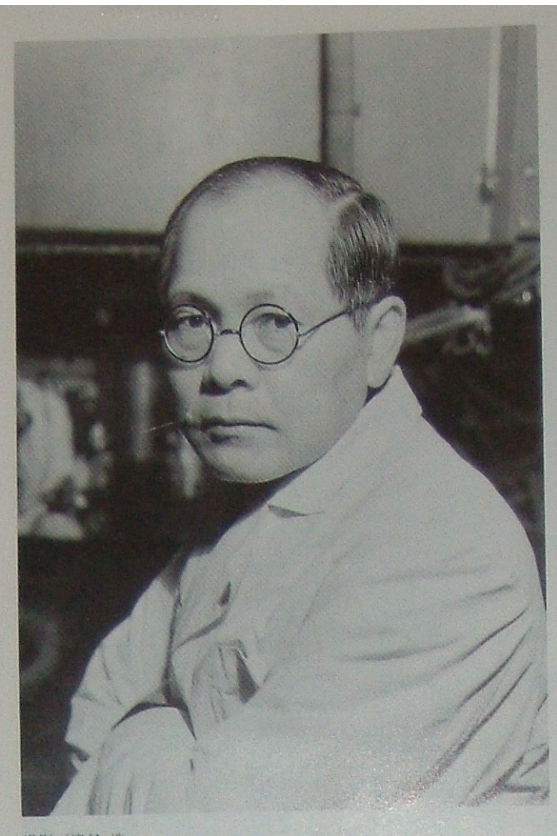




**1908--1991**



Yoshio Nishina  
1890-1951



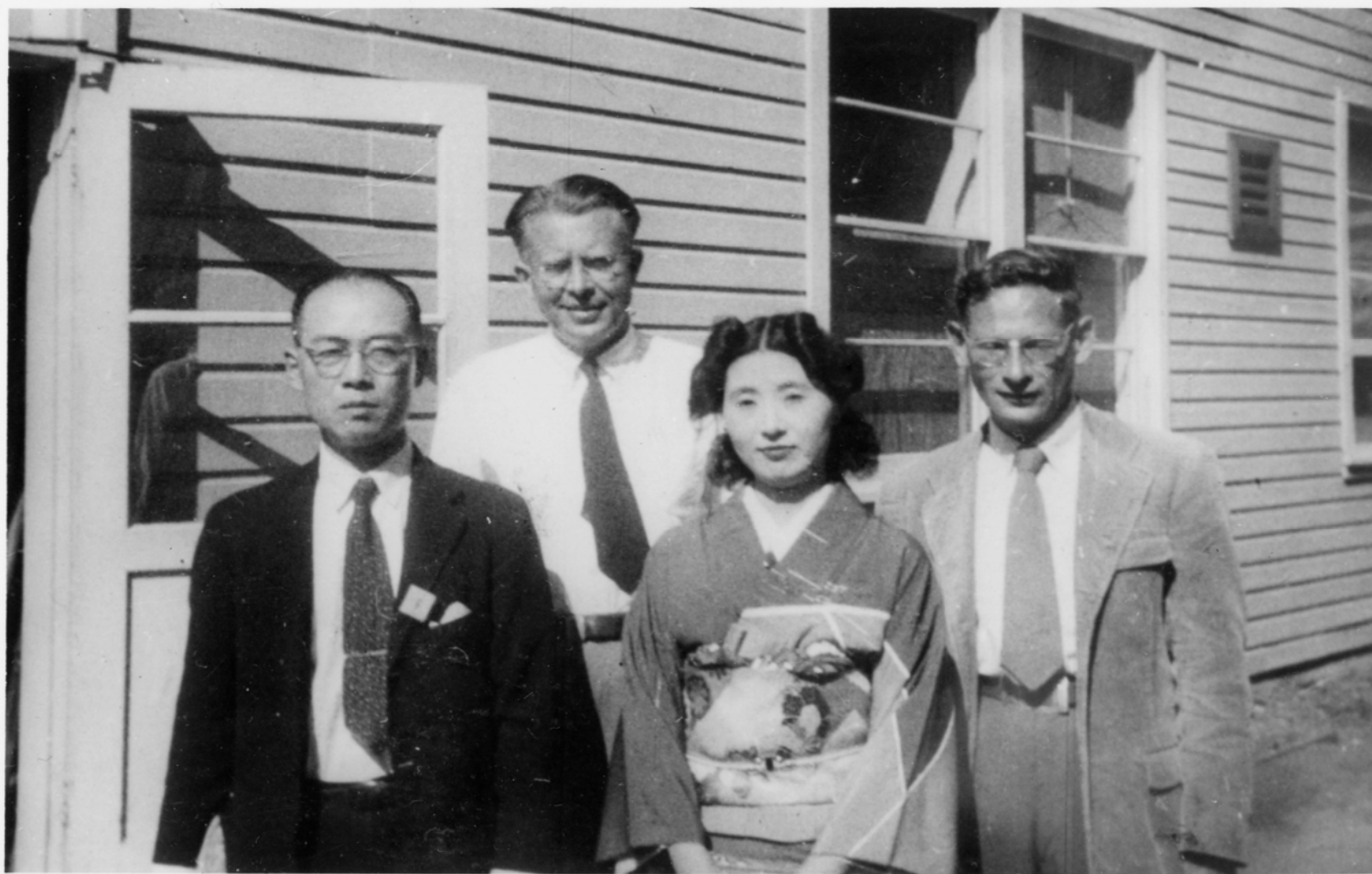
Hideki Yukawa  
1907-1981

Sin-itiro Tomonaga  
1906-1979



**Ryogo Kubo 1920 - 1995**

At Berkeley  
Yukawa, Lawrence, Mrs. Yukawa, Serber



## Brief history of particle physics since the 1930s

Neutron, positron

Cyclotron (Lawrence)

