REVIEWS of MODERN PHYSICS

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1947 ***Colloquium*: Ettore Majorana and the birth of autoionization**

E. Arimondo
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Ettore Majorana's life is surrounded by mystery since his disappearance in the late 1930s. He left behind, in only nine published papers, results, however, that are still having impact in physics up to these very days. In this Colloquium the authors discuss from a historical point of view his contributions to the issue of "autoionization," i.e., the problem of localized states immersed in a continuum. Those states were first observed in atomic spectra in the 1930s but since the 1960s autoionization has become a pervasive effect in different areas of physics. Several interesting puzzles in the treatment of Majorana's seminal work in subsequent developments towards the modern theory of autoionization are pointed out.

1959 **Berry phase effects on electronic properties**

Di Xiao
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The concept of the Berry phase arises when the evolution of a wave function is studied while some external parameters evolve along a closed loop in parameter space. It has been shown to have important consequences, and provide additional insight, for many problems involving electrons in solids. This review provides a pedagogical treatment of this important concept and its applications.

2009 **Charge symmetry at the partonic level**

J. T. Londergan
J. C. Peng
A. W. Thomas

The notion of isospin dates back to Heisenberg's 1932 suggestion that the near-identity of proton and neutron could be explained by treating them as two states of a single entity, the nucleon. Isospin is an approximate symmetry broken by interactions of electromagnetic origin. Charge symmetry represents a rotation in isospin space, and has been shown to be obeyed at low energies. At the partonic level breaking of charge symmetry occurs due to small mass differences between up and down quarks and other electromagnetic effects. This review discusses how charge symmetry breaking effects should lead to measurable differences in parton distribution functions. It summarizes the theoretical understanding of this area, reviews the experimental limits on partonic charge symmetry violation, and suggests experiments which could measure partonic charge symmetry violation.

2053 **Liquid xenon detectors for particle physics and astrophysics**

E. Aprile
T. Doke

Liquid xenon is widely used as a medium for radiation detection. Due to its high atomic number and density it has the highest stopping power for penetrating radiation, and the highest ionization and scintillation light yield of any rare gases in the liquid phase. Detectors exploiting the high sensitivity and excellent spatial and time resolution are being developed for a wide variety of applications, ranging from searches for dark matter and extremely rare processes that extend beyond the current standard model of particle physics to applications in medical imaging.

2099 **Normalization and global analysis of perturbations of the hydrogen atom** — K. Efstathiou, D. A. Sadovskiĭ

The hydrogen atom in the presence of a weak static electric or magnetic field was analyzed in detail in the early days of quantum mechanics. However, when both fields are present, with an arbitrary orientation and increased strength, the analysis is much more challenging. In recent years there has been significant progress in understanding such systems in cases when an integrable approximation can be used. These developments are reviewed in this article.

2155 **Quantum phase transitions in the shapes of atomic nuclei** — Pavel Cejnar, Jan Jolie, Richard F. Casten

Nuclear physicists early recognized that the structure of a complex nucleus is often governed by dynamic symmetries, founded in a group theoretical basis, or by simple geometrical descriptions, and attributed these structures to the features of the interaction between the constituents. This is also true for nuclear shape transitions: they can be studied using algebraic or geometric techniques that associate specific mathematical solutions with different nuclear shapes. In this review article it is shown in a straightforward and elegant way how the theory of phase transitions can be applied to describe the nuclear ground-state shapes in regions of structural change across the chart of the nuclides.

2213 **Hearing shapes of drums: Mathematical and physical aspects of isospectrality** — Olivier Giraud, Koen Thas

In this review the authors address the problem of isospectrality: the extent to which a physical system (e.g., the shape of a drum) is determined by its spectrum. Many mathematical and physical issues are raised by this problem and hence the literature on isospectrality is large. The authors concentrate their discussion primarily on questions connected to properties of planar two-dimensional domains with Dirichlet boundary conditions, often called billiards. In a gallery of examples it is shown that there are 17 known families of isospectral pairs in case of planar billiards.

2257 **Fano resonances in nanoscale structures** — Andrey E. Miroshnichenko, Sergej Flach, Yuri S. Kivshar

Fano resonances, long known in atomic physics, have received renewed interest recently in the context of nanostructures that act as "artificial atoms." This review article explains the underlying principles as well as the latest applications of this important analogy.

2299 **Nobel Lecture: Sand from centuries past: Send future voices fast** — Charles K. Kao

2305 **Nobel Lecture: CCD—An extension of man's view** — Willard S. Boyle

2307 **Nobel Lecture: The invention and early history of the CCD** — George E. Smith

The 2009 Nobel Prize for Physics was shared by Charles K. Kao, Willard S. Boyle, and George E. Smith. These papers are the text of the address given in conjunction with the award.

2313 **Quantum information with Rydberg atoms**

M. Saffman
T. G. Walker
K. Mølmer

The hyperfine states of most atomic systems are well isolated from the environment and can thus store quantum information reliably. However, in order to process such information (to build, for instance, a quantum computer), atoms must interact with each other. In typical atomic systems, those interactions are too weak. This review shows how by exciting the atoms to Rydberg states one can obtain very strong interactions which can then be used to carry out quantum gates, or to generate many-particle entangled states. The paper also explains recent exciting experiments in which some of those features have been demonstrated.

2365 **Magnetic dipole excitations in nuclei: Elementary modes of nucleonic motion**

Kris Heyde
Peter von Neumann-Cosel
Achim Richter

Magnetic properties of an atomic nucleus arise from orbital and spin magnetism of the constituent protons and neutrons. This review discusses various facets of the nuclear magnetic dipole response to electromagnetic and hadronic probes. Depending on proton and neutron number and excitation energy, collective magnetic modes can be excited. These are discussed within a broader many-body context of two-component or two-fluid quantum systems.

