

## Crafting the Quantum

Arnold Sommerfeld and the Practice of Theory, 1890–1926

Suman Seth

The MIT Press  
Cambridge, Massachusetts  
London, England

© 2010 Massachusetts Institute of Technology

All rights reserved. No part of this book may be reproduced in any form by any electronic or mechanical means (including photocopying, recording, or information storage and retrieval) without permission in writing from the publisher.

For information on special quantity discounts, email [special\\_sales@mitpress.mit.edu](mailto:special_sales@mitpress.mit.edu).

Set in Stone sans and Stone serif by Toppan Best-set Premedia Limited. Printed and bound in the United States of America.

Library of Congress Cataloging-in-Publication Data

Seth, Suman, 1974–

Crafting the quantum : Arnold Sommerfeld and the practice of theory, 1890–1926 / Suman Seth.

p. cm. — (Transformations : studies in the history of science and technology)

Includes bibliographical references and index.

ISBN 978-0-262-01373-4 (hardcover : alk. paper)

1. Sommerfeld, Arnold, 1868–1951. 2. Quantum theory. 3. Physics. I. Title.

QC16.S76S48 2010

530.09'04—dc22

2009022212

10 9 8 7 6 5 4 3 2 1

## Index

- Abraham, Max, 31, 170
- Arrhenius, Svante, 98, 99, 105, 106, 110–112
- Atombau und Spektrallinien*
- aesthetics and, 202
  - as “bible” of quantum spectroscopy, 178
  - correspondence principle in, 228, 234–238, 254
  - electrodynamics in, 155, 156, 227–230
  - Ellipsenverein* in, 218
  - experimental data in, 173
  - models and *Gesetzmässigkeiten* in, 214, 221–224, 238, 254, 257
  - pedagogy and, 241
  - quantum numbers in, 259, 260
  - reception of, 204, 205
  - relativity in, 170, 260
  - structure of, 227–229
  - World War I and, 90
- Atomic spectra, 162–165, 168–171, 205–213
- Bethe, Hans, 9, 60, 62, 182, 264, 267
- Black-body theory
- and electromagnetic worldview, 39–43, 145
  - Planck’s development of, 8, 95, 112, 114–131, 145, 157
  - Sommerfeld and, 14, 30, 35–39
- Bohr model, 9, 155, 162–169, 214–223, 251–256
- Bohr, Niels
- and Born, 60, 61
  - and correspondence principle, 233–235, 238–240
  - and planetary atomic model, 162
  - and principles, 2, 185, 194–198
  - second atomic theory of, 251–254, 259
  - and Sommerfeld, 9, 183, 185, 219, 225–227, 232–236, 239–241
  - and Sommerfeld School, 143
  - on Sommerfeld’s work, 170, 171
- Boltzmann, Ludwig
- at Munich, 49, 50
  - and Ostwald, 144
  - and Planck’s black-body derivation, 35, 36, 116, 119–126, 132, 136
- Born, Max
- pedagogy of, 58, 61
  - on Planck, 183
  - on Sommerfeld, 4, 184, 203–205, 223
  - on Sommerfeld School, 3, 48
  - as “virtuoso,” 186
  - and World War I, 73–76, 179
- Cahan, David, 5
- Cambridge Tripos, 56, 65–68, 191, 193
- Cantor, Matthias, 112, 113
- “Classical” physics, 1, 139, 155, 157
- Compton, Arthur Holly, 236
- Compton effect, 236, 237
- Constructive theories, 184, 187, 190–193
- Correspondence principle, 9, 196–198, 221, 225–227, 232–241, 256

