Einstein’s Photoelectric Effect

How ONE electron tells the story of GAZILLION electrons
Overview

- Photo-electric effect and Angle Resolved Photo-Electron Spectroscopy (ARPES)
- Emergent behaviors
- High temperature superconductivity and ARPES
- Unconventional emergent behaviors and ARPES
History: The Photoelectric Effect

- Hertz (1887)

- Thompson & Lenard (1897-1902) Photo-electrons are involved

- Einstein (1905, 1921 Nobel Prize) Quantum theory (Photon)

\[ E_k = h\nu - E_b - \Phi \]
Albert Einstein (1879 - 1955) published his theory of the photoelectric effect in 1905, the same year in which he published the Special Theory of Relativity and the paper on molecular dimensions which earned him his PhD from the University of Zurich. However, his reintroduction of the idea of a corpuscular nature for light met with considerable scientific resistance. Even Planck rejected an idea which seemed to set science back one hundred years. As late as 1913, when Einstein was proposed for membership in the Prussian Academy of Science, the nominating committee felt it necessary to apologize for this "mistake" as a singular error in a series of successes. Then, in 1921 Einstein won the Nobel Prize for the theory of the photoelectric effect.
Einstein's Theory - Controversial

In a recommendation for Einstein's membership in the Prussian Academy of Science, the sponsors wrote

“In sum, one can say that there is hardly one among the great problems in which modern physics is so rich to which Einstein has not made a remarkable contribution. That he may sometimes have missed the targeting his speculations, as, for example, in his hypothesis of light-quanta, cannot really be held too much against him, for it is not possible to introduce really new ideas even in the most exact sciences without sometimes taking a risk”

Current Understanding

Quantum Mechanics Governs Both Light (Photon) and Electron

- Light Wave energy is discrete ($h\nu$, $2h\nu$, $3h\nu$...)
  The quantum of energy ($h\nu$): Photon Particle
  Photon Particle is described by a Wave Function
- Electron Particle is described by a Wave Function

Particle Wave Duality
Current Understanding (Particle)

**Initial**
- $p_p$, $E_p$

**Final**
- $p_e$, $E_e$
- $p_e = p_p + p_x$
- $E_e = E_p + E_x$

Momentum Conservation
Energy Conservation
Current Understanding (Wave)

Initial

$p_p, E_p$

$p_x, E_x$

Final

$p_e, E_e$

$p_e = p_p + p_x$

$E_e = E_p + E_x$
Current Understanding (Wave)

Initial

\[ k_p, \ \omega_p \]

\[ k_x, \ \omega_x \]

Final

\[ k_e, \ \omega_e \]

\[ p_e = p_p + p_x \]

\[ E_e = E_p + E_x \]
What is measured and what is not

However, $\omega$ and $k$ are not independent. 

**DISPERSION RELATION**

For instance, $\omega = ck$ for light (photon).

Homework…

$\mathbf{k}_p, \omega_p$

$k_x, \omega_x$

$\mathbf{k}_e, \omega_e$

$p_e = p_p + p_x$

$E_e = E_p + E_x$

$k = \text{wave number} = \frac{2 \pi}{\lambda}$

$\omega = \text{angular freq.} = 2 \pi \nu = \frac{2 \pi}{T}$

$k = \text{momentum} \quad p = \hbar k / (2 \pi)$

$\omega = \text{energy} \quad E = \hbar \omega / (2 \pi)$
Photo-Electric Effect is Cool

- Photon Detectors
- Digital Camera, Camcorder, Solar Cells, ...
- Angle Resolved Photoelectron Spectroscopy
Synchrotron

Advance Light Source
Lawrence Berkeley National Laboratory
Synchrotron = Electron Shaker

Electron Storage Ring

Beam Line

End Station
ARPES End Station

7.6e2 Torr outside, 3e-11 Torr inside

Sample transfer

Characterization chamber

Photon In

Electron Analyzer

ARPES chamber
History of ARPES

- Electron Spectroscopy for Chemical Analysis (ESCA or XPS) (Siegbahn, 1951-, 1981 Nobel Prize)
  - X-ray sources, electron spectrometer, chemical shift

- Photoelectron spectroscopy in UV (UPS) (Spicer, 1955-)
  - UV light sources and vacuum technology

- ARPES (Smith, 1973-)

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Nov 28, 2006
G.-H. Gweon, Physics 10, UCSC
Emergent Behaviors

R. P. Feynman: QED

“I must clarify something: When I say that all the phenomena of the physical world can be explained by this theory, we don’t really know that. Most phenomena we are familiar with involve such tremendous numbers of electrons that it’s hard for our poor minds to follow that complexity.”
Tyranny of Power

- Computer memory of one particle wavefunction: $X$
- Number of particles: $N$
- Total memory: $X^N$

Say, $X = 2$ (minimum).

