In mid-May 1950,

just 59 years ago,

we met in Sarov.

Next 4 years, I

worked by him ...

Symmetry Breaking at Phase Transitions

D.V. SHIRKOV

Bogoliubov Lab, JINR, Dubna

SC-IV, 20 May 09

What is the Symmetry

that breaks at

Phase Transition ?

Motivation

- Spontaneous Symmetry Breaking;
  From magnetics to Quantum Statistics
- Broken Symmetries in Quantum Field Theory

and . . . . . . Nobel Prize in Physics 2008

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- Spontaneous Symmetry Breaking;
  From magnetics to Quantum Statistics
- Broken Symmetries in Quantum Field Theory
  and . . . . . . Nobel Prize in Physics 2008
- What is the (broken) Symmetry
  - of a physical system ?
  - of the physical problem ?

Phase transition and broken symmetry

Connection btwn Phase transition and symmetry breaking was evident before the QM creation –> e.g., from physics of crystals

Landau 1937 theory of phase transitions :

- starts with Introduction in Symmetries,

Phase transition and broken symmetry

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Landau 1937 theory of phase transitions :

- starts with Introduction in Symmetries,
- but, only discrete symmetries :
- on SuperFluidity – “He II is not a liquid crystal !”

Meanwhile, Landau’s “Mechanics”(1937/40) is based upon continuous symmetries, invariance and conservation laws.

Symmetries and groups

Symmetries and groups : discrete and continuous.

Continuous group –> Lie group of transformations.

Lagrangian –> Invariance –> Nöther theorem –> current –> conservation law.

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Quantum Symmetries :

- Non-relativistic 2nd-quantized neutral field Phase transformation= $a \to e^{-i\alpha} a, \;\; a^* \to e^{i\alpha} a^*$ –> N = const. Conserving Number of particles
- Charged (2-, 3-component) field; Gauge=phase transformation –> Current; Charge conservation

Quantum Symmetries

Qu-Symmetries: Phase, Gauge, Chiral, SuSy,

Qu-Symmetries are quite different from "Classical" ones, like spatial (boosts, rotations, Lorentz) and internal (isospin, flavor) ones.

For their formulation and understanding one has to use quantum notions :

* unobservability of the ψ-function phase;
* spin, chirality ;
* difference btwn Bose– and Fermi–statistics.

Bogoliubov model for SF He II

Bogoliubov 1946 microscopic theory – non-ideal

$$H_{\mathrm{B-gas}} = \sum_{\vec{p}} \frac{p^2}{2m} a_p^+ a_p + \frac{1}{2V} \sum v(p_1 - p_2) a_{p_1}^+ a_{p_2}^+ a_{p_2} a_{p_1} \; ;$$

Bose gas with weak repulsion $v(p) > 0$.

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The Hamiltonian has $\boxed{a \to e^{-i\alpha} a, \; a^* \to e^{i\alpha} a^* \; =}$

phase symmetry –> No of particles conservation,

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Bogoliubov's physical hypothesis:

"macroscopic condensate" $\mathbf{N_{p=0} = a_0^+ \, a_0} \sim \mathrm{N_A}$

Corollary: condensate operators $a_0^+, a_0 \sim \sqrt{N_0} =$ c-numbers

Bogoliubov SuperFlu model

Shift $\boxed{\psi(\mathbf{x}) = \mathbf{\Psi_0} + \phi(\mathbf{x})}$ by “big” constant $\Psi_0 \sim \sqrt{N_0}$ results in bilinear approximate Hamiltonian

$$\mathbf{H_{Bog}} = \sum_{\mathbf{p}\neq\mathbf{0}} \left(\frac{\mathbf{p^2}}{\mathbf{2m}} + \frac{\mathbf{N_0}}{\mathbf{V}} \mathbf{v}(\mathbf{p}) \right) \mathbf{b}^+_{\mathbf{p}} \mathbf{b}_{\mathbf{p}}, \; + \; \frac{N_0}{2V} \sum_{p\neq 0} v(p) [b^+_p b^+_{-p} + b_p b_{-p}]$$

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with b^+_p, b_p – "above-condensate" Bose-operators.

