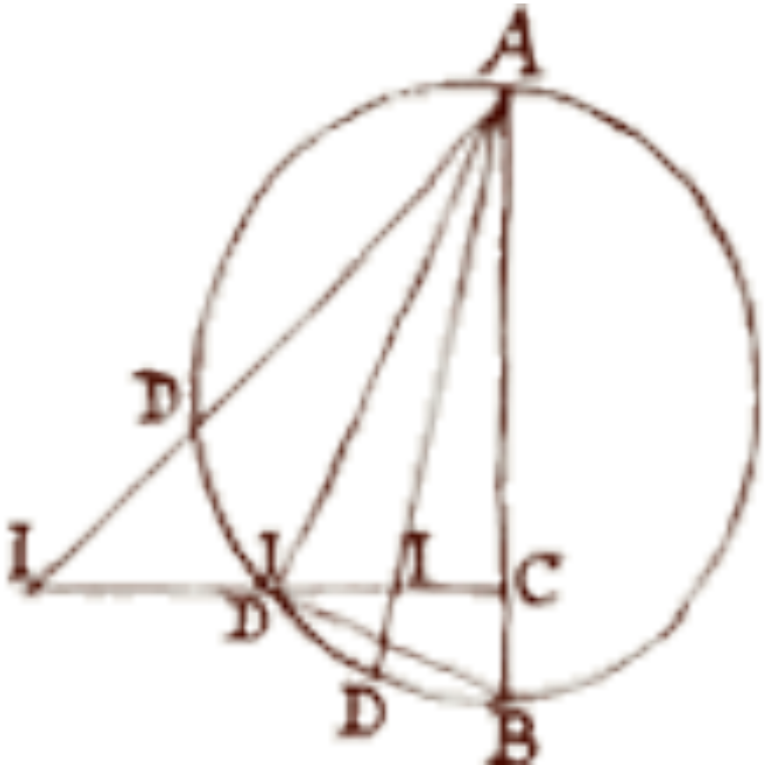
The Advent of Quantum Field Theoretical Methods in Solid State Physics



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Overview

- general claims
- case study in postwar theoretical physics: the quantum plasma from early theories to Gell-Mann and Brueckner
- lessons from the case study
- working hypotheses

Work in progress!

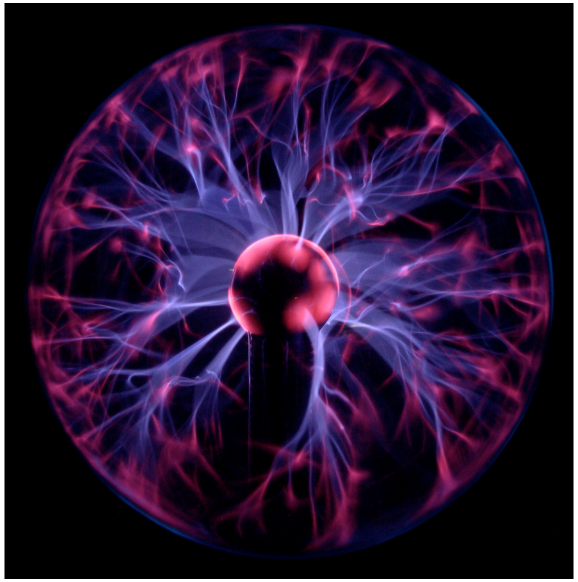
General Claims: History of „Squalid“ State Physics

- Condensed matter physics is one the of the central disciplines of 20th century physics, yet receives much less love from historians and philosophers of science than other areas.
- In the 1950s, a fundamental revolution took place in solid state physics.
- Emergence of effective models describing solids in terms of fictitious new entities (quasiparticles and collective excitations).
- However, the postwar history of solid state physics remains essentially unstudied.
- This is not due to a lack of sources (e.g. International Project on the history of SSP).

QUANTUM HISTORY

Case Study

- Why quantum plasma? Model for electrons in metals!
- high-density ionized (electron-ion) gas behaves like a new state of matter: plasma
- term coined by Langmuir (1927, gas discharge tubes) in analogy to blood plasma
- intricate order: correlations, screening, plasma oscillations, turbulence, filamentations
- plasmas cover range from behavior of nucleons over electrons in metals to the Earth's ionosphere, the solar corona and the interior of neutron stars



QUANTUM HISTORY

Early Theories

(interacting) many-body problem!

