

J. Claycomb, Jonathan Quoc P. Tran

Introductory Biophysics Perspectives on the Living State

生物物理学导论



INTRODUCTORY BIOPHYSICS

PERSPECTIVES ON THE LIVING STATE

JAMES CLAYCOMB, PHD

Houston Baptist University

JONATHAN QUOC P. TRAN

University of Texas

Southwestern Medical Center



JONES AND BARTLETT PUBLISHERS

Sudbury, Massachusetts

BOSTON TORONTO LONDON SINGAPORE

NOT FOR SALE OUTSIDE OF THE CHINESE MAINLAND
Export or sale of this book outside the Chinese mainland is illegal

图书在版编目 (CIP) 数据

生物物理学导论 = Introductory Biophysics: Perspectives on the Living State: 英文 / (美) J. 克莱科姆 (J. Claycomb), J. Q. P. 特兰 (Jonathan Quoc P. Tran) 著 . —影印本 . —北京: 世界图书出版有限公司北京分公司, 2018.12

ISBN 978-7-5192-4860-4

I . ①生… II . ①J… ②J… III . ①生物物理学—教材—英文 IV . ①Q6

中国版本图书馆 CIP 数据核字 (2018) 第 173924 号

中文书名 生物物理学导论
英文书名 Introductory Biophysics: Perspectives on the Living State
著 者 J. Claycomb, Jonathan Quoc P. Tran
责任编辑 刘 慧 高 蓉
装帧设计 刘敬利

出版发行 世界图书出版有限公司北京分公司
地 址 北京市东城区朝内大街 137 号
邮 编 100010
电 话 010-64038355 (发行) 64033507 (总编室)
网 址 <http://www.wpcbj.com.cn>
邮 箱 wpcbjst@vip.163.com
销 售 新华书店
印 刷 北京建宏印刷有限公司
开 本 787 mm × 1092 mm 1/16
印 张 23.5
字 数 436 千字
版 次 2019 年 1 月第 1 版
印 次 2019 年 1 月第 1 次印刷
版权登记 01-2018-5239
国际书号 ISBN 978-7-5192-4860-4
定 价 99.00 元

版权所有 翻印必究

(如发现印装质量问题, 请与所购图书销售部门联系调换)

World Headquarters

Jones and Bartlett Publishers
40 Tall Pine Drive
Sudbury, MA 01776
978-443-5000
info@jbpub.com
www.jbpub.com

Jones and Bartlett Publishers
Canada
6339 Ormindale Way
Mississauga, Ontario L5V 1J2
Canada

Jones and Bartlett Publishers
International
Barb House, Barb Mews
London W6 7PA
United Kingdom

Jones and Bartlett's books and products are available through most bookstores and online book-sellers. To contact Jones and Bartlett Publishers directly, call 800-832-0034, fax 978-443-8000, or visit our website www.jbpub.com.

Substantial discounts on bulk quantities of Jones and Bartlett's publications are available to corporations, professional associations, and other qualified organizations. For details and specific discount information, contact the special sales department at Jones and Bartlett via the above contact information or send an email to specialsales@jbpub.com.

Copyright © 2011 by Jones and Bartlett Publishers, LLC

All rights reserved. No part of the material protected by this copyright may be reproduced or utilized in any form, electronic or mechanical, including photocopying, recording, or by any information storage and retrieval system, without written permission from the copyright owner.

QuickField™ is a trademark of Tera Analysis, Ltd. Copyright © 2009, Tera Analysis.

MATLAB® is a registered trademark of The MathWorks, Inc. Copyright © 2010, The MathWorks, Inc.

Production Credits

Publisher: David Pallai

Editorial Assistant: Molly Whitman

Production Manager: Tracey Chapman

Production Assistant: Ashlee Hazeltine

Associate Marketing Manager: Lindsay Ruggiero

V.P., Manufacturing and Inventory Control: Therese Connell

Composition: Lapiz Online

Cover Design: Scott Moden

Cover Image: Courtesy of Jacques Descloitres, MODIS Rapid Response Team, NASA/GSFC

Printing and Binding: Malloy, Inc.