$\mathrm{H_{Bog}}$ describes creation of pairs of Helium atoms with opposite momenta from condensate and their "annihilation" into condensate.

Interaction btwn pairs is small $\sim N_0^{-1/2}$ and omitted.

Total No of these correlated pairs is not fixed.

Symmetry of Bogoliubov SF model

$$H_{\text{Bog}} = \sum_{p \neq 0} \left(\frac{p^2}{2m} + \frac{N_0}{V} v(p) \right) b_p^+ b_p +$$

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Violates phase invariance

$$\boxed{b \to e^{-i\phi}\, b \,,\; b^+ \to e^{i\phi}\, b^+}$$

due to non-conservation of number of above-condensate particles (responsible for the phase transition);

Bogoliubov SF Hamiltonian *

$$H_{\rm Bog} = \frac{N_0}{2V} \sum_{p \neq 0} v(p) [b_p^+ b_{-p}^+ + b_p b_{-p}] + \sum_{p \neq 0} \left(\frac{p^2}{2m} + \frac{N_0}{V} v(p) \right) b_p^+ b_p,$$

Diagonalized by Bogoliubov (u, v) transformation

$$\boxed{\xi_p = u_p b_p + v_p b_{-p}^+ = U_\alpha^{-1} b_p U_\alpha; \quad \xi_p^+ = u_p b_p^+ + v_p b_{-p}\,.}$$

$$U_\alpha = e^{\sum_p \alpha(p)\,[b_p^+ b_{-p}^+ - b_p b_{-p}]}; \quad \alpha(p) = f[\epsilon(p), g(p)].$$

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New ground state and its exitations, like

$$\Psi_0^{\text{Bog}} \sim e^{\sum_p \alpha(p)\, b_p^+ b_{-p}^+}\ \Psi_0\,;\ \ \Psi_1^{\text{Bog}}(k) = \xi_k^+\ \Psi_0^{\text{Bog}}\,,\ \ldots$$

contain superposition of indefinite number of He II atom pairs with opposite momenta.

Bogoliubov – Landau spectrum *

Resulting Hamiltonian

$$H = E_0 + \sum_{p \neq 0} E(p)\, \xi_p^+\, \xi_p\,, \qquad E(p) = \sqrt{\left(\frac{p^2}{2m}\right)^2 + \frac{p^2}{2m}\, v(p)}$$

describes collective excitations = coherent

superposition of correlated pairs with total zero mom.

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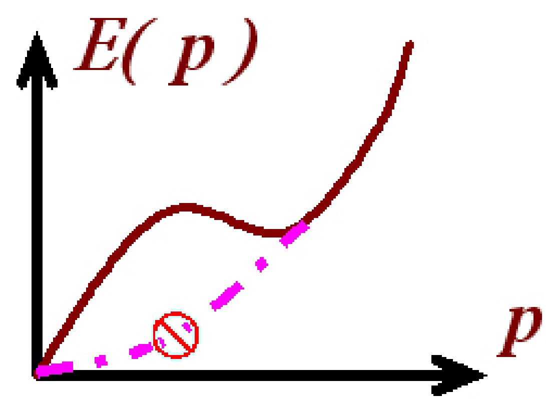
describes collective excitations = coherent superposition of correlated pairs with total zero mom.

$$E(p \to 0) = c\,p;\;\; c = \sqrt{\frac{v(0)}{m}}$$

like, e.g. $\quad v(p) \sim \frac{sin(a\,p)}{a\,p}$



The spectrum joints phonons and “rotons”.

Phase symmetry breaking in SF state

Initial Hamiltonian $H_{B-g}(a_p^+ \, , a_p)$ for normal states $< a_p >= 0$ is invariant with respect to the

Gauge (phase) transformation $a_p \longrightarrow a_p \, e^{i \, \varphi}$ (PhT)

related to conservation of particles number $< a_p^+ a_p >= n_p \, .$

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The bilinear Bog's model Hamiltonian $H_{\mathrm{Bog}}(b_p^+ ,\, b_p)$, as well as the (u, v) canonical transformation, is not compatible with PhT.