- 1920s
  - Langmuir, Debye and Hückel: static screening
- 1930s
  - Mott and Jones: Thomas-Fermi screening
  - Wigner: variational calculation of correlation energy in low-density limit (Wigner crystal)
  - Bardeen: logarithmic divergences for intermediate and high densities
- 1940s
  - Bohm: dynamical screening (borrowed from Schwinger‘s QED)

Growing Interest

- Wartime plasma research
  - < 100 scientists worldwide
  - highly interdisciplinary (electrical engineering, solid state physics, nuclear physics, astrophysics, radiation physics)
  - famous example: David Bohm
- early 1950s: growing interest
  - 1950 David Pines: PhD with Bohm on quantum plasmas
  - 1950 Macke: partial summation of perturbation series for the correlation energy
  - 1954 Bohm and Pines: collective modes (plasmons) and screening within RPA

divergences!

QUANTUM HISTORY

Early Theories: Methods

	QED and nuclear physics	electron gas and solid state
variational techniques	Dirac 1933 Tomonaga and Schwinger 1951 Brueckner 1955	Wigner 1936 BCS 1957
collective coordinate / canonical transformation methods	Schwinger 1948 Bogoliubov and Zubarev 1955	Tomonaga-Luttinger 1950 Bohm and Pines 1953 Bogoliubov and Valatin 1958
equation-of-motion approach	Dyson 1949	Bohm and Pines 1954 Anderson 1958

(unidirectional) knowledge transfer from QED and nuclear physics

Divergences

But: still no resolution of divergences!

Pines (1981): „One had the classical situation in physics where you find when you do the problem a little bit better you‘re led to all kinds of divergences... And when you fix up one part of the problem, you‘re led to deep problems with the other... That I think is one of the conditions which require a wholly new approach.“

cited from Hoddeson et al., Out of the Crystal Maze (1992)

Gell-Mann and Brueckner

resolved the problem of divergences in 1956

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Correlation Energy of an Electron Gas at High Density*

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AND

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(Received December 14, 1956)

The quantity ϵ_c is defined as the correlation energy per particle of an electron gas expressed in rydbergs. It is a function of the conventional dimensionless parameter r_s, where r_s^{-3} is proportional to the electron density. Here ϵ_c is computed for small values of r_s (high density) and found to be given by $\epsilon_c = A \ln r_s + C + O(r_s)$. The value of A is found to be 0.0622, a result that could be deduced from previous work of Wigner, Macke, and Pines. An exact formula for the constant C is given here for the first time; earlier workers had made only approximate calculations of C. Further, it is shown how the next correction in r_s can be computed. The method is based on summing the most highly divergent terms of the perturbation series under the integral sign to give a convergent result. The summation is performed by a technique similar to Feynman's methods in field theory.

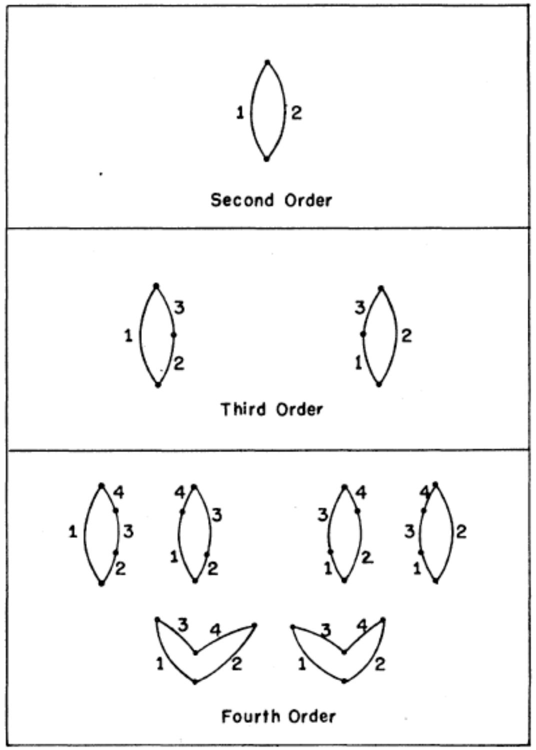

FIG. 1. The relevant second-, third-, and fourth-order processes represented diagrammatically. In second order the process may take place with or without exchange. In higher orders, exchange is neglected.

QUANTUM HISTORY

Gell-Mann and Brueckner

- work resulting from RAND corporation studies on thermonuclear fusion
- calculation of correlation energy in high-density limit
- explicit summation of perturbation series to infinite order
- usage of Feynman-like diagrams
- proof that divergences in earlier theories were due to incomplete summation of perturbation series
- full summation yields geometric series
- divergences cancel

Bottleneck Passed

	QED and nuclear physics	electron gas and solid state
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Feynman diagrammatic methods	Feynman 1948	Gell-Mann and Brueckner 1956 Goldstone 1956 Gorkov 1958 Nambu 1960

