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# Nanoscience and Engineering in Superconductivity

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（影印版）

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# Nanoscience and Engineering in Superconductivity

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# 序　言

物理学是研究物质、能量以及它们之间相互作用的科学。她不仅是化学、生命、材料、信息、能源和环境等相关学科的基础,同时还是许多新兴学科和交叉学科的前沿。在科技发展日新月异和国际竞争日趋激烈的今天,物理学不仅囿于基础科学和技术应用研究的范畴,而且在社会发展与人类进步的历史进程中发挥着越来越关键的作用。

我们欣喜地看到,改革开放三十多年来,随着中国政治、经济、教育、文化等领域各项事业的持续稳定发展,我国物理学取得了跨越式的进步,做出了很多为世界瞩目的研究成果。今日的中国物理正在经历一个历史上少有的黄金时代。

在我国物理学科快速发展的背景下,近年来物理学相关书籍也呈现百花齐放的良好态势,在知识传承、学术交流、人才培养等方面发挥着无可替代的作用。从另一方面看,尽管国内各出版社相继推出了一些质量很高的物理教材和图书,但系统总结物理学各门类知识和发展,深入浅出地介绍其与现代科学技术之间的渊源,并针对不同层次的读者提供有价值的教材和研究参考,仍是我国科学传播与出版界面临的一个极富挑战性的课题。

为有力推动我国物理学研究、加快相关学科的建设与发展,特别是展现近年来中国物理学者的研究水平和成果,北京大学出版社在国家出版基金的支持下推出了“中外物理学精品书系”,试图对以上难题进行大胆的尝试和探索。该书系编委会集结了数十位来自内地和香港顶尖高校及科研院所的知名专家学者。他们都是目前该领域十分活跃的专家,确保了整套丛书的权威性和前瞻性。

这套书系内容丰富,涵盖面广,可读性强,其中既有对我国传统物理学发展的梳理和总结,也有对正在蓬勃发展的物理学前沿的全面展示;既引进和介绍了世界物理学研究的发展动态,也面向国际主流领域传播中国物理的优秀专著。可以说,“中外物理学精品书系”力图完整呈现近现代世界和中国物理

科学发展的全貌，是一部目前国内为数不多的兼具学术价值和阅读乐趣的经典物理丛书。

“中外物理学精品书系”另一个突出特点是，在把西方物理的精华要义“请进来”的同时，也将我国近现代物理的优秀成果“送出去”。物理学科在世界范围内的重要性不言而喻，引进和翻译世界物理的经典著作和前沿动态，可以满足当前国内物理教学和科研工作的迫切需求。另一方面，改革开放几十年来，我国的物理学研究取得了长足发展，一大批具有较高学术价值的著作相继问世。这套丛书首次将一些中国物理学者的优秀论著以英文版的形式直接推向国际相关研究的主流领域，使世界对中国物理学的过去和现状有更多的深入了解，不仅充分展示出中国物理学研究和积累的“硬实力”，也向世界主动传播我国科技文化领域不断创新的“软实力”，对全面提升中国科学、教育和文化领域的国际形象起到重要的促进作用。

值得一提的是，“中外物理学精品书系”还对中国近现代物理学科的经典著作进行了全面收录。20 世纪以来，中国物理界诞生了很多经典作品，但当时大都分散出版，如今很多代表性的作品已经淹没在浩瀚的图书海洋中，读者们对这些论著也都是“只闻其声，未见其真”。该书系的编者们在这方面下了很大工夫，对中国物理学科不同时期、不同分支的经典著作进行了系统的整理和收录。这项工作具有非常重要的学术意义和社会价值，不仅可以很好地保护和传承我国物理学的经典文献，充分发挥其应有的传世育人的作用，更能使广大物理学人和青年学子切身体会我国物理学研究的发展脉络和优良传统，真正领悟到老一辈科学家严谨求实、追求卓越、博大精深的治学之美。

温家宝总理在 2006 年中国科学技术大会上指出，“加强基础研究是提升国家创新能力、积累智力资本的重要途径，是我国跻身世界科技强国的必要条件”。中国的发展在于创新，而基础研究正是一切创新的根本和源泉。我相信，这套“中外物理学精品书系”的出版，不仅可以使所有热爱和研究物理学的人们从中获取思维的启迪、智力的挑战和阅读的乐趣，也将进一步推动其他相关基础科学更好更快地发展，为我国今后的科技创新和社会进步做出应有的贡献。

“中外物理学精品书系”编委会 主任
中国科学院院士，北京大学教授
**王恩哥**
2010 年 5 月于燕园

# Preface

The key technologies of the twenty-first century have been recently identified: energy, transport, nanotechnology, information/communication technology, health care, and environment. Remarkably, for several of them, superconductivity is of special interest, since it deals with the flow of charged particles (electron pairs) without dissipation, thus enabling superior performance needed for new energy-saving technologies. This unique property is a very valuable asset for developing a variety of fascinating technologies belonging to *grand challenges*. To name a few, these technologies range from next generation self-healing superconducting electricity grids, saving up to 15% of the transported electricity, superconducting generators with improved performance deployable among others in off-shore wind turbines or for ship propulsion, superconducting induction heater for power-saving metal processing, International Thermonuclear Reactor (ITER) with the superconducting magnet holding a very hot plasma making possible the fusion reaction, the levitating train operating at speeds exceeding 500 km/h, superconducting elements for quantum computing, to medical diagnostics tomography and magnetoencephalography with highest resolution.

