

## Index

### **a**

absolute charged-current (cc) 122, 169, 172–177, 179, 201, 204, 206  
 absolute neutral-current (nc) 169, 172–177, 179, 201  
 absolute neutrino mass scale 111–120  
 accelerator based neutrino experiments 131  
 accelerator experiments 79, 94, 96, 109–110  
 acrylic vessel (AV) 170–174  
 AGSS09 composition 34, 45, 57  
 Alven-waves 203  
 ancillary helium gas purging system 142  
 $^{37}\text{Ar}$  counting 144  
 arbitrary hadronic final state 86  
 argon extraction efficiency 144  
 astrophysical factors 27, 30, 58–59  
 asymmetric dark matter massive particles (ADM) 66  
 atmospheric neutrinos 1, 74, 84–94, 105, 109–110, 128–129, 153, 164, 169, 175  
 atomic diffusion 12–15  
 attenuation length of light 147  
 Auger electrons 115, 144–145, 155  
 Avogadro number 82  
 axion-like particles (ALPs) 66–67  
 axions 66–67

### **b**

$^8\text{B}$  solar neutrino flux 45, 46, 149, 151, 164, 199

$^8\text{B}$  solar neutrinos 146, 149–151, 156, 164, 172, 174, 177, 179, 189, 191, 199  
 B16-AGSS09 model 52, 55–56  
 B16-GS98 52, 55–56  
 B16 SSMs 45, 54–55, 59  
 baryon number 15–16  
 baryonic acoustic oscillations (BAO) 119  
 baryons 15–16, 65–66, 69, 117–119, 121  
 $^7\text{Be}$  solar neutrinos 43, 45, 46, 139, 179, 184–185, 187, 189–190, 198, 201  
 BEGe detectors 124  
 Bing Bang nucleosynthesis (BBN) 118  
 Birmingham Solar Oscillations Network (BiSON) 48–49  
 Boltzmann–Saha equations 19  
 Borex program 179  
 Borexino 2, 45, 109–110, 139, 162, 178–192, 195–202  
 Borexino fluid handling system 181  
 Borexino rates 189  
 Borexino scintillator 184, 197  
 bound-bound (bb) transitions 21, 24  
 bound-free (bf) transitions 23–24

### **c**

Cabibbo angle 102  
 calibrating standard solar models  
     free parameters 35–36  
     solar age 31  
     solar luminosity 32  
     solar mass 31  
     solar radius 32  
     surface composition 32–35