Beta decay theory

Meson theory (Yukawa)

Muon (second lepton)

\*Pion (first meson)

QED and renormalization

\*Non-Abelian gauge fields

\*Various hadrons ( $\rho, \omega$ , etc.) and flavor symmetry

\*Parity violation with V - A weak interaction

\*Chiral symmetry

\*Spontaneous symmetry breaking and mass generation

\*Quark model

Regge trajectories of hadrons

\*Electroweak unification

Quark color and QCD

The standard model

$SU(3) \times SU(2) \times U(1)$  gauge fields,

3 generations of quarks and leptons



Gregor Wentzel 1898-1978

Search for hadron internal symmetries

Flavor symmetry

Isotopic spin  $SU(2)$  for  $(p,n), (\pi^\pm, \pi^0)$

$SU(3)$  octet hadrons

Chiral symmetry (handedness)

$V - A$  weak interaction

symmetry broken by fermion mass

almost conserved axial vector current

(PCAC,  $\sigma$  model)

Vector meson ( $\rho, \omega$ ) dominance ansatz

Colored quarks and color  $SU(3)$  gauge field (QCD)

## The collective modes

Langmuir plasma

$$\omega_p^2 = e^2 \rho / m$$

Debye screening

$$e^{-\mu r} / r, \mu = \omega_p / v_T$$

Bohm and Pines

longitudinal and transverse  
collective modes

Tomonaga effective theory for 1-D  
fermionic systems

London theory of superconductivity

$$\mathbf{j} = (1/\Lambda) \mathbf{A}, \quad 1/\Lambda = \omega_p$$

Simple transcription

$$H = \int \psi^\dagger p^2 / (2m) \psi + 1/2 \int \int' (\psi^\dagger \psi) V(\psi^\dagger \psi)'$$

$\psi, \psi^\dagger \rightarrow \rho^{1/2} \exp(\pm i\theta), \quad [\theta, \rho] = i$

## BCS theory

Cooper pairing and gap formation around the Fermi surface

## Bogoliubov-Valatin quasiparticles

$$\Psi = \alpha\psi_{\uparrow} + \beta\psi_{\downarrow}^{\dagger}$$

$$H_{BV} = \Psi^{\dagger}(\tau_3\varepsilon + \tau_1\Delta)\Psi, \quad \Psi = (\psi_{\uparrow}, \psi_{\downarrow}^{\dagger})$$

## Collective modes

$$\pi \sim \Psi^{\dagger}\tau_2\Psi, \quad m = 0 \quad (\text{NG})$$

$$\sigma \sim \Psi^{\dagger}\tau_1\Psi, \quad m = 2\Delta \quad (\text{Higgs})$$

## London relation

$$\mathbf{J} = \mathbf{A}/\Lambda$$

## Conserved current

$$\mathbf{J} = \Psi^{\dagger}(\mathbf{p} - \tau_3 e\mathbf{A})\Psi - \nabla\pi$$

$$\rho = \Psi^{\dagger}\tau_3\Psi - (1/v^2)\pi$$

$$v^2 = v_F^2/3$$

$$\partial\rho/\partial t + \nabla\cdot\mathbf{J} = 0$$

## Chiral problem and nucleon mass generation

### Chiral invariants

vector, axial vector, (scalar, pseudoscalar)

→ SSB of chiral symmetry by mass scalar

$$H_N = \Psi^\dagger (\rho_1 \boldsymbol{\sigma} \cdot \mathbf{p} + \rho_3 M + g \rho_2 \pi) \Psi$$

### Chiral (axial) current

$$j_{A\mu} = \Psi^\dagger (\rho_1, \boldsymbol{\sigma}) \Psi,$$

$$\partial \cdot j_A = -2M \Psi^\dagger \rho_2 \Psi,$$

$$J_{A\mu} = j_{A\mu} - f \partial_\mu \pi$$

$$f = 2M/g \quad (\text{Goldberger-Treiman})$$

$$\partial \cdot J = f m_\pi^2 \quad \text{PCAC}$$

### Collective modes (mesons)

$\pi$       mass  $\sim 0$

$\sigma$       mass  $2M$

Quark model  $M_N \rightarrow M_q$  (  $\sim M_N/3$  )

## General mass relations

	NG fermion "Higgs"			
	0	1	2	
BCS	0	1	2	
hadrons	0	1	2	
${}^3\text{He B}$				
$\sigma \cdot p$	0	1	2	J=0
$\sigma \times p$	0	1	2	J=1
$\sigma_i p_k$	$2(2/5)^{1/2}$	1	$2(3/5)^{1/2}$	J=2
	$m_1^2 + m_3^2 = 4m_2^2$			

Quarks and Higgs mass relations?