- Coster, Dirk, 258, 259
- Craft of the quantum, 6, 9, 201–204, 212, 225
- Creativity, 7, 66–70
- Crisis, 265–269
- Darrigol, Olivier, 226, 227
- Debye, Peter  
 on quantum theory, 141, 217  
 and Sommerfeld School, 2, 48, 58, 60, 62  
 as “virtuoso,” 186
- De Sitter, Willem, 191
- Dirac, Paul, 193, 194, 265
- Disciplining, 65–69
- Dynamical method  
 and quantum, 8, 142, 143  
 of Sommerfeld, 142, 143, 149–156, 161, 162, 165, 171, 173
- Dyson, Frank, 184, 190
- Eddington, Arthur Stanley, 184, 190–193
- Ehrenfest, Paul, 35, 36, 166, 185–187, 196
- Einstein, Albert  
 and Mach, 188, 189  
 and observability, 262, 263  
 and politics, 90, 178, 180  
 on principles, 2, 184–190  
 and relativity, 90, 184, 185, 189–191  
 on Sommerfeld, 79, 80  
 on Sommerfeld School, 3, 48, 242
- Electromagnetic worldview  
 and method, 32, 37, 38, 44–46, 145  
 and quantum world, 154–156, 229–231, 234, 235  
 and relativity, 31  
 and resistance to quantum, 30–32, 37–43, 145  
 Sommerfeld’s adherence to, 3, 6, 14, 30–33, 37, 38, 42, 44, 141, 142, 145, 151, 154–156  
 and Sommerfeld School, 33, 44, 156, 242
- Electron theory  
 and electromagnetic worldview, 31–33, 38–43, 142, 145  
 and impulse theory, 146, 147  
 and quantum theory, 37–43
- Sommerfeld and, 17, 31–33, 38, 40, 42, 142, 145, 147, 156, 163, 164
- Ellipsenverein*, 217, 218, 221
- Energeticists, 97, 143–145
- Engineering  
 in Germany, 20, 21  
 and mathematics, 21–25  
 and Sommerfeld’s physics, 2, 5, 6, 14, 19, 22–25, 201  
 and Sommerfeld School, 28, 52  
*technische Hochschule* and, 5, 19–21
- Epstein, Paul, 61, 171
- Ewald, Paul  
 on Sommerfeld’s pedagogy, 17, 47, 49, 62, 63  
 on Sommerfeld’s physics, 46  
 and World War I, 75, 76, 85
- Exclusion principle, 247–251, 256, 257
- Forman, Paul, 212, 225, 260, 265, 267
- Foucault, Michel, 48, 64–69
- Fuchs, R., 87–89
- Garber, Elizabeth, 145
- Gesetzmässigkeiten* (lawful regularities)  
 and Pauli exclusion principle, 249, 250, 256, 257  
 reception of, 223–225  
 Sommerfeld’s adoption of, 9, 204, 205, 212–214, 219, 223, 263  
 Sommerfeld’s search for, 4, 207–209  
 and spectroscopic laws, 209–211
- Gibbs, Josiah Willard, 108
- Glitscher, Karl, 170, 242
- Graetz, Leo, 50, 51
- Gyroscopic motion, 6, 25–27, 79, 84
- Haber, Fritz, 73–77
- Heilbron, John, 266
- Heisenberg, Werner  
 on atomic spectra, 250, 263  
 experimental incompetence of, 182  
 and quantum mechanics, 262–264

- and Sommerfeld school, 9, 51, 52, 57–61, 182, 183, 241, 242, 244, 248  
and *Umdeutung*, 248, 262–264
- Helmholtz, Hermann von, 95, 96, 106, 115, 137
- Hermann, Armin, 171
- Hertz, Heinrich, 114, 115, 118, 119, 137
- Hoerschelmann, Hermann von, 82
- Høffding, Harald, 197–200
- Hondros, Demetrios, 49
- Hopf, Ludwig  
on aircraft design, 85–89  
and hydrodynamics (turbulence), 18, 28, 29, 45, 49, 85–89  
and Sommerfeld School, 28, 29, 49, 87, 89  
and World War I, 7, 71, 72, 85–89, 90
- Hüter, Wilhelm, 75, 83
- Ideal processes, 7, 8, 98, 99, 107–113, 132–136, 173
- Jeans, James, 14, 36, 43, 193
- Kaiser, David, 64–66
- Kaiser's physicists, 7, 72, 73, 84
- Kaufmann, Walter, 31
- Kirchhoff, Gustav, 95, 115, 137, 145, 146
- Klein, Felix, 16, 19, 24–26, 56, 57
- Kohlrausch, Friedrich, 5
- Kossel, Walter, 211, 214
- Kragh, Helge, 237
- Kriegsphysik*, 77, 86, 90
- Kroo, Jan, 217, 218
- Kuhn, Thomas  
on black-body theory, 122, 145  
on crises and revolutions, 10, 265–269  
on pedagogy, 64, 65  
on quantum discontinuity, 30, 39, 40, 43
- Ladenburg, Rudolf, 75, 76
- Landé, Alfred, 221, 224, 239, 244, 249, 250, 260
- Langevin, Paul, 8, 142, 150, 158, 165
- Lenard, Phillip, 180
- Lenz, Wilhelm, 7, 83, 85
- Lorentz, Hendrik Antoon  
and electromagnetic worldview, 31, 38–42  
and electron theory, 17, 31, 37, 38, 39  
and quantum discontinuity, 30, 31, 39–42  
on Zeeman effect, 163, 164
- Lummer, Otto, 39
- Mach, Ernst, 97, 133, 134, 143, 188, 189, 198
- Matrix mechanics, 264, 265
- Maxwell, James Clerk, 41, 66, 143, 159, 160
- McCormach, Russell, 32
- Mechanical worldview, 32, 97, 134
- Modellmässig* (model-based) approach  
Bohr and, 162–165, 239, 251–254  
Heisenberg and, 10, 250, 264  
Pauli and, 9, 223, 250, 251, 256, 258, 261  
Sommerfeld and, 9, 163–173, 204–223, 227, 228, 235, 238–240, 244, 254, 245  
“Modern” physics, 1, 139, 155
- Natural radiation, 114, 121–126,
- Nernst, Walther, 79, 106, 139, 141
- Neumann, Franz, 15, 69
- Noether, Fritz, 7, 84
- Olesko, Kathryn, 69
- “On the Unity of the Physical World  
Picture,” 133–136
- Orr, William McFadden, 133
- Ostwald, Wilhelm, 105, 143, 144
- Paschen, Friedrich, 163, 164, 170
- Pauli, Wolfgang  
and crisis, 265  
and exclusion principle, 247, 249, 251, 256, 257, 261  
and models, 223, 245, 250, 256  
and “Pauli effect,” 181  
and Sommerfeld school, 9, 62, 257  
and *Zweideutigkeit*, 257, 258, 261
- Pauling, Linus, 9, 51, 266