- $\gamma$ -catcher 106–107  
 CERN Neutrino Platform 133  
 charge leptons 86  
 charged current weak interaction 72,  
   201  
 charged muons 79, 85, 102  
 chemical composition, changes in  
   atomic diffusion 12–15  
   convective mixing 11–12  
   macroscopic and microscopic mixing  
   processes 16  
   nuclear reactions 15–16  
 constitutive physics  
   equation of state (EoS) 18–21  
   nuclear reaction rates 25–31  
   radiative opacity 21–25  
 Cherenkov muon veto 182  
 Cherenkov radiation 146, 171  
 CI-chondrites 34  
 $^{37}\text{Cl}$  experiment 140–145, 153  
 CNO-bicycle 25–26, 29–31, 37–39,  
   42–44, 46–47, 62, 67  
 CNO-neutrino detection 196, 199  
 cold dark matter 66, 117–118, 120  
 conduction 5–7, 21  
 conservation of momentum in spherical  
   symmetry 4  
 constitutive physics 18–31, 61–62  
 contributing isotopes 101  
 convection 5, 7, 9–12, 16, 18, 20, 23,  
   32–33, 35, 38, 41–42, 62, 65, 165,  
   183, 190  
 convective diffusion coefficient  
   12  
 convective mixing 11–12, 36  
 core mass-luminosity 39  
 cosmic microwave background (CMB)  
   117–119, 135  
 cosmic muon flux 197  
 cosmic muons 86, 99, 104, 107, 114,  
   124, 147, 197, 199  
 cosmic-ray muons 149, 154, 159, 165  
 cosmology 117, 123, 135  
 Cowling 49  
 CUORE experiment crystals  
   124
- d**  
 Daya-Bay experiment 105–110, 137  
 $\beta$  decay emitter 147  
 $\beta$  decay nuclei 148  
 Deep Underground Neutrino  
   Experiment (DUNE) 2, 97,  
   132–135, 206–207  
 DeepCore detector 92  
 detection threshold 145–146, 149, 163,  
   165, 172–174, 178, 188, 204, 206  
 differential solar neutrino flux 146  
 diffusion approximation 6, 17  
 diffusion coefficient 12, 14, 64  
 dimethylphthalate (DMP) 182–183  
 Dirac and Majorana neutrinos 2, 119  
 Dirac particles 120–127  
 dominant cosmogenic long-lived  
   isotopes 201  
 Double Chooz 105–107, 110  
 double  $\beta$  decaying nuclei 72, 120–123,  
   127  
 dynamical instability, criterion for 7–9
- e**  
 Eddington atmosphere 18  
 effective oscillation length 81  
 elastic neutrino electron scattering  
   experiments 74, 199, 200  
 elastic scattering (ES) interaction  
   145–146, 169, 177, 199–201, 204,  
   206  
 electromagnetic coupling constant 74,  
   119  
 electron anti-neutrino survival  
   probability 103  
 electron number density 14  
 electron recoil spectrum 185  
 electron scattering 23–24, 74,  
   200–201, 203  
 electron-antineutrinos 100, 103–104,  
   145  
 electrostatic filter potential 112  
 element abundances 32, 34, 62  
 energy conservation and transport  
   convection 9–11  
 criterion for dynamical instability  
   7–9

- by radiation and conduction 5–7  
 equation of state (EoS) 8–9, 11–12,  
   18–21, 37, 53, 60  
 extended maximum likelihood fit 167
- f**  
 fast coincidence Bi-Po decays 187  
 fast neutron breeder reactor BN-600  
   161  
 Fermi constant 73–74, 81, 111, 119  
 Fermi matrix elements 141  
 Fermi's golden rule 111  
 fermions 69, 71, 73, 198  
 fiducial volume 87–88, 91, 148–151,  
   162–163, 165–166, 173–174,  
   185–188, 190, 195, 198–200, 203  
 flavor changing neutral currents  
   (FCNC) 84  
 forward scattering amplitude 80  
 free parameters 10, 35–36, 42, 54, 64,  
   76, 91, 119, 160, 167, 178  
 free-free (ff) transitions 23–24  
 Friedman–Robertson–Walker metric  
   117
- g**  
 Ga-based experiments 153  
 GALLEX detector monitored solar  
   neutrinos 155, 158  
 Gallium Neutrino Observatory (GNO)  
   155–157, 161  
 Gamow peak 27–29  
 Gamow–Teller matrix elements 141,  
   153  
 Gd-loaded liquid scintillators 106  
 Gd-loaded scintillator 107  
 Ge-semiconductor detectors 124  
 general Lagrange-density-function 73  
 GERDA experiment Ge-detectors  
   124–125  
 Glashow–Salam–Weinberg theory 74  
 global structure inversions 51–53  
 global uncertainties in SSMs 60–62  
 gravothermal energy 5, 37, 40–41  
 GS98 composition 34, 57  
 1-GW reactor 100
- h**  
 Hamiltonian  $H^\alpha$  81  
 helioseismic techniques 9, 34, 51  
 helioseismology 1  
   global structure inversions 51–53  
   other constraints 53–54  
   overview 4  
 Hertzsprung–Russell diagram (HRD)  
   36  
 high efficient muon tracking algorithm  
   201  
 high energy electron-neutrinos 83  
 high-resolution  $\beta$ -spectrometer 112  
 Homestake experiment 75, 140–143,  
   145, 149  
 Homestake solar neutrino experiment  
   1  
 Hubble parameter 119  
 Hubble Space Telescope (HST) 119  
 Hyper-Kamiokande 2, 134, 204–206
- i**  
 IceCube 92, 128–129  
 imaging water Cherenkov experiment  
   140, 162  
 inductively-coupled plasma mass  
   spectrometer (ICP-MS) 159  
 inverse  $\beta$  decay 70, 101–102, 115  
 inverse bremsstrahlung 23  
 inverted ordering (IO) 110–111, 123  
 isospin groups 70  
 isotopic purity 144
- j**  
 Jiangmen Underground Neutrino  
   Observatory (JUNO) project 2,  
   130, 199–204, 207
- k**  
 Kaija, Takaaki 75  
 Kajita, Takaaki 1, 85, 88, 89, 92, 169  
 Kamiokande 2, 88, 90, 110, 115,  
   145–146, 151–153, 162–164, 169  
 Kamiokande-II experiments 139,  
   145–153, 164