To enable the emerging new technologies, the superconducting materials with a superior performance can be developed by manipulating the appropriate "elementary building blocks" through nanostructuring. For superconductivity, such "elementary blocks" are *Cooper pairs* and *fluxons*.

To support this research, in 2007 the European Science Foundation (ESF) had launched the 5-year Programme *Nanoscience and Engineering in Superconductivity – NES* (http://www.kuleuven.be/inpac/nes/).

Integration and efficient use of the NES experimental and theoretical techniques of the teams from the 15 EU countries participating in this program is achieved through the following activities:

- Implementation of coordinated joint scientific research
- Sharing complimentary equipment
- Joint applications for EU, ESF, and other international projects
- Joint supervision of the PhD work
- Keeping intense electronic exchange of reprints, preprints, data bases, etc
- Joint publication of original and review articles

- Exchange of lecturers, researchers, samples, software, and databases
- Creating and regularly updating dedicated NES website

The main objective of this program is to investigate the effects of the nanoscale confinement of condensate and flux on superconductivity to reveal its nanoscale evolution and to determine the fundamental relations between quantized confined states and the physical properties of these systems. Along the line of the main objective, the ESF-NES research activities are focused on the following topics

- Evolution of superconductivity at the nanoscale

The correlation between the nanograin size and the superconducting gap and the critical temperature $T_c$ is investigated theoretically and experimentally. By systematically reducing the characteristic size of the grains and nanocells the crossover between the bulk superconducting regime and fluctuation-dominated superconductivity regime will be revealed

- Superconductivity in hybrid superconducting – normal (SN) and superconducting – ferromagnet (SF) nanosystems with tuneable boundary condition

Confined condensate is studied in superconducting nano-islands surrounded by normal metallic or ferromagnetic material. The role of proximity effects and the Andreev reflection in modifying the transparency of the sample boundaries will be revealed. The variation of the superfluid density near the boundary is mapped using the local scanning tunneling spectroscopy (STS) techniques. Different vortex configurations, including those with symmetry induced antivortices, and their dynamics are investigated in individual nanostructures of different geometries. Here strong effects of the specific boundary conditions on confined flux and condensate are expected.

- Confined flux in nanostructured superconductors and hybrid SN and SF nanosystems

Nanostructured superconductors and individual nanocells are investigated using local probe techniques, such as scanning tunneling microscopy (STM) and scanning Hall-probe microscopy, the distributions of the order parameter density and local magnetic fields are determined and then compared with the calculations of these parameters based on the solution of the Ginzburg–Landau (GL) equations with the realistic boundary conditions imposed though nanostructuring. Hybrid SN and SF arrays are also studied. Magnetic dots are used to generate local vortex–antivortex loops, which are strongly interacting with the flux lines in superconductors, creating a tunable magnetic periodic confinement. Here we can anticipate a very interesting interplay between flux generated by an applied field and magnetic dipoles, which can substantially enhance flux pinning.

- Josephson effects and tunneling in weakly coupled condensates

Josephson phenomena and phase-shifting effects are investigated in coupled superconducting condensates, where nanoscale coupling can be provided to tune the coupling strength. These phenomena are compared with Josephson effects in superfluids, mostly based on $^3$He.

- Fundamentals of fluxonics, superconducting devices

Different devices that control the motion of flux quanta in superconductors are designed and studied. One of the focal points is on the removal of trapped magnetic flux that produces noise. The controllable vortex motion is used in nanostructured superconductors for making pumps, diodes and lenses of quantized magnetic flux. Vortex ratchets effects are investigated and then used to achieve vortex manipulation.

This book highlights the recent advances achieved along these research lines in the framework of the ESF-NES Program and presents the new ways superconductivity and vortex matter can be modified through nanostructuring and the use of the nanoscale magnetic templates. The basic nano-effects visualized by the STM/STS techniques, vortex and vortex–antivortex patterns, vortex dynamics, guided vortex motion and vortex ratchets, Josephson phenomena, critical currents, interplay between superconductivity and ferromagnetism at the nanoscale, and potential applications of nanostructured superconductors are presented. The book targets researchers and graduate students working on and/or actively interested in superconductivity and nanosciences.

Leuven — *Victor Moshchalkov*
Jülich — *Roger Wördenweber*
Vienna — *Wolfgang Lang*
September 2010

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