Physically, this corresponds to non-conserved number of relevant above-condensate particles.

Symmetry in SuperConductivity ?

– Along with S.Weinberg (2007) :

“BCS SuperCond $\longrightarrow$ Gauge symmetry $\longrightarrow$ Charge conserving violated.”

– Which Symmetry is Broken indeed in SC ?

1. In Ginzburg-Landau (1950) phenomenological theory ? :

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1. In Ginzburg-Landau (1950) phenomenological theory ? :

There, $\Psi(r)$ - effective classic function =

2-component order parameter $\Psi(r) = |\Psi(r)| e^{i\Phi(r)}$
entering free energy functional

$$F = F_n + \int \left(\frac{\hbar}{2m^*} |\vec{\nabla}\Psi(r)|^2 + A\,|\Psi(r)|^2 + b|\Psi(r)|^4 \right) dV$$

with $A \sim T - T_c\,,$ changing sign at $T = T_c$

(and $b\,, m^*$ – not depending on temperature T .)

Ginzburg-Landau [1950] Macro SuperConductivity

$\Psi(r) \sim$ 2-component order parameter – for SC transition – in Free energy functional

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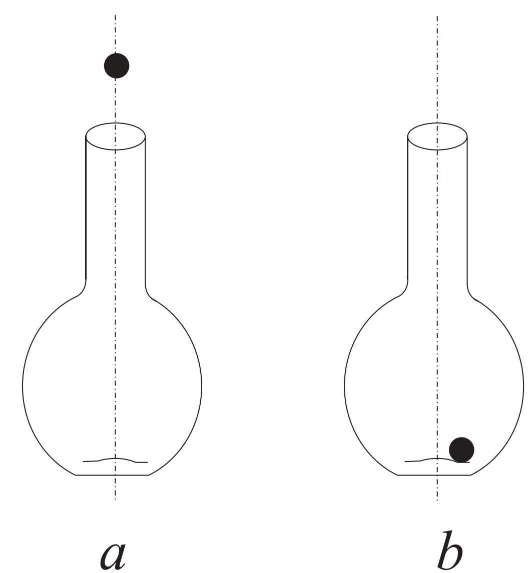
Effective potential

$V(|\Psi|) = A\,|\Psi|^2 + b|\Psi|^4$.

corresponds to Fig.1. The G-L Symmetry is like of the Champagne bottle with convex bottom



Symmetry in BCS+Bogoliubov SC

What symmetry is broken in BCS+Bogoliubov SC ?

(not Gauge one, related to Electric charge conservation !)

to Remind :

- Symmetry in Bog's SuperFlu = Phase factor Symm. SSB related to non-conservation of correlated pairs of He II atoms responsible for Phenomenon

to Announce :

- In BCS and Bog's it's broken Phase Symmetry
- In BCS – non-phase-symm trial ψ_{BCS} function.
- broken Phase Symmetry in Bog's SC –

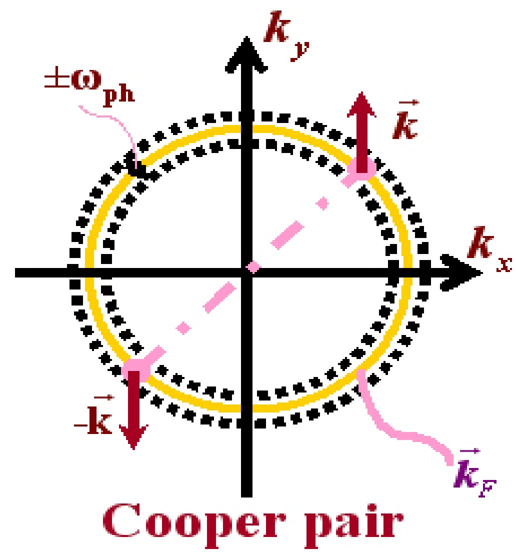
  due to non-conservation of Cooper pairs No.