Kamiokande-III 145–153, 164  
 KamLAND detector 104  
 kaons 85  
 KATRIN collaboration 114  
 Kramers' law 23

**I**

Laboratory of Underground Nuclear Astrophysics (LUNA)  
 experiment 28  
 Large Apparatus for Grand Unification and Neutrino Astrophysics and Long Baseline Neutrino neutrino Oscillations (LAGUNA-LBNO) 131–132  
 Large Area Picosecond Photo-Detectors (LAPPDs) 204  
 large electron positron (LEP) collider 69  
 large mixing angle 104, 109  
 large water Cherenkov detector 86  
 Ledoux criterion 9  
 Lee–Weinberg limit 119  
 left-handed leptons 70–73  
 leptogenesis mechanism 121  
 lepton number 72, 75, 120–122  
 leptons 69–73, 75–76, 79, 86–88, 91, 94, 96, 102, 110, 119–122, 127  
 $\tau$ -leptons 102  
 light collection efficiency 185  
 linear accelerator (LINAC) 163, 165  
 liquid argon TPCs 132–133  
 liquid scintillator 186  
 liquid scintillator detector 44, 99, 101, 103, 106, 124, 130–132, 140, 142, 178–181, 183–184, 186, 188–190, 195–197, 199, 201, 203–204  
 local thermodynamic equilibrium (LTE) 6–7, 33, 56  
 long baseline experiment 94, 97–100, 105, 131  
 low energy (LE) threshold 165, 199  
 Low Energy Neutrino Astrophysics (LENA) 2, 132, 199–204

**m**

magnetic-adiabatic collimation electrostatic (MAC-E) filter 112–113  
 Majorana neutrinos 2, 121–123, 126  
 Majorana-particles 76, 120–122, 127  
 MARE collaboration 115  
 matter effects 2, 43, 66, 69, 80–95, 98, 109, 127–129, 131–132, 134, 169, 178, 202–203, 207  
 McDonald, Arthur 1, 75, 178  
 measured solar neutrino flux 1, 167  
 mechanical structure of stars 3  
 mesons 1, 69, 85–87, 92, 94  
 meteoritic abundances 34  
 5.7 MeV total recoil electron energy 162  
 6.5 MeV total electron recoil energy 162  
 Michelson Doppler Imager (MDI) 48–49  
 microscopic diffusion 14–16, 38–39, 59, 61  
 mixing length theory (MLT) 10–12, 32, 42  
 mono-energetic 7Be solar neutrino line 185  
 mono-energetic pep-neutrino measurement 83  
 Mton water Cherenkov detector 134  
 muon neutrino 77, 83, 93, 97, 100  
 muon-induced fast neutrons 141  
 muon-induced spallation products 164  
 muon-like neutrinos 85  
 muon-neutrino spectrum 100  
 muon-veto systems 106  
 35 MW thermal power Siloé reactor 158

**n**

natural radioactivity 141–142, 146, 171  
 near detector 93–94, 96, 98–99, 102, 106, 132, 134, 137, 206  
 Neutral Current Detectors (NCDs) 171–172, 175  
 neutral Higgs boson 69  
 neutrino interaction vertex 87