Cover Printing: Malloy, Inc.

Library of Congress Cataloging-in-Publication Data

Claycomb, James R.

Introductory biophysics: perspectives on the living state / James R. Claycomb, Jonathan Quoc P. Tran.
p. cm.

ISBN-13: 978-0-7637-7998-6 (hardcover)

ISBN-10: 0-7637-7998-9 (ibid.)

1. Biophysics. I. Tran, Jonathan Quoc P. II. Title.

QH505.C53 2011

571.4—dc22

ORIGINAL ENGLISH LANGUAGE EDITION PUBLISHED BY

Jones & Bartlett Learning, LLC

5 Wall Street

Burlington, MA 01803 USA

jblearning.com

Phone: 800-832-0034

Introductory Biophysics: Perspectives on the Living State, J. R. Claycomb © Copyright 2010 JONES & BARTLETT LEARNING, LLC. ALL RIGHT RESERVED

NOT FOR SALE OUTSIDE OF THE CHINESE MAINLAND.

Export or sale of this book outside the Chinese mainland is illegal.

*Dedicated to the memory of
John Vay*

Introduction

Physics is the most basic natural science. It is the lowest-level science on a tree diagram representing the natural sciences. Other sciences such as chemistry and biology are higher-level sciences. Now it is possible to begin on one of the natural science branches and proceed quite a distance without knowledge of the more basic physical principles such as Newton's laws and gravitation. General physics, for example, is rarely a prerequisite for introductory biology and chemistry. To sprout new branches in our understanding of nature, and biology in particular, the tools of basic physics and chemistry are often required.

One goal of this textbook is to introduce biophysical theory concurrently with computer simulation. Another goal is to emphasize several important themes such as the role of entropy and the ubiquity of the statistical Boltzmann factor describing many aspects of the living state from the establishment of membrane potentials to the sedimentation of cell cultures. A key perspective of the textbook considers life in relation to the universe as a whole.

Additional computer simulation examples and exercises in the text and on the companion CD enable modeling of biophysical phenomena such as diffusion, establishment of membrane potential, bioimpedance, and the electrical response of cells and organelles to external fields. Dynamical models include the propagation of action potentials, nonlinear oscillations in population dynamics, and DNA vibrational modes. The formation of fractal structures, branching networks, and patterns in biology are also simulated. Contact with simulation methods further reinforces biophysical theory and strengthens the connection between physics and the life sciences.

Topics are arranged in increasing size scale and complexity. Chapters 1 and 2 give an introductory overview of biological structure and molecular forces. Chapters 3 through 6 cover heat transfer, thermodynamics, statistical mechanics, and diffusion, which play important roles in the biological domain. Chapter 7 covers fluid dynamics and the motion of bodies in fluid media. Bioenergetics, molecular motors, and the light absorption of biomolecules are discussed in Chapter 8. Chapters 9 through 11 discuss electrical and mechanical aspects of biophysics, including the passive response of cells and tissue to electric fields, field-induced stresses in biomaterials, and the propagation of action potentials in nerve cells. Biomagnetism and magnetic

measurements are discussed in Chapter 12. Nonlinearity, chaos, and complexity in the life sciences are covered in Chapters 13 and 14. The textbook concludes with an introduction to astrobiology in Chapter 15.