BSC SuperConductivity

BCS model: $H = T + H_{BCS}$

$$H = \sum_{\vec{k},\sigma} \varepsilon_{\vec{k}}\, c^{+}_{\vec{k}\sigma} c_{\vec{k}\sigma} + \sum_{\vec{k},\vec{k}'} V_{\vec{k},\vec{k}'}\, c^{+}_{\vec{k}\uparrow} c^{+}_{-\vec{k}\downarrow} c_{-\vec{k}'\downarrow} c_{\vec{k}'\uparrow}\,,$$

- eff. Cooper pairs (antipodes) attraction $\varepsilon_{\vec{k}} = \frac{\vec{k}^2}{2m} - \varepsilon_F$ - electron energy above ε_F



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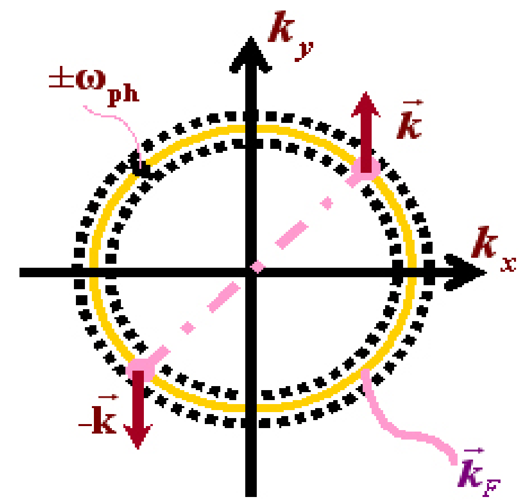

Effective electron attraction in the vicinity of Fermi surface

$$V(\vec{k},\vec{k}') = \begin{cases} -V_C, & |\varepsilon_{\vec{k}} - \varepsilon_{\vec{k}'}| < \omega_{ph} \\ 0, & |\varepsilon_{\vec{k}} - \varepsilon_{\vec{k}'}| > \omega_{ph} \end{cases}$$

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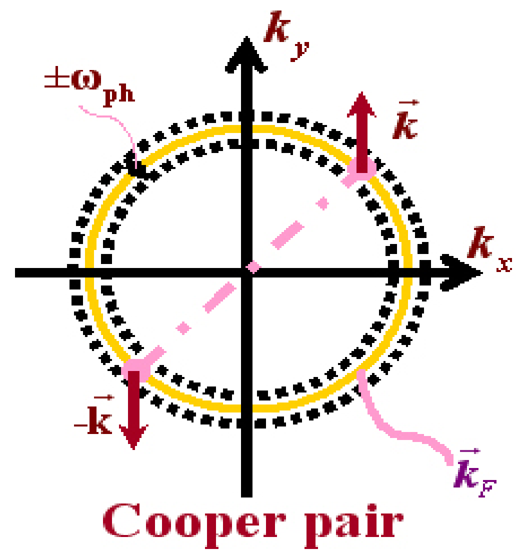

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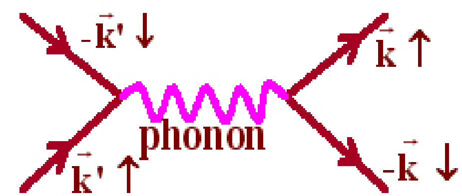
Trial BCS function $\Phi_0^{\mathrm{BCS}} = \prod_{\vec{k},\sigma} \left(u_k + \sqrt{1 - u_k^2}\, c^+_{\vec{k}\uparrow}\, c^+_{-\vec{k}\downarrow} \right) \Psi_0$ with Cooper pairs

BSC SuperConductivity: 3 comments

1. In the position space, H_{BCS} corresponds to factorizable expression

$$H_{BCS} = \int dx C^{+}(x)\, C^{+}(x)\, V_{BCS} \int dy\, C(y)\, C(y)$$

There is no $(x - y)$ dependence in the kernel V_{BCS}; phonon from diagram does not transfer the momentum. As it was well-known, this destroys the current continuity.