QUANTUM HISTORY

Solid State Physicists armed with Diagrams

- once the bottleneck was passed, results kept flowing
  - 1957 Gell-Mann: specific heat of electron gas
  - 1957 Hubbard: diagrammatic treatment of collective modes
  - 1957 Sawada, Brueckner, Fukada and Brout: plasma oscillations
  - 1957 Wentzel: diamagnetism of the electron gas
  - 1958 Galitskii and Migdal: connection to one- and two-particle Green functions
  - 1958 Migdal: coupled electron-phonon system and Fröhlich interaction
  - 1958 Pines and Nozières: dielectric constant
  - 1958 Bogoliubov and Valatin: canonical transformation technique for superconductivity
  - 1959 Gorkov: field-theoretic approach to superconductivity
  - 1959 Hugenholtz and Pines: interacting bosons
  - 1962 Luttinger and Nozières: diagrammatic derivation of Landau Fermi Liquid Theory
  - ...
- the new methods spread quickly
  - 1958 first Les Houches Summer School on many-body techniques
  - 1961 first textbook by Abrikosov, Gorkov, Dzyaloshinksi: „bible“ for generations to come
  - 1961 commented reprint volume „The Many Body Problem“ by Pines (great sourcebook for this talk)
- solid state physics becomes source of models for quantum field theory in general
  - end of lopsided knowledge transfer

QUANTUM HISTORY

Abrikosov, Gorkov, Dzyaloshinski

„In recent years, remarkable success has been achieved in statistical physics, due to the extensive use of methods borrowed from quantum field theory. The fruitfulness of these methods is associated with a new formulation of perturbation theory, primarily with the application of „Feynman diagrams". The basic advantage of the diagram technique lies in its intuitive character: operating with one-particle concepts, we can use the technique to determine the structure of any approximation (...) These new methods make it possible not only to solve a large number of problems which did not yield to the old formulation of the theory, but also to obtain many new relations of a general character."

Author's preface to the Russian edition of „Methods of Quantum Field Theory in Statistical Physics" (1961), cited from the 1963 english translation

Lessons from the Case Study

- continuous knowledge transfer from QED and nuclear physics to solid state theory
- field-theoretic methods (Schwinger, Dyson, Feynman), available from QED since early 1950s, only slowly transferred to solid state theory
- crucial component came from outside: Gell-Mann and Brueckner interested in thermonuclear fusion
- remarkable growth of SSP as a field of research ignited by development of a unified point of view toward many-body problems in the solid state:
  - solution of model problems
  - interrelationship between quasiparticle and collective modes and their emergence from the basic interactions
  - new, intuitive concepts and pictures (correlation holes, quasiparticles, collective modes, effective interactions)
- deep transformation of working style and heuristics in SSP

Working Hypotheses (1)

- Why was the knowledge transfer so slow?
  - The astonishing success of simple single-electron models was curse rather than blessing!
    - e.g. Drude-Sommerfeld theory of metals
  - Divergences were not taken seriously in „dirt“ physics!
    - see e.g. discussion in Pines book
  - Postwar many-body theorists concentrated on nuclear physics!
    - nuclear physics on the rise during the War (evidence in many biographies)
    - slow (re-)conversion of nuclear physicists to SSP in the 1950s
    - Landau school primarily interested in nuclear many-body phenomena
    - Gell-Mann and Brueckner work resulted from project on thermonuclear fusion
  - Postwar SSP is a model system to study frictional effects of Cold War and McCarthyism!
    - different schools of thought in East and West, hindered knowledge transfer
    - Bohm‘s ejection from the United States

QUANTUM HISTORY

Working Hypotheses (2)

- Was the Gell-Mann-Brueckner work the crucial missing piece?
  - Yes, because divergences were the central obstacle!
    - removal by full summation of the perturbation series using Feynman diagrams
- Why (and how) did the Gell-Mann-Brueckner work ignite the dynamics of the field?
  - Conceptual simplificaton led to deep transformation of solid state theory!
    - effective single-particle description using quasiparticles and collective modes
    - resulting effective models extremely successful
  - But: What is the exact relation of the removal of degeneracies to the emergence of the effective models?
- What is the role of experiment in this story?
- How did solid state theory cross-fertilize the fields from which it drew its original inspiration?
  - SSP has a lower degree of abstraction and richer phenomenology!
    - spontaneous symmetry-breaking and the renormalization group

Summary

- general claims
- case study in postwar theoretical physics: the quantum plasma
- lessons from the case study
- working hypotheses

Work in progress!

SSP and QM

- The study of the history of Condensed Matter Physics holds great promises, also with respect to fundamental aspects of quantum mechanics:

  superconductivity, quantum Hall effects, (quantum) phase transitions, geometric phases, fractional statistics, renormalization group, symmetry breaking, complexity, emergence, ...