Acknowledgments

We would like to acknowledge Vladimir Podnos for helpful suggestions for implementing QuickField™ for biophysical applications, software support from The MathWorks, Inc. and Tera Analysis. Thanks to Barbara Benitez-Gucciardi for sharing insights in computational biology and the F–N model. We are thankful for many helpful conversations with Saul Trevino and Gardo Blado on protein folding and statistical physics, respectively. Many thanks are due John H. Miller, Jr. for introducing us to many topics covered here from biomagnetism to torque generation in ATP synthase. We are grateful for helpful suggestions from Audrius Brazdeikis and for supplying fetal magnetocardiography data using SQUIDS. Thanks to Cindy Troung and Anum Umer for their investigations on the effects of microgravity on the human body. We are grateful for figure support from NASA and ADInstruments. J. R. C. acknowledges support of the Texas Center for Superconductivity at the University of Houston.

Table of Contents

Introduction v

Chapter 1 Building Blocks and Structure 1

- 1.1 Atoms and Ions 1
 - 1.1.1 Subatomic Particles 1
 - 1.1.2 Atomic Constituents of Life 3
 - 1.1.3 Ions 3
- 1.2 Molecules Essential for Life 4
 - 1.2.1 Water 4
 - 1.2.2 Proteins 5
 - 1.2.3 Lipids 8
 - 1.2.4 Carbohydrates 10
 - 1.2.5 Cholesterol 10
 - 1.2.6 Nucleic Acid 11
- 1.3 What Is Life? 11
 - 1.3.1 Requirements for Life 12
 - 1.3.2 Domains of Life 12
 - 1.3.3 Characteristics of Living Cells 12
 - 1.3.4 Structure of Living Cells 13
 - 1.3.5 Boundary of Life 13

Chapter 2 Living State Interactions 17

- 2.1 Forces and Molecular Bonds 17
 - 2.1.1 Ionic Bonds 18
 - 2.1.2 Covalent Bonds 19
 - 2.1.3 Hydrogen Bonds 19
 - 2.1.4 Van der Waal Forces 20
- 2.2 Electric and Thermal Interactions 20
- 2.3 Electric Dipoles 21
 - 2.3.1 Polarization and Induced Dipoles 23

| | | |
|------------------|--|-----------|
| 2.4 | Casimir Interactions | 24 |
| 2.5 | Domains of Physics in Biology | 26 |
| | Exercises | 27 |
| Chapter 3 | Heat Transfer in Biomaterials | 29 |
| 3.1 | Heat Transfer Mechanisms | 29 |
| 3.1.1 | Conduction | 30 |
| 3.1.2 | Convection | 30 |
| 3.1.3 | Radiation | 31 |
| 3.2 | The Heat Equation | 32 |
| 3.2.1 | Transient Heat Flow | 32 |
| 3.2.2 | Steady State Heat Flow | 34 |
| 3.3 | Joule Heating of Tissue | 35 |
| | Exercises | 37 |
| Chapter 4 | Living State Thermodynamics | 39 |
| 4.1 | Thermodynamic Equilibrium | 40 |
| 4.2 | First Law of Thermodynamics and Conservation of Energy | 40 |
| 4.3 | Entropy and the Second Law of Thermodynamics | 41 |
| 4.3.1 | Does Life Violate the Second Law? | 41 |
| 4.3.2 | Measures of Entropy? | 42 |
| 4.3.3 | Free Expansion of a Gas | 42 |
| 4.4 | Physics of Many Particle Systems | 43 |
| 4.4.1 | How Boltzmann Factors in Biology | 44 |
| 4.4.2 | Canonical Partition Function | 45 |
| 4.4.3 | Average Energy | 46 |
| 4.4.4 | Entropy and Free Energy | 47 |
| 4.4.5 | Heat Capacity | 48 |
| 4.5 | Two-State Systems | 49 |
| 4.6 | Continuous Energy Distribution | 50 |
| 4.7 | Composite Systems | 50 |
| 4.7.1 | DNA Stretching | 51 |
| 4.8 | Casimir Contribution to the Free Energy | 53 |
| 4.8.1 | Lipid Bilayer Tubes | 53 |
| 4.8.2 | Rouleaux | 53 |
| 4.9 | Protein Folding and Unfolding | 55 |
| 4.9.1 | Protein Unfolding | 55 |
| 4.9.2 | Levinthal's Paradox | 55 |
| 4.9.3 | Energy Landscape | 56 |