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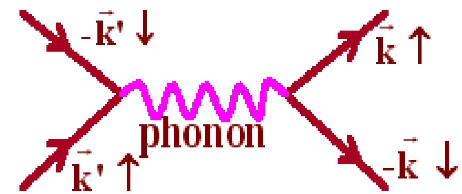

2. BCS trial variational function

$$\Phi_0^{\rm BCS} = \prod\nolimits_{\vec{k},\sigma} (u_k + \sqrt{1-u_k^2}\, c^{+}_{\vec{k}\uparrow}\, c^{+}_{-\vec{k}\downarrow})\Psi_0$$

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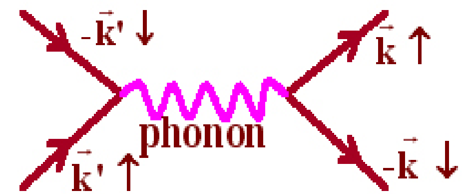

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3. G-L order parameter $\Psi(\mathbf{k}) = \langle c^{\dagger}_{\mathbf{k}\uparrow} c^{\dagger}_{-\mathbf{k}\downarrow}\rangle$ Gor'kov - '59

Bogoliubov micro SC theory

Fröhlich electron-phonon model: $H_{Fr} =$

$$= \sum_{\vec{k},\sigma} \varepsilon_{\vec{k}} c^{+}_{\vec{k}\sigma} c_{\vec{k}\sigma} + \sum_{\vec{q}} \omega_{\vec{q}} b^{+}_{\vec{q}} b_{\vec{q}} + g_{Fr} \sum_{\vec{k},\vec{k}',\sigma} \sqrt{\frac{\omega(\vec{q})}{2V}} c^{+}_{\vec{k}\sigma} c_{\vec{k}'\sigma} (b^{+}_{\vec{q}} + b_{-\vec{q}})$$

Bogoliubov (u,v) transformation:

$$\alpha_{\vec{k}\uparrow} = u_{\vec{k}}\, c_{\vec{k}\uparrow} - v_{\vec{k}}\, c^{+}_{-\vec{k}\downarrow}; \quad \alpha_{\vec{k}\downarrow} = u_{\vec{k}}\, c_{\vec{k}\downarrow} + v_{\vec{k}}\, c_{-\vec{k}\uparrow^{+}} \qquad (u-v)$$

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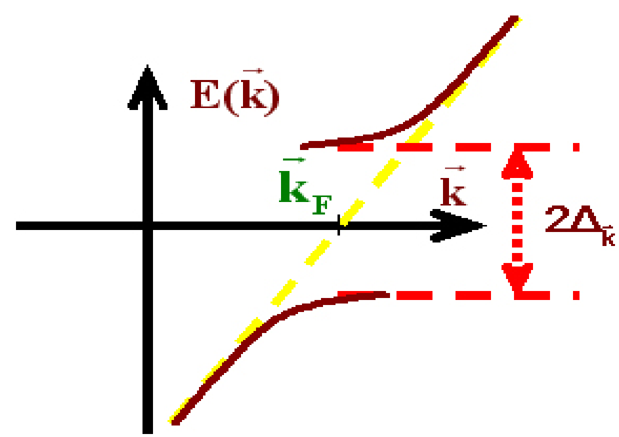
Gap solution : $\boxed{\triangle_B = \widetilde{\omega}\, exp\left(-\frac{1}{\rho_B}\right)}$ $\rho_B = g^2_{Fr} N_0$

Excitation spectrum of quasiparticles (“Bogolons”)

$$H_{Fr} \rightarrow H_B = \sum E_{\vec{k}}\, \alpha^{+}_{\vec{k},\sigma}\, \alpha_{\vec{k},\sigma}$$

$$E_{\vec{k}} = \sqrt{\varepsilon^2_{\vec{k}} + |\triangle_{\vec{k}}|^2}$$



Spectrum with gap; Bogolon dissociation *

To elucidate Bogolon's physical content, take spectral function of quasiparticle excitations in SC phase

$$A_{sc}(\mathbf{k}, \omega) = u_{\mathbf{k}}^2 \, \delta(\omega - E_{\mathbf{k}}) + v_{\mathbf{k}}^2 \, \delta(\omega + E_{\mathbf{k}}), \qquad (1)$$