- neutrino mass eigenstates 2, 75, 111–112, 128  
 neutrino mass hierarchy (NMH) 91, 99–100, 127–135  
 neutrino oscillation experiments 1, 75  
   appearance experiments 84  
   atmospheric neutrinos 84–92  
   reactor neutrino 100–109  
 neutrino-electron elastic scattering 145, 146, 206  
 neutrinoless double  $\beta$  decays 120–121, 123, 196  
 neutrino physics  
   matter effects 80–84  
   neutrino oscillation experiments, *see*  
     neutrino oscillation experiments  
 neutrino oscillations 75–80  
 neutrinos in the standard model 69–75  
 neutrinos in the standard model 69–75  
 Newton–Raphson scheme 36  
 non-oscillated neutrino spectrum 102  
 non-oscillated reactor neutrino spectrum 102  
 non-relativistic neutrinos 119  
 non-scintillating buffer liquid 107  
 non-standard particle physics 65–67  
 non-standard solar physics 63–65  
 non-trivial neutrino mixing parameter 75  
 non-vanishing neutrino masses 1  
 non-zero neutrino masses 75, 115  
 normal ordering (NO) 25, 38, 110–111, 123, 131  
 normalization constant 146  
 normalized two-component spinors 71  
 nuclear rate uncertainties 61  
 nuclear reaction rates 25–31, 37, 44, 52, 58–59, 61  
 nuclear reactions 15–16, 42, 58, 67
- o**  
 obey Maxwellian distributions 25  
 organic liquid scintillator experiment 140, 179
- oscillation wavelength 78  
 oscillation-generated  $\tau$ -neutrinos 91  
 overadiabaticity 11, 42
- p**  
 pep neutrinos 29, 30, 43, 45, 46, 62, 83, 154, 190, 197–199  
 phenylxylylethane 181  
 photomultiplier tubes (PMTs) 147–149, 162, 164–166, 170–171, 175, 179–182, 185–187, 189, 199, 204  
 Planck mission 118  
 Pontecorvo, Bruno 75, 141  
 Pontecorvo–Maki–Nakagawa–Sato matrix 76  
 positron annihilation energy 102  
 pp chains 25, 26, 29, 30, 37, 40, 41, 43  
 pp neutrinos 30, 43, 45, 46, 62, 40, 43, 139, 153–154, 187, 190, 198, 203  
 Precision IceCube Next Generation Upgrade (PINGU) project 128–129  
 pressure ionization 20  
 ProtoDUNE modules 133  
 pseudocumene (PC) 179, 181–183  
 pseudocumene unloading 183  
 PXE based scintillator 181
- q**  
 quark-antiquark pairs 69  
 quarks 69, 72, 86  
 quasi-elastic scatter interactions 86, 88  
 quenching factor 185  
 quenching parameter 184
- r**  
 radiative neutrino decay 117  
 radiative opacity 6, 24, 41, 55, 57, 59  
 $^{232}\text{Th}$  radioactive decay chain 146, 200  
 radiochemical detectors 146  
 radiochemical experiments 2, 44, 65, 140–141, 191  
 reactor neutrino 79, 100–109, 129–130, 136, 199–200  
 real time sub-MeV solar neutrino detector 181