$2^{10} = 1024$, $2^{30} = 1.07e9$, $2^{100} = 1.3e30$

$N = 10^{23} \rightarrow X^N \sim 10^{3e22}$
Emergent Behaviors

- More is different (Anderson) - Symmetry Breaking
- Patterns, Life, Brain, Colony, ...
  Phases, Temperature, Heat, Friction, ...
  Laws, Particles ...
- Physics, Chemistry, Biology, Psychology, Social Sciences ...
Renormalization Group

- Start with the full Hamiltonian
- Integrate out the high energy dynamics
- Obtain effective low energy Hamiltonian

E.g., “block spin” transformation

ccmp1.phys.metro-u.ac.jp/ccmp/simulation/xy.gif
No problem in physics in our time has received more attention, and with less in the way of concrete success, than that of the behavior of the cuprate superconductors, whose superconductivity was discovered serendipitously, and whose properties, especially in the underdoped region, continue to surprise. As the high-Tc community has learned to its sorrow, deduction from microscopics has not explained, and probably cannot explain as a matter of principle, the wealth of crossover behavior discovered in the normal state of the underdoped systems, much less the remarkably high superconducting transition temperatures measured at optimal doping. Paradoxically high-Tc continues to be the most important problem in solid-state physics, and perhaps physics generally, because this very richness of behavior strongly suggests the presence of a fundamentally new and unprecedented kind of quantum emergence.

Applications of Superconductivity

- Magnetic Levitation Devices—Trains (Superconducting Coil)
- Magnetic Resonance Imaging (MRI)
- Power Lines
- Particle Accelerators
- Motors
- SQUIDs
What is Superconductivity?

1911  K. Onnes Superconductivity in Hg

1933  Meissner effect

**RESISTANCELESS CONDUCTION**

**MEISSNER EFFECT:**
Perfect diamagnetism

![Graph showing resistivity versus temperature for metals and superconductors](image)

- **Resistivity**
- **Metal**
- **Superconductors**
- **$T_c$**
- **Temperature**
Meissner Effect

http://www.fys.uio.no/super/levitation/
Meissner Effect

http://www.fys.uio.no/super/levitation/
High Tc is Complicated - Work in Progress
What can ARPES do?

Slope = Velocity

$V \sim \frac{1}{m^*} \sim \frac{\partial \omega(k)}{\partial k}$

$\text{Energy} \quad \text{TiTe}_2$

Electron detector

Crystal

$E - \phi$

$\theta$

$h\nu$

Slope = Velocity

Momentum
Electrons are Fermions

Statistics, High and Low Energy

Low Energy State

High Energy State
Why does the velocity change suddenly?

"Kink"

\[ V \sim \frac{1}{m^*} \sim \frac{\partial E(k)}{\partial k} \]
Qualitative Understanding

“Kink”

- Peak is sharp - Stable
- Area Under Curve $\ll 1$
  (Many body state)

- Peak is broad - Unstable
- Area under curve $\sim 1$
  (Electron like state)
Qualitative Understanding

Renormalization: Emergence of Heavy Electron

Bare Electron
Free Electron
Non-interacting Horse

Real Electron
Heavy Electron
Bare Electron + All Others

Electron → Feynman Diagram

Real Excitation = Electron + Other Stuff + …
Qualitative Understanding

- Peak is sharp – Stable
- Area Under Curve $\ll 1$
  (Many body state)

ARPES measures bare electron, i.e. bare horse, one at a time.

- Peak is broad – Unstable
- Area under curve $\sim 1$
  (Electron like state)

Eigenstates of Low $E$ Effective Hamiltonian

Eigenstates of High $E$ Hamiltonian
Why care about Kink?

Renormalization, Emergence

Kink = Interaction
Interaction mediates SC

Two Kinks

Low E Kink = Lattice
(~ 70 meV)

GHG et al.,
Nature 430, 187 (04)
GHG et al.,
PRL 97, 227001 (06)

High E Kink = Spin
(~ 600 meV)

Graf, GHG et al.,
cond-mat/0607319
SC is dance of electron pairs

All to the same tune!
Phase coherent SC condensate

Bound Pair by Interaction

Binding energy = SC gap

Signature of this emergence?