2421 **Progress and perspectives on electron-doped cuprates**

N. P. Armitage
P. Fournier
R. L. Greene

Assessing the similarities and differences between the electron-doped and the more numerous hole-doped cuprates provides a critical understanding of the nature of high temperature superconductivity in the cuprate family. This review summarizes the experimental status of electron-doped cuprates, paying particular attention to the order parameter symmetry, the phase diagram, and the normal state electronic structure. The presentation of a consistent viewpoint offers unique insight into what aspects of these compounds are universal, what aspects are not universal, and what aspects are crucial for the existence of high temperature superconductivity.

2489 **Hadronization of partons**

S. Albino

A critical issue for the interpretation of experimental data at high energy colliders is the relation between the observed hadrons and the underlying quarks and gluons in the interaction, i.e., the hadronization of partons. This article reviews understanding of the production of light hadrons in short distance processes. Topics treated include the basic formalism based on the factorization theorem; complications such as hadron mass and resummation effects; the status of global fits to determine the fragmentation functions using data from LEP, HERA, the Tevatron, and RHIC.

2557 **Positron-molecule interactions: Resonant attachment, annihilation, and bound states**

G. F. Gribakin
J. A. Young
C. M. Surko

The collision of a low energy positron and a molecule often results in a temporary bound state of the two collision partners. This process, which occurs via resonant excitation of one or more molecular vibrational modes, results in greatly increased positron annihilation rates. This article surveys theories and calculations of resonant annihilation and positron-molecule binding and compares their predictions with experimental results for a wide variety of molecular sizes and structures.

2609 ***Colloquium*: Trapped ions as quantum bits: Essential numerical tools**

Kilian Singer
Ulrich Poschinger
Michael Murphy
Peter Ivanov
Frank Ziesel
Tommaso Calarco
Ferdinand Schmidt-Kaler

One of the extreme examples of human control over matter comes from the field of atomic and molecular optics. Atoms can be cooled down to the lowest temperatures and manipulated to a huge degree of precision, leading to the proposal that these systems may even be used in quantum computation. Numerical simulations of cold atom systems can play an important role in projecting new experiments and architectures but also understanding the behavior of these systems. This Colloquium discusses the essential numerical tools for the description of these systems.

2633 **Jammed hard-particle packings: From Kepler to Bernal and beyond**

S. Torquato
F. H. Stillinger

Packing problems pervade physical phenomena from crystalline and liquid-crystalline ordering, to the arrangement of genetic information in cells and viruses, to the processing of powders and grains. In this review, the authors offer a scientific history and critical review of the purely geometric aspects of jammed packings, epitomized by the problem of hard spheres—a system which appears to have only one parameter, the volume fraction. Herein we learn that this simple characterization is insufficient and the notion of order metrics is reviewed. Concrete examples are discussed, along with nontrivial generalizations and compelling conjectures regarding packing of more complex objects in two, three, and higher dimensions.

2673 ***Colloquium*: The transport properties of graphene: An introduction**

N. M. R. Peres

Graphene, a single atom thick honeycomb layer of carbon atoms, is a truly two-dimensional material that has unique transport properties. This Colloquium begins by discussing simple models that show the emergence of a linear electronic spectrum of massless Dirac electrons having an electronic wave function that is chiral in nature. An intuitive understanding of recent experimental and theoretical results on the conductivity minimum, the electron mobility, the effect of strain and disorder, weak (anti)localization, and optical conductivity is presented.

2701 **Discrete flavor symmetries and models of neutrino mixing**

Guido Altarelli
Ferruccio Feruglio

All data on neutrino mixing are consistent with the "tri-bimaximal" pattern, which predicts precise values for the mixing angles, independent of the mass eigenvalues. This article reviews the attempts to understand neutrino mixing in terms of discrete flavor symmetries, especially the groups (A_4) S_4 of (even) permutations of four objects. The implications for leptogenesis, flavor changing processes, and possible extensions to quarks are discussed.

2731 **Ultrafast optical manipulation of magnetic order**

Andrei Kirilyuk
Alexey V. Kimel
Theo Rasing

Manipulation of magnetic order using femtosecond laser pulses offers the possibility to control and probe the magnetic state of a medium on a time scale that is equivalent to the exchange interaction, ultimately responsible for the existence of magnetic order itself. This review summarizes the experimental and theoretical studies of ultrafast optical manipulation of spins in all classes of both ferromagnetically and antiferromagnetically ordered solids, including metals, semiconductors, and dielectrics. The review elucidates the roles of electronic band structure, spin-orbit coupling, and magnetic structure in the optical control of magnetism. The relevant spin-orbit, spin-lattice, and electron-phonon interactions, which span a time scale from picoseconds to nanoseconds within these various materials, are discussed and compared.

2785 **Vortices in quantum droplets: Analogies between boson and fermion systems**

H. Saarikoski
S. M. Reimann
A. Harju
M. Manninen

Vortices are ubiquitous in classical and quantum fluids. In quantum fluids, vortices typically form regular arrays, a unique signature of quantization. One might expect that bosonic and fermionic fluids would display very different vortex properties but this review of the many-body physics of small particle systems reveals unexpected similarities. Systems of interest include atomic Bose-Einstein condensates and degenerate fermionic systems, quantum Hall states in a 2D electron gas, and quantum dots in strong magnetic fields. The major sections of the review are on many-body wave functions, computational many-body methods, and single-component and multicomponent quantum droplets.

Forthcoming articles