- 4.9.4 Folding on a Lattice 57
- 4.9.5 Monte Carlo Methods 58
- 4.9.6 Folding@home 59

Exercises 59

Chapter 5 Open Systems and Chemical Thermodynamics 61

- 5.1 Enthalpy, Gibbs Free Energy, and Chemical Potential 61
- 5.2 Chemical Reactions 64
 - 5.2.1 First-Order Reactions 64
 - 5.2.2 Second-Order Reactions 65
- 5.3 Activation Energy and Rate Constants 66
 - 5.3.1 Detailed Balance 68
 - 5.3.2 Nitrogen Fixation 69
- 5.4 Enzymatic Reactions 70
- 5.5 ATP Hydrolysis and Synthesis 73
- 5.6 Entropy of Mixing 74
- 5.7 The Grand Canonical Ensemble 74
- 5.8 Hemoglobin 76

Exercises 77

Chapter 6 Diffusion and Transport 79

- 6.1 Maxwell–Boltzmann Statistics 79
- 6.2 Brownian Motion 81
- 6.3 Fick’s Laws of Diffusion 84
 - 6.3.1 Fick’s First Law 84
 - 6.3.2 Fick’s Second Law 85
 - 6.3.3 Quantum Diffusion 86
 - 6.3.4 Time-Independent Concentrations 86
 - 6.3.5 Fick’s Law for Growing Bacterial Cultures 87
- 6.4 Sedimentation of Cell Cultures 88
- 6.5 Diffusion in a Centrifuge 89
- 6.6 Diffusion in an Electric Field 91
- 6.7 Lateral Diffusion in Membranes 92
- 6.8 Navier–Stokes Equation 93
 - 6.8.1 Reynolds Number 94
- 6.9 Low Reynolds Number Transport 95
 - 6.9.1 Purcell’s “Life at Low Reynolds Number” 95
 - 6.9.2 Coasting Distance of a Bacterium 95
- 6.10 Active and Passive Membrane Transport 97

Exercises 98

Chapter 7 Fluids 101

- 7.1 Laminar and Turbulent Fluid Flow 101
- 7.2 Bernoulli's Equation 102
- 7.3 Equation of Continuity 103
- 7.4 Venturi Effect 104
- 7.5 Fluid Dynamics of Circulatory Systems 106
 - 7.5.1 Viscous Flow 106
 - 7.5.2 Vessel Constriction and Aneurysm 107
 - 7.5.3 Variation of Blood Pressure with Depth 108
 - 7.5.4 Microgravity Effects 108
- 7.6 Capillary Action 109
- Exercises 110

Chapter 8 Bioenergetics and Molecular Motors 111

- 8.1 Kinesins, Dyneins, and Microtubule Dynamics 111
- 8.2 Brownian Motors 113
 - 8.2.1 Feynman Ratchet 113
 - 8.2.2 Kinesin Brownian Dynamics 115
 - 8.2.3 Myosin Brownian Dynamics 115
- 8.3 ATP Synthesis in Mitochondria 116
 - 8.3.1 Electron Transport Chain 116
 - 8.3.2 ATP Synthase 117
 - 8.3.3 Torque Generation in ATP Synthase 118
- 8.4 Photosynthesis in Chloroplasts 118
 - 8.4.1 Photosystem II 120
 - 8.4.2 Photosystem I 120
- 8.5 Light Absorption in Biomolecules 120
- 8.6 Vibrational Spectra of Biomolecules 122
 - 8.6.1 Square Well Potential 122
 - 8.6.2 Harmonic Oscillator Potential 122
- Exercises 125

