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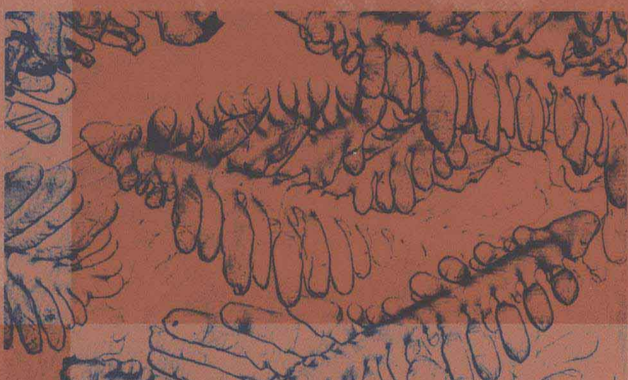
The Physics of Phase Transitions

Concepts and Applications



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Tranlated from the French by S. L. Schnur

With 175 Figures

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by Pierre Papon, Jacques Leblond and Paul H.E. Meijer

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The cover picture shows dentrites from a Co–Sm–Cu alloy, by courtesy of Prof. W. Kurz, Laboratoire de métallurgie Physique, Ecole Polytechnique fédérale de Lausanne, Lausanne, Switzerland.

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The Physics of Phase Transitions

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This program of advanced texts covers a broad spectrum of topics which are of current and emerging interest in physics. Each book provides a comprehensive and yet accessible introduction to a field at the forefront of modern research. As such, these texts are intended for senior undergraduate and graduate students at the MS and PhD level; however, research scientists seeking an introduction to particular areas of physics will also benefit from the titles in this collection.

Foreword

We learned in school that matter exists in three forms: solid, liquid and gas, as well as other more subtle things such as the fact that "evaporation produces cold." The science of the states of matter was born in the 19th century. It has now grown enormously in two directions:

1) The transitions have multiplied: first between a solid and a solid, particularly for metallurgists. Then for magnetism, illustrated in France by Louis Néel, and ferroelectricity. In addition, the extraordinary phenomenon of superconductivity in certain metals appeared at the beginning of the 20th century. And other superfluids were recognized later: helium 4, helium 3, the matter constituting atomic nuclei and neutron stars... There is now a real zoology of transitions, but we know how to classify them based on Landau's superb idea.

2) Our profound view of the mechanisms has evolved: in particular, the very universal properties of fluctuations near a critical point – described by Kadanoff's qualitative analysis and specified by an extraordinary theoretical tool: the renormalization group.

Without exaggerating, we can say that our view of condensed matter has undergone two revolutions in the 20th century: first, the introduction of quantum physics in 1930, then the recognition of "self-similar" structures and the resulting scaling laws around 1970.

It would be naïve to make too much of these advances: despite all of this sophistication, we are still very unsure about certain points – for example, the mechanism governing superconducting oxides or the laws of the glass transition. However, a body of doctrines has been formed, and it is an important element of scientific culture in the year 2000.

This knowledge is generally expressed solely in works dedicated to only one sector. The great merit of the book by Drs. Papon, Leblond and Meijer is to offer a global introduction, accessible to students of physics entering graduate school. Of course, given the enormous expansion of the subject, many older readers will regret not finding their pet subject here (for example, in my case demixing transitions involving linear polymers). However, the panorama is broad enough for the young public targeted here: I hope the book will guide them soundly.

I wish it great success.

Paris, France
December 2001

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Preface

This book takes up and expands upon our teachings on thermodynamics and the physics of condensed matter at the School of Industrial Physics and Chemistry and Diplôme d'Etudes Approfondies in Paris and at the Catholic University of America in Washington D.C. It is intended for graduate students, students in engineering schools, and doctoral students. Researchers and industrial engineers will also find syntheses in an important and constantly evolving field of materials science.

The book treats the major classes of phase transitions in fluids and solids: vaporization, solidification, magnetic transitions, critical phenomena, etc. In the first two chapters, we give a general description of the phenomena, and we dedicate the next six chapters to the study of a specific transition by explaining its characteristics, experimental methods for investigating it, and the principal theoretical models that allow its prediction. The major classes of application of phase transitions used in industry are also reported. The last three chapters are specifically dedicated to the role of microstructures and nanostructures, transitions in thin films, and finally, phase transitions in large natural and technical systems. Our approach is essentially thermodynamic and assumes familiarity with the basic concepts and methods of thermodynamics and statistical physics. Exercises and their solutions are given, as well as a bibliography.