- red giant branch (RGB) phase 38–39  
 relativistic Lorentz boost factor 88  
 relic neutrinos 117, 119, 166, 169  
 RENO 105–107, 110  
 RENO-50 131  
 right-handed charged leptons 70  
 Rosseland mean opacity 7, 17, 21,  
     23–24, 57
- s**
- Sanford Underground Research Facility (SURF) 132–133, 141, 206  
 satellite based X-ray telescopes 120  
 Schwarzschild criterion 9, 55, 64  
 see-saw mechanism 121  
 short baseline reactor neutrino experiment 103  
 Smirnov–Cramer–Von Mises method 159  
 solar abundances 12, 33–35, 56–57  
     problem 1, 47, 54–59, 62, 140, 191,  
     195  
     tables of 34  
 solar age 31, 35, 39  
 solar CNO-neutrinos 83  
 solar composition/solar modeling  
     problem 1, 19, 34, 42, 44–46,  
     52, 56, 59  
 solar convective envelope 11–12, 14,  
     41, 48  
 solar luminosity 32, 40, 43, 45, 59,  
     66–67, 153, 198  
 solar mass 31  
 solar metallicity 195  
 solar modeling 1, 56, 65  
 solar models beyond SSM 2, 62–67  
 solar neutrino problem (SNP) 65,  
     139–140, 149, 151, 153–154, 156,  
     195  
 solar neutrino puzzle 2  
 solar neutrino survival probability  
     1777–178  
 solar neutrinos 1  
     fluxes 44  
     neutrino production 42  
     power-law 45  
     solar abundance problem 47  
     solar luminosity 43  
 solar neutrino experiments 140  
     Borexino 178–190  
      $^{37}\text{Cl}$  experiment 140–145  
     Deep Underground Neutrino Experiment (DUNE) 206–207  
     Hyper-Kamiokande 204–206  
     JUNO and LENA 199–204  
     Kamiokande-II experiments 139  
     Kamiokande-II/III 145–153  
     positron annihilation 139  
     super-Kamiokande 162–169  
 solar radius 32, 35, 41, 59, 83  
 solar structure and evolution  
     changes in chemical composition  
     11–17  
     energy conservation and transport,  
         *see* energy conservation and  
         transport  
     full Set of equations and boundary  
         conditions 17–18  
     mechanical structure of stars 3  
 solar zenith angle distribution 173  
 solar maximum mission 117  
 Soviet-American Gallium neutrino Experiment (SAGE) 136, 153,  
     159–162  
 spectroscopic abundances 32–34, 65  
 $\beta$  spectroscopy 112  
 standard solar models 3, 31–42, 58, 65,  
     145, 150–152, 196  
     previous and future evolution  
     36–39  
 Stefan–Boltzmann constant 18  
 sterile neutrinos 2, 84, 119–120, 127,  
     135–137, 170, 175, 197–198  
 sub-MeV solar neutrino detection 179,  
     181, 196  
 Sudbury Neutrino Observatory (SNO)  
     2, 45, 109, 139, 162, 169–178,  
     189, 191–192, 196, 206  
 The Sun today 39–42, 67  
 super low energy (SLE) threshold 165  
 Super-Kamiokande (SK) experiment 2,  
     74, 85–88, 90–97, 109–110, 116,  
     128, 139, 153, 162–169, 174, 189,  
     191–193, 204

Supernova modeling 115  
 surface composition 32–35, 44, 54

**t**

tachocline 64  
 Teflon-lined chemical reactors 159  
 terrestrial (geo-) neutrinos 104  
 thermal nuclear reactions 25  
 thermo-nuclear fusion reactions 1, 203  
 Thomson scattering 23  
 threshold effect 146  
 time-dependent Friedmann equation 117  
 total atmospheric neutrino flux 85  
 total solar irradiance (TSI) 32  
 trimethylborate (TMB) 179  
 two-component spinors 71, 121  
 two-dimensional Pauli-matrices 71

**u**

U- and Pu-isotopes 101–102  
 uncertainties in SSMs  
     equation of state 60  
     luminosity and age 59  
     microscopic diffusion 59  
     nuclear reaction rates 58–59  
     radiative opacity 59  
     solar composition 59  
     solar radius 59  
 underground water detector  
     SuperKamiokande 74

unoscillated rate ratio 167, 168, 185–186

unstable mesons 85  
 upgraded Kamiokande detector 147

**v**

Valle–Schechter theorem 121  
 vinyl ester resin 155  
 virial theorem 36  
 visible energy 101–102, 169, 171–173, 187, 199, 201

**w**

warm dark matter 120  
 water Cherenkov detectors 44, 85–86, 91, 134, 145, 153, 165  
 water Cherenkov Hyper-Kamiokande 204  
 wave number-frequency diagram 48  
 weak coupling constant 73–74, 102  
 weak exchange bosons 72, 74  
 weak screening/Salpeter approximation 29  
 weakly interacting massive particles (WIMPs) 65  
 Weinberg-angle 73–74

**y**

Yukawa couplings 121, 135

