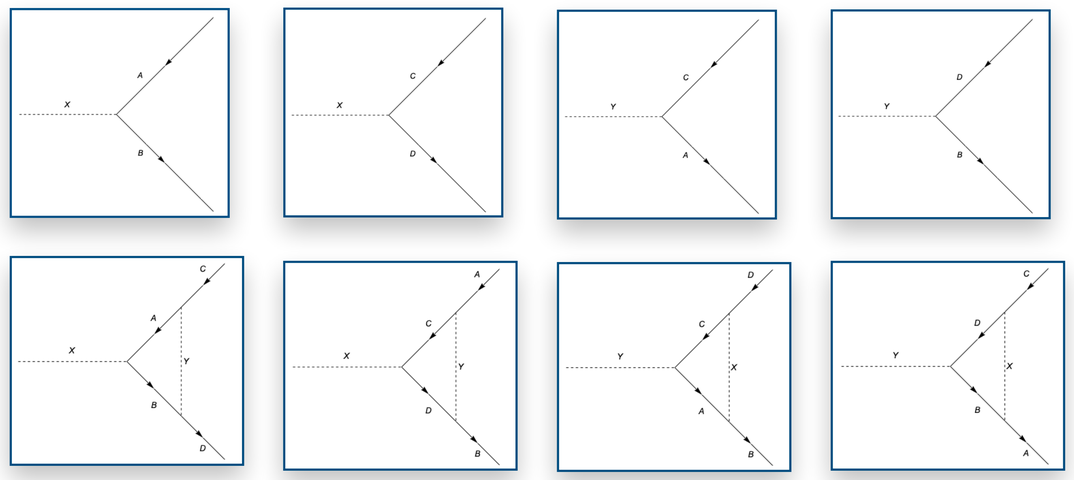


$$\Delta_4(K_a, (\pi\pi)_i, K_b, (\pi\pi)_j) = f^*_{ai}f_{bi}f^*_{bj}f_{aj}$$

$\Delta_4 \Rightarrow$ Rephasing invariant measure of CP violation

$$\phi_g = -arg(\Delta_4)$$

Bargmann Invariants in the Theory of Baryogenesis



Rephasing invariant

$$\delta_B = f^*_{1a*b}f_{1cd*}f^*_{2ac*}f_{2b*d}$$

$$|R_L\rangle = |R_2\rangle + \delta_B|R_1\rangle$$
$$|R_S\rangle = |R_1\rangle + \delta_B|R_2\rangle$$

Net baryon number produced in the decay of X and Y

$$\Delta B \propto Im(\delta_B)$$

$$R_1 = B^\dagger A; R_2 = D^\dagger C$$
$$(R_1, R_j) = \delta_{ij}$$

$$\Delta_3(R_L, R_S, R_1) - \Delta_3(R_L, R_S, R_2) = 4iRe(\delta_B)Im(\delta_B)$$

$$\Delta_3(R_L, R_S, R_1) - \Delta_3(R_L, R_S, R_2) \propto \Delta B$$

Summary

- We have constructed the Bargmann invariants for kaon decay and oscillation from effective meson field theory, without going into the quark level.
- We have then shown the connection between the BIs and the CP violating phases of those systems.
- This connection, in turn, has shown the relation between geometric phases of the system with the CP violating phases, hence the geometric origin of CP violation.
- A similar connection has been shown for the XY model of Baryogenesis.

Acknowledgement

We would like to thank Prof. Arghya Taraphder, IIT Kharagpur for his encouragement. S.S. would like to thank Indian Institute of Technology Kharagpur, India and Ministry of Education, India.

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Email - swarup.phys@gmail.com