Chapter 9 Passive Electrical Properties of Living Cells 127

- 9.1 Poisson-Boltzmann Equation 127
 - 9.1.1 One-One Valent Electrolytes 129
 - 9.1.2 Low Field Limit 130
 - 9.1.3 Spherical Solution 130
- 9.2 Intrinsic Membrane Potentials 131
- 9.3 Induced Membrane Potentials 132
 - 9.3.1 Plasma Membrane 132

| | | |
|-------|---|-----|
| 9.3.2 | Liposome in a Static Electric Field | 134 |
| 9.3.3 | Spherical Cell in an Alternating Electric Field | 135 |
| 9.3.4 | Inertial Effects in Field-Induced Counterion Motion | 136 |
| 9.3.5 | Induced Potentials in Organelle Membranes | 136 |
| 9.3.6 | Mitochondrion in an Alternating Electric Field | 137 |
| 9.4 | Bioimpedance | 138 |
| 9.4.1 | Time Harmonic Current Flow | 138 |
| 9.4.2 | Dielectric Spectroscopy | 139 |
| 9.4.3 | Debye Relaxation Model | 142 |
| 9.4.4 | Cole Equation | 142 |
| 9.4.5 | Maxwell–Wagner Effect | 143 |
| 9.4.6 | Skin Impedance | 144 |
| 9.4.7 | Electrode Polarization | 144 |
| 9.5 | Bioimpedance Simulator | 145 |
| 9.6 | Nonlinear Effects | 148 |
| | Exercises | 149 |

Chapter 10 Nerve Conduction 153

| | | |
|--------|---|-----|
| 10.1 | Nerve Impulses | 153 |
| 10.2 | Neurotransmitters and Synapses | 154 |
| 10.3 | Passive Transport in Dendrites | 155 |
| 10.4 | Active Transport and the Hodgkin–Huxley Equations | 156 |
| 10.5 | Simulation of Action Potential | 160 |
| 10.5.1 | Excitation Threshold | 160 |
| 10.5.2 | Neuronal Refractoriness | 160 |
| 10.5.3 | Repetitive Spiking | 161 |
| 10.6 | FitzHugh–Nagumo Model | 163 |
| 10.7 | Action Potentials in the Earthworm Nerve Fiber | 166 |
| | Exercises | 168 |

Chapter 11 Mechanical Properties of Biomaterials 169

| | | |
|--------|---|-----|
| 11.1 | Elastic Moduli | 169 |
| 11.1.1 | Young’s Modulus | 169 |
| 11.1.2 | Shear Modulus | 170 |
| 11.1.3 | Poisson’s Ratio | 171 |
| 11.2 | Electric Stresses in Biological Membranes | 172 |
| 11.3 | Mechanical Effects of Microgravity During Spaceflight | 172 |
| | Exercises | 173 |

Chapter 12 Biomagnetism 177

- 12.1 Biomagnetic Field Sources 177
 - 12.1.1 Current Dipole Model 179
 - 12.1.2 Vector Potential Formulation 180
- 12.2 Nerve Impulses 180
- 12.3 Magnetotactic Bacteria 181
- 12.4 SQUID Magnetometry 182
 - 12.4.1 Josephson Effect 184
 - 12.4.2 Flux-Locked Loop 186
 - 12.4.3 Intrinsic Noise Factors 187
 - 12.4.4 Extrinsic Noise Factors 187
 - 12.4.5 Digital Filters 189
- 12.5 Magnetocardiography 189
- 12.6 Fetal Magnetocardiography 190
- 12.7 Magnetoencephalography 191
- Exercises 193