- Pearson, Karl, 56
- Pedagogical economy, 6, 48, 61, 63, 68
- Pfrang, Hans, 242, 243
- Physics of problems  
 and crises and revolutions, 267–269  
 historical context of, 5, 7, 19, 72, 91  
 and physics of principles, 2, 3, 43  
 and Sommerfeld School, 2, 5, 19, 30, 54, 72, 85, 241–243, 249  
 as Sommerfeld's style, 3, 44, 45
- Planck, Max  
 and anthropomorphism, 134–136, 160, 173, 187  
*Antrittsrede*, 95, 96, 107  
 and Arrhenius, 98, 99, 105, 106, 110–112  
 and black-body theory, 8, 95, 112, 114–131, 145, 157  
 decline of, 183, 184  
 on dilute solutions, 101–105  
 on experiment, 97, 109, 136, 137  
 on ideal processes, 7, 8, 98, 99, 107–113, 132–136, 173  
 on irreversibility, 114, 117, 119, 120, 124, 126, 129, 135, 136  
 pedagogical practices of, 56  
 on principles, 2, 3, 97, 98, 133–138, 173, 187  
 on quantum hypothesis, 8, 141, 156–161  
 on quantum of action, 158–161  
 second theory of, 157, 160, 161  
 at Solvay Congress, 157–160  
 “statistical” method of, 8, 142, 143, 150, 156–162  
 theoretical methodology of, 107–110  
 on theory and experiment, 97, 109, 110, 132, 133  
 on thermochemistry, 95, 98, 99, 107, 109, 127, 128  
 and “thermodynamic method,” 97–99, 106, 113, 138, 145, 173
- Pockels, Friedrich, 133
- Poincaré, Henri, 155
- Principles  
 Bohr and, 2, 185, 194–198  
 in Britain, 194  
 crises and revolutions and, 268, 269  
 Eddington and, 192, 193  
 Einstein and, 184–190  
 Høffding and, 198–200  
 Jeans and, 193  
 Mach and, 134, 188, 189  
 physics of, 2, 3, 5, 7, 43, 184, 187, 188, 268, 269  
 Planck and, 2, 3, 97, 98, 133–138, 173, 187  
 practice of, 2, 7, 97  
 Sommerfeld and, 57, 58  
 Pringsheim, Ernst, 39
- Quantum hypothesis  
 and electromagnetic worldview, 31, 37–43  
 Planck's postulation of, 8, 141, 156–161  
 Sommerfeld on, 30, 33–39, 140, 143, 147–149, 151, 153
- Rayleigh-Jeans equation, 37–41
- Relativity, 31, 42, 170, 189, 190–193
- Revolutions, 264–269
- Reynolds, Osborne, 28
- Riedler, Alois, 19, 21
- Roentgen, Wilhelm, 1, 13, 50, 76
- Routh, Edward, 56, 57, 67
- Rubinowicz, Adalbert, 228, 231, 232
- Runge, Carl, 163, 164, 207
- Rydberg, Johannes, 211
- Scherzer, Otto, 52
- Schrödinger, Erwin, 10, 183, 203, 223, 249, 264
- Schwarzschild, Karl, 77, 90, 171
- Serwer, Daniel, 248
- Solvay Conference (1911), 8, 30, 139–143, 149–151, 156–159
- Sommerfeld, Arnold  
 at Aachen Hochschule, 5, 19, 24  
 and aesthetics, 202, 203, 212, 225  
 on atomic spectra, 162–165, 168–171, 205–213