Finally, we would we like to thank J. F. Leoni who assisted in the preparation of the manuscript and the drawings and diagrams and Dr. S. L. Schnur who put much effort into translating the book as well as J. Lenz and F. Meyer from Springer-Verlag who provided helpful advice in publishing the book. We are also grateful to our colleague Prof. K. Nishinari, from Osaka City University, for his valuable comments on our manuscript.

Paris, France, *Pierre Papon*
Paris, France, *Jacques Leblond*
Washington, D.C., U.S.A., *Paul H. E. Meijer*
December 2001

Principal Notation

A	Area
$\boldsymbol{B}$	Magnetic induction
C_p	Specific heat at constant pressure
c_p	Specific heat at constant pressure per unit of mass
C_v	Specific heat at constant volume
c_v	Specific heat at constant volume per unit of mass
d	Intermolecular distance
$D(\varepsilon)$	Density of states
e	Elementary charge
E	Energy
$\boldsymbol{E}$	Electric field
f	Free energy per unit of mass, radial or pair distribution function
F	Free energy (Helmholtz function)
$\boldsymbol{F}$	Force
g	Free enthalpy per unit of mass or volume
G	Free enthalpy (Gibbs function)
$g(E)$	Degeneracy factor
H	Enthalpy
h	Enthalpy per unit of mass or volume, Planck's constant
$\boldsymbol{H}$	Magnetic field, Hamiltonian
$\mathcal{H}$	Hamiltonian
$\boldsymbol{j}$	Current density per unit of surface
J	Flux, grand potential
$\boldsymbol{k}$	Wave vector
k	Boltzmann constant
L	Latent heat
l	Latent heat per unit of mass or volume, length
m	Mass
M	Molecular weight
$\boldsymbol{M}$	Magnetization
n	Particle density (N/V)
N	Number of particles
N_0	Avogadro's number
p	Pressure

$\boldsymbol{p}$	Momentum
P	Order parameter, probability
$\boldsymbol{P}$	Electric polarization
q	Position variable
Q, q	Quantity of heat
$\boldsymbol{r}$	Distance
R	Ideal gas constant
s	Entropy per unit of mass or volume
S	Entropy
t	Time
T	Absolute temperature (Kelvin)
T_C	Critical temperature
U	Internal energy
u	Internal energy per unit of mass or volume, pair-potential
V	Volume
v	Velocity, variance
W	Number of states, work
w	Probability distribution
x	Concentration
X	Extensive variable
Y	Intensive variable (field)
z	Coordination number
Z	Partition function, compressibility factor
α	Volume expansion coefficient
β	Reciprocal temperature parameter, $1/kT$
χ	Magnetic susceptibility, helical pitch
Δ, δ	Increase in a variable
ε	Elementary particle energy, $\lvert T - T_C \rvert / T_C$
γ	Surface tension
η	Viscosity
$\varXi$	Grand partition function
$\varTheta$	Debye temperature
κ	Compressibility
λ	Wavelength, thermal conductivity
$\varLambda$	de Broglie thermal wavelength
μ	Chemical potential
ν	Frequency
ρ	Density
τ	Relaxation time
ω	Acentric factor, frequency
$\varPsi$	Thermodynamic potential, wave function
ξ	Correlation length
$\varOmega$	Grand potential
$\varOmega(E)$	Number of accessible states

Table of Principal Constants.

Avogadro's number	N_0	6.02205×10^{23}
Boltzmann's constant	k	1.38066×10^{-23}J K^{-1}
Gas constant	R	8.31141J K^{-1} mole^{-1}
Planck's constant	h	6.62618×10^{-34} J s
Standard atmosphere	p_0	1.01325×10^5N m^{-2}
Triple point of water	T_0	273.16 K
Electron charge	e	1.60219×10^{-19} C
Electron mass	m_e	9.10953×10^{-31} kg
Bohr magneton ($eh/4\pi m_e$)	μ_B	0.927408×10^{-23}A m^2
kT at 300 K	–	4×10^{-21}J $= 1/40$ eV

Energy: 1 Joule = 10^7 ergs = 0.2389 cal = 9.48×10^{-4} btu

Pressure: 1 Pascal = 1 Newton m^{-2} = 10^{-5} bar = 10 dynes cm^{-2}

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