Chapter 13 Nonlinearity and Chaos in Biological Systems 195

- 13.1 Chaotic Dynamics 195
 - 13.1.1 Characteristics of Chaotic Dynamics 196
 - 13.1.2 Sensitive Dependence on Initial Conditions 197
 - 13.1.3 Phase Space 197
 - 13.1.4 Phase Space Reconstruction 198
 - 13.1.5 Poincaré Sections 199
 - 13.1.6 Lyapunov Exponents 200
 - 13.1.7 Power Spectra 200
- 13.2 Population Growth in a Limited Environment 202
- 13.3 Predator–Prey Models of Population Dynamics 203
- 13.4 Discrete Logistic Equation 204
 - 13.4.1 Period-Doubling Route to Chaos 206
 - 13.4.2 Bifurcation Diagrams 210
 - 13.4.3 Lyapunov Exponent of the Logistic Equation 212
 - 13.4.4 Shannon Entropy 213
- 13.5 Chaos in the Heart 215
- 13.6 Reaction Diffusion Equations 216
 - 13.6.1 Action Potentials 216
 - 13.6.2 Fertilization Calcium Waves 216
 - 13.6.3 Pattern Formation 217
- 13.7 Dynamics of the Driven Hodgkin–Huxley System 217
- 13.8 Models of DNA Motility 218
- Exercises 221

Chapter 14 Fractals and Complexity in the Life Sciences 225

- 14.1 Fractal Geometry 225
 - 14.1.1 Computing Fractal Dimension 228
- 14.2 Fractal Structures in Biology 231
 - 14.2.1 Fractal Ferns 231
 - 14.2.2 Diffusion-Limited Aggregation 233
- 14.3 Power Laws in Biology 233
- 14.4 Self-Organized Criticality 235
 - 14.4.1 BTW Sandpile Model 236
- 14.5 Extinction in the Bak–Sneppen Model 238
- 14.6 Power Law Behavior in Chemical Reactions 239
- 14.7 The Game of Life 241
 - 14.7.1 SOC in the Game of Life 244
- Exercises 245

Chapter 15 Life and the Universe 247

- 15.1 Astrobiology 247
- 15.2 Extremophiles 248
- 15.3 Primordial Soup, Interstellar Gas, and Dust 249
 - 15.3.1 The Miller Experiment 249
 - 15.3.2 Chemistry of the Interstellar Medium 250
- 15.4 Searches for Life in the Solar System 251
 - 15.4.1 Mars 251
 - 15.4.2 Europa 256
 - 15.4.3 Lake Vostok 257
- 15.5 Search for Life Outside the Solar System 258
 - 15.5.1 Extrasolar Planets 258
 - 15.5.2 SETI Initiatives 258
 - 15.5.3 Anticoded Signals 259
 - 15.5.4 Frequency Domain Searches 259
 - 15.5.5 Radio Interferometry 260
 - 15.5.6 The Drake Equation 261
- 15.6 Implications for Life in the Multiverse Picture 263
 - 15.6.1 The Multiverse 263
 - 15.6.2 The Anthropic Principle 264
 - 15.6.3 Multiverse Cosmological Models 265
- Exercises 269

| | |
|--|------------|
| Appendix 1: Mathematical Formulas | 273 |
| Appendix 2: Overview of MATLAB® | 281 |
| Appendix 3: Derivation of the Heat Equation | 289 |
| Appendix 4: Derivation of Shannon's Entropy Formula | 291 |
| Exercises | 294 |
| Appendix 5: Thermodynamic Identities | 295 |
| Appendix 6: Kramers–Kronig Transformations | 297 |
| Appendix 7: Solution to the One-Dimensional Schrödinger Equation | 299 |
| Exercises | 302 |
| Appendix 8: Biophysical Applications of QuickField™ | 303 |
| Appendix 9: Biological Material Properties | 309 |
| Appendix 10: Solutions of the Linearized Poisson–Boltzmann Equation | 313 |
| Exercises | 323 |
| References and Further Reading | 325 |
| Index | 339 |