as in the Figure

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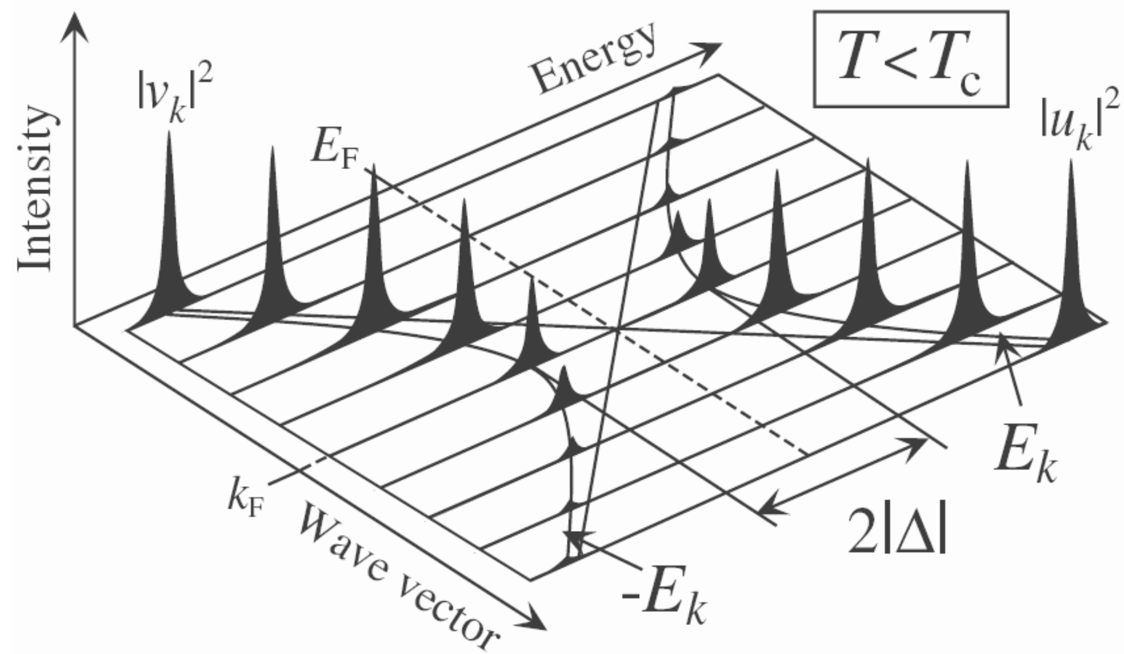
as in the Figure



Spectral function of 1-electron quasipartical exitations in Bog's theory

Different Symmetries in Macro- and Micro-

Thus, the Broken Symmetry of micro-theory of SuperConductivity (like in Bog's SuperFluidity) – is the phase Symmetry.,

Nonconservation of the No of Cooper pairs or He II atoms relevant for the phase transition.

Different Symmetries in Macro- and Micro-

Thus, the Broken Symmetry of micro-theory of SuperConductivity (like in Bog's SuperFluidity) – is the phase Symmetry.,

Nonconservation of the No of Cooper pairs or He II atoms relevant for the phase transition.

Compare with Champagne bottle Symmetry of macro-phenomenological Ginzburg-Landau theory.

Micro and Macro Symmetries are different

Essentially different !

Symmetries: exact and approximate

What is Symmetry (broken) of physical problem ?

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* In theory we deal with –

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* Do they relate to Symmetry of physical system ?

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At least 3 levels of Symmetries :

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- Among Qu-Sym, approximate (in pQCD)

Modern Pilatus vs Critical phenomena

– What is the Symmetry of a physical system ?

(Symmetry involved in phase transition)

– In classical case, it is evident (bottle, crystals)

– Can it be formulated independently of models ?

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Heretical form : – Does the symmetry exist only in the conscience of theoreticians ?

Modern Pilatus vs Critical phenomena

– What is the Symmetry of a physical system ?

(Symmetry involved in phase transition)

– In classical case, it is evident (bottle, crystals)

– Can it be formulated independently of models ?

Heretical form : – Does the symmetry exist only in the conscience of theoreticians ?

“What is the Verity ?” = that’s the old question.

The new one :

What is the Symmetry ?

Pilatus

"Quid est symmetria ?"