- and Atom-Mystik, 9, 202, 203, 225, 239, 251, 256
- on black-body theory, 14, 30, 34–39
- and Bohr, 9, 60, 183, 185, 219, 225–227, 232–236, 239–241
- on Bohr’s model, 9, 155, 162–169, 214–223, 254
- on connection of quantum and electromagnetic, 154–156, 230, 231, 234
- on correspondence principle, 9, 228, 233–241
- on diffraction, 145–147
- dynamical method of, 142, 143, 149–156, 161, 162, 165, 171, 173
- and electromagnetic worldview, 3, 6, 14, 30–33, 37, 38, 42, 44, 141, 142, 145, 151, 154–156
- on energetics, 144
- historiography of, 248
- on impulse theory, 146–149
- and Klein, 25–27
- as mathematician, 16, 24, 25
- at Munich, 51
- pedagogical practices of, 13, 14, 48, 51–60, 66–68, 172, 242
- and quantum hypothesis, 30, 33–39, 42, 140, 143, 147–153, 166
- on quantum of action, 148–151, 154, 155
- and quantum numbers, 168, 169, 205, 206, 210–212, 231, 232, 259, 260, 266
- “refashioning” of, 14, 18
- at Solvay Conference (1911), 139, 149–155
- on spectral laws, 209–211
- and spherical wave theory, 229–232, 236, 237
- style of, 3, 13, 44, 45, 142
- upbringing of, 15
- vision of theoretical physics of, 18, 25, 29, 30, 44, 142
- and World War I, 80–82
- Sommerfeld School
  - and construction of theoretical physics, 6, 14, 28, 44
  - and creativity, 66, 68, 70
  - and crises and revolutions, 267–269
  - informal pedagogical economy of, 61–63
  - practice of pedagogy in, 6, 28, 44, 47, 51–60, 91, 183, 241, 242
  - and problems, 2, 7, 15, 28, 44, 63, 64, 67, 79, 83–89, 241–244
  - and quantum physics, 9, 143, 156, 242–244
  - and “seminary,” 59–61
  - success of, 3, 9, 47, 48
  - and World War I, 7, 72, 79, 82–87, 91
- Stark, Johannes, 147, 180
- Statistical method
  - of Planck, 142, 143, 150, 156–162
  - and quantum, 8, 142, 143
  - Sommerfeld’s use of, 165–167, 172
- Stenström, W., 219, 220
- Stokes, George Gabriel, 145
- Stoner, E. C., 254–256
- Technik*, 201–204
- Technische Hochschulen, 5, 20–23
- Theoretical physics
  - construction of, 4, 5, 14, 18, 29, 30
  - development of in Munich, 47
  - and experiment, 3, 18, 29, 45, 97, 170, 173, 180–183
  - status of, 1, 4, 18, 137, 179–182
  - World War I and, 72–78, 90, 91, 179, 180
- Thermochemistry, 95, 98, 99, 107, 109, 127, 128
- Thermodynamic method, 97–99, 106, 113, 138, 145, 173
- Traweek, Sharon, 65, 181
- Über die Theorie des Kreisels*, 25–27, 57, 84
- Umdeutung*, 248, 262, 263
- van ’t Hoff, Jacobus, 98, 101, 104, 108, 110, 111
- Voigt, Woldemar
  - on classical and modern physics, 1
  - and phenomenology, 133, 212, 213, 263
  - and Sommerfeld, 16, 164, 212, 213, 263
- Volkman, Paul, 15, 17
- Von Jolly, Phillip, 137

*Vorlesungen über die Theorie der**Wärmestrahlung*, 14, 30, 33, 39, 158, 161

Warwick, Andrew, 6, 44, 64–66, 191

Wave mechanics, 249, 264

Wentzel, Gregor, 237, 238, 245, 258, 259

Wiechert, Emil, 13, 16, 145, 146

Wien, Max, 75

Wien, Wilhelm, 4, 32, 39–42, 73–75, 154,  
179, 182, 183, 202, 203

Wien's law, 129–131

Wireless telegraphy, 44, 45, 75, 76, 79–83,  
242, 243

## World War I

Hopf in, 7, 71, 72, 85–90

Sommerfeld and, 80–82

Sommerfeld School and, 7, 72, 79, 82–87, 91  
and theoretical physics, 72–78, 90, 91, 179,  
180

## X-rays

Sommerfeld on, 46, 146–151

and Sommerfeld School, 85

spectra of, 214–223, 260

and World War I, 76, 77, 85

## Zeeman effect

Heisenberg on, 244, 263

Lorentz on, 163, 164

Pauli on, 249, 251, 265

Sommerfeld on, 164, 207–209, 214, 219

Zenneck, Jonathan, 82

*Zweideutigkeit*, 251, 257, 258, 261