An unification of light and electron

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Three turning points in my life

- After 10 years of closure, Deng Xiao-Ping reopened universities in 1977. I entered USTC that year.

- After 30 years of disconnection, TD Lee set up the CUSPEA program in 1980 to help Chinese students to come to US to study physics. I entered Princeton in 1982.

- I switched from superstring theory to condensed matter theory in 1987. I have had a great fortune to work with world leading physicists in both fields — and the field in between :-(
What is CUSPEA program?
China-U.S. Physics Examination and Application
(1980 - 1988)

No GRE and no TOEFL in China that time. After 30 years isolation, US universities cannot gauge Chinese students.

- TD persuaded Chinese government to organize a national exam to select physics students. (500-800/year participants and 100/year selected)
- TD persuaded near 100 universities in US to admit physics graduate students through this unusual channel.
- TD personally manage the application process to help all selected students to go to the schools of their choice.
Some CUSPEA students – we are all TD’s students

Hu MIT
Wang MIT
Shen Stanford
Dai Stanford
Huang Stanford
Ji Maryland

Qiu Berkeley
Niu Austin
Tang UCSF
Zhang H.K.
Lin H.K.
Tang H.K.
Tian Beijing U

Chen IOP B.J.
Lou TsingHua
Peng Beijing U
Xiao H.K.
Qi IHEP B.J.
Zhang Sohu
What is the origin of photons and electrons?
Reductionist approach

A deeper understanding is gained by dividing things into smaller parts
Emergence approach

Particle-wave duality → origin of particles = origin of waves

Three very famous wave equations

- Navier equation: \( \partial_t^2 u^i - T_{im}^{ijk} \partial_j \partial_k u^m = 0 \)
  → sound waves in crystals.

- Euler equation: \( \partial_t^2 \rho - v^2 \partial_i^2 \rho = 0 \)
  → density waves in (super) fluids.

- Maxwell equation: \( \partial \times E + \partial_t B = \partial \times B - \partial_t E = 0 \)
  → electromagnetic waves and light.

What is the origin of those waves?
**Principle of emergence**

Different organizations (orders) of particles leads to different kinds of waves and wave equations.

Crystal order → Navier equation → Transverse and longitudinal phonons

Quantum ground state: $|\Phi\rangle = \begin{bmatrix} \text{Quantum state} \end{bmatrix}$

Liquid order → Euler equation → Longitudinal phonons

Ground state: $|\Phi\rangle = \sum_{\text{all conf.}} \begin{bmatrix} \text{Confined state} \end{bmatrix} = \text{Bose condensed state}$

Different organizations → different waves → different kinds of particles

*Originate from organization = principle of emergence*
Reductionist approach does not apply to phonons

- A phonon has no smaller parts and is not formed by anything.
- Phonons originate from the motions of organized particles that fill the whole space.

Should we understand photons in the same way?

- May be all elementary particles originate this way, from the *things* that fill our vacuum.
  The simplest choice: the *things* = bosons/spins on some lattices.

- The key is to find a particular organization of bosons whose collective waves are described by Maxwell equations $\rightarrow$ photons.
String-net condensation $\rightarrow$ Emergence of light

An organization of bosons that produces Maxwell eq. Levin & Wen 04

- bosons form strings (string-nets)
- string-nets form a quantum liquid

\[ |\Phi\rangle = \sum_{\text{all conf.}} \left| \begin{array}{c}
\end{array} \right\rangle \rightarrow \text{String-net condensed state} \]

- Waves in string-net liquid are described by Maxwell equations
  Light is the waving of condensed strings
What really are the photons in our world?

Fundamental building blocks or Collective motions of string-nets

- Is the ether really a string-net liquid?

**String-net picture also explains the origin of Fermi statistics**

- Strings are unobservable in string-net condensed state.
- Ends of strings behave like independent particles.

They are *charges* of the gauge field.
For string-net condensed state $|\Phi\rangle = \sum_{\text{all conf.}} |\rangle$

The end of strings are bosons.

For string-net condensed state $|\Phi\rangle = \sum_{\text{all conf.}} \pm |\rangle$

The end of strings are fermion.

*The different statistics of ends of strings is determined by the different kinds of string-net condensation.*

*String-net condensation provides a way to unify gauge interactions and Fermi statistics*
From lattice bosons/spins, how far can we go?

- Constructed a spin model whose string-net condensed state leads to $U(1) \times SU(3)$ gauge bosons, leptons and quarks. (2/3 of standard model)
- Can also have $SU(2)$, but the gauge coupling is not CHIRAL!
  After many years hard work, we still do not know how to get gauged chiral fermions in a system with a finite cut-off.
  We do not know how to get the standard model from lattice bosons/spins.

After so many failed attempts,
*we wish our world does not violate parity.*
Chiral fermion is one of deepest mysteries of nature

Seven mysteries/wonders of universe:

(1) Identical particles  (2) Fermi statistics
(3) Tiny masses of fermions (proton mass $\sim 10^{-20}$ Planck mass)
(4) Chiral fermions  (5) Gauge interactions
(6) Lorentz invariance  (7) Gravity

Starting from lattice bosons/spins, we can explain 4 of seven: Identical particles, Fermi statistics, Gauge interactions, Small masses, and, may be even Gravity.

Parity violation and chiral fermions carry a deep message, I believe, from the Planck scale. 50 years after its discovery, we still do not know how to decode it.

Parity violation and chiral fermions, like a light house in dark ocean, will guide us to sail into unknown territory.