Phys. Today, March ‘04
Signature of SC Condensate

Intensity ~ SC Condensate Size

Pair Binding Energy SC Gap

Fedorov et al. PRL '99
High Tc is Complicated - Work in Progress

- strange metal
- pseudogap
- metal
- superconductor
- AFM

Temperature (K)

hole doping
**Signature of SC Condensate**

The real mystery is normal state!

- Intensity ~ SC Condensate Size
- Pair Binding Energy
- SC Gap

Fedorov et al.
PRL '99
Another Emergent Behavior

Electron Fractionalization

High Tc
Low-Dimensional Metals
Fractionalization?

Quasi-electron $\approx$ Electron

Opposite of Fractionalization

Fermi Liquid
Fractionalization?
Fractionalization?
Fractionalization?

NOT Fractionalization

Dead Horse cannot move. (Electron cannot be cut.)

Dead Horse

Nov 28, 2006 G.-H. Gweon, Physics 10, UCSC
Low-D Metal Example - Li Purple Bronze

Quasi-1D Metal

Onoda ('87)

Whangbo ('88)
Dimensionality Matters

New State of Matter beyond Landau Fermi Liquid

No individual particle motion, but only collective density wave motion

Quantum world → Charge and Spin wave

Charge and Spin propagate separately due to different charge-charge and spin-spin interaction
Low Dimensional Metals

- $\text{Li}_{0.9}\text{Mo}_6\text{O}_{17}$ (Li Purple Bronze)
- $\text{K}_{0.3}\text{MoO}_3$ (K Blue Bronze)
- $\text{AMo}_6\text{O}_{17}$ (A=Na,K) (Purple Bronze)
- HTSC cuprates
- $\text{SmTe}_3$
- $\text{TiTe}_2$

Plot: Dimensionality of $E_F$ Electronic Structure

"Strangeness" vs Dimensionality of $E_F$ Electronic Structure

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Signature of Electron Fractionalization

Non-Interacting Electrons

Density of States (DOS)

Momentum-Integrated PES

Number of Electrons per $\Delta E$

Momentum Integration

Energy (eV)

$0.0$ $-0.2$

$0.3$ $0.4$

$E_F$ $E$

$\Delta E$

$E_F$

$E$

$k_F$

$k$

$E$

$\Delta E$
Signature of Electron Fractionalization

Fermi Liquid

Density of States (DOS)

Number of States per $\Delta E$

Area Under Curve $\ll 1$
(Many body state)
Signature of Electron Fractionalization

Fractionalization

Density of States (DOS)

Momentum-Integrated PES

Number of Electrons per $\Delta E$

"Pseudo-Gap"
Signature of Electron Fractionalization

- **Au**
- **Li Purple**

E - E_F (eV)

Quasi-1D
Li_{0.9}Mo_{6}O_{17}
T = 300 K
Finite T LL fit
(\alpha=0.9)

Quasi-1D
K_{0.3}MoO_{3}
T = 300 K
Finite T LL fit
(\alpha=0.8)

Quasi-2D
NaMo_{6}O_{17}
T = 300 K
Finite T LL fit
(\alpha=0.3)

Quasi-2D
TiTe_{2}
T = 25 K
Fermi edge
Signature of Electron Fractionalization

Sato et al, Physica C ('00)

Pseudo-Gap
Electron Fractionalization

- "Horse Mass" Wave (=Charge Wave)
- "Roll" or Spin Wave (quantum horse)

Single Horse Moves in the form of Many Collective Waves

No Quasi-Horse Motion

Fractionalization!

Horse Mass + Roll

No Individual Horse Motion (No Quasi-Electron)!
Charge Wave ("Holon") and Spin Wave ("Spinon")

Spin Charge Separation - suggestive but not definite

1D Li Purple Bronze ($\text{Li}_{0.9}\text{Mo}_6\text{O}_{17}$) - Luttinger Liquid

J. D. Denlinger, GHG et al, PRL 99
GHG et al., PRB 03; F. Wang et al., PRL 06
Almost an emergence?

SrCuO$_2$

Kim et al., Nature Physics, 2, 397 (2006)

Also, see TTF-TCNQ
Claessen et al., 88, 096402 (2002)

Two dispersing things but at high energy!
Spin Charge Separation in Cuprates

Graf, GHG, et al., PRL in review
Conclusions

- Complex physics in condensed matter systems (High Tc, Low-D conductors, etc)

- Signatures of various types of emergence - New era of condensed matter physics beyond simple Landau Fermi Liquid paradigm

- One electron carries the message of emergence of gazillion electrons through wave function overlaps
Further Reading

- P. W. Anderson, “More is different,” Science vol. 177, 393 (1972)