1

Building Blocks and Structure

- 1.1 Atoms and Ions
 - 1.1.1 Subatomic Particles
 - 1.1.2 Atomic Constituents of Life
 - 1.1.3 Ions
- 1.2 Molecules Essential for Life
 - 1.2.1 Water
 - 1.2.2 Proteins
 - 1.2.3 Lipids
 - 1.2.4 Carbohydrates
 - 1.2.5 Cholesterol
 - 1.2.6 Nucleic Acids
- 1.3 What Is Life?
 - 1.3.1 Requirements for Life
 - 1.3.2 Domains of Life
 - 1.3.3 Characteristics of Living Cells
 - 1.3.4 Structure of Living Cells
 - 1.3.5 Boundary of Life

■ 1.1 Atoms and Ions

1.1.1 Subatomic Particles

All matter essential to life is made up of atoms consisting of protons, neutrons, and electrons. The electron is a stable particle belonging to a class of subatomic particles known as fermions. The electron is elementary and without internal structure. Table 1.1 gives a list of elementary particles according to the standard model of particle physics. Protons and neutrons are composite particles made out of combinations of three up (u) and down (d) quarks. The proton is (uud) while the neutron is (ddu). The four other quarks: strange (s), charm (c), top (t), and bottom (b) do not form stable particles and therefore do not participate in the physics of the living state.

Another particle essential to life is the photon (γ) that is a massless member of the Boson class of particles. Without the photon, energy could not travel from the Sun to

Table 1.1 Particles of the Standard Model

| Fermions | | | Bosons |
|-----------------------|-----------|------------|----------|
| <i>u</i> | <i>c</i> | <i>t</i> | γ |
| <i>d</i> | <i>s</i> | <i>b</i> | <i>Z</i> |
| ν_e | ν_μ | ν_τ | <i>W</i> |
| <i>e</i> [−] | μ | τ | <i>g</i> |

the Earth and warm our planet. Plants absorb photons to produce adenosine triphosphate (ATP) and to fix carbon that is consumed by more complex organisms on the food chain such as humans.

In Paul Dirac’s theory of relativistic quantum mechanics, antiparticles were predicted that were later discovered in cloud chamber experiments. It turns out that for every particle species in nature there is a corresponding antiparticle, although antimatter is quite scarce, at least on Earth. Antimatter plays a key role in the strong nuclear force through the exchange of π mesons. These mesons are quark–antiquark pairs exchanged between nucleons binding the nucleus together. Antimatter is therefore essential for the existence of stable atoms and hence, life. Antimatter is also employed in medical imaging using positron emission tomography (PET) where the positron e^+ is the positively charged antiparticle of the electron. Gamma rays are detected in PET scans that are produced by the annihilation of matter and antimatter according to the reaction $e^+ + e^- \rightarrow 2\gamma$. From Einstein’s mass energy relation and the energy of each photon $E = hf$ with $f\lambda = c$, the wavelength of the gamma rays emitted in PET are $\lambda = h/m_e c = 2.43\text{ pm}$.

The neutrino (ν), or “little neutral one,” predicted by Wolfgang Pauli, is a participant of beta decay and other nuclear reactions. Roughly 10^{12} solar neutrinos pass through our bodies each second. Neutrinos are weakly interacting, so this rate does not change during the night as neutrinos pass straight through the Earth, only very occasionally interacting with matter. Without neutrinos, nuclear reactions essential to stars would not take place. The little neutral one is therefore essential for life in this regard.

The gluon (g) is a key participant in the strong nuclear force binding quarks in nucleons and mesons. Other particles of the standard model may not contribute directly to the physics of the living state but may be a natural consequence of a universe capable of sustaining life.

Highly energetic subatomic particles in cosmic rays can also influence life processes by breaking molecular bonds and causing genetic mutations. Fortunately, the Earth’s atmosphere serves to greatly attenuate the flux of cosmic rays. The ozone layer is especially important in absorbing harmful solar ultraviolet radiation. Astronauts in space habitats are more vulnerable to solar protons that can cause health problems if received in excessive doses. Solar flares and coronal mass ejections can generate lethal