Study Outline for the Part III Oral

In

Experimental Particle and Nuclear Physics

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Based on Oct. 1994 Particle Physics guide by L.S. Osborne, L. Rosenberg and P. Sphicas and 1988 Nuclear Physics guide (author(s) unknown)

The Part III oral is meant to examine the graduate student in his or her field of interest in the areas of experimental particle and nuclear physics. The oral is *not* an in depth discussion of the student's particular research interest, but a broad survey of his or knowledge of experimental techniques and detectors, current state of the field, underlying physical ideas and important experiments.

The study outline that follows indicates the general scope of the exam. The student is expected to have some familiarity with all the topics listed, but not necessary detailed knowledge of each topic. The outline is organized as follows: Section I is Fundamental Topics and should be viewed as things the student should know at an advanced undergraduate level. Section II corresponds to the topics at a 8.701 level treatment of introductory particle and nuclear physics. Sections III and IV are at the level of 8.711 and 8.811, respectively.

For specific details of the format and scheduling of the Part III exam, you should contact Brian Canavan and the chair of the Part III committee. We have asked the Part III committee chair to meet with all the students planning to take Part III that term and answer any questions you may have. For other matters, please contact the division head.

At thirteen pages, you may find this outline long and daunting. Most likely, you know much of the material in it and only need remind yourself of what you have learned. Keep in mind that, at this point, you have passed Parts I and II, no easy feat! As a faculty, we have confidence that you can do well on this examination.

I. Fundamental Topics

A. Quantum Mechanics
   1. Fermi's golden rule
   2. Partial wave Scattering with and without spin. Argand diagrams.
   3. Relativity
      a) Transformations: $\vec{r}$ and t but also $\vec{E}$ and $\vec{B}$, etc.
      b) Four vectors, use in kinematic problems, particle masses from decay products.
   4. Phase space for multiparticle final states
      a) In 4 dimensions

B. Dalitz plots

C. Breit-Wigner resonance description

D. Time dependent perturbation theory — 1st and 2nd order

E. SU(N)
   1. Meaning
   2. Multiplication of groups; Young diagrams; sym. and antisym groups. Klein-Gordon Equation

F. Dirac theory
   1. Spin
   2. Gamma matrices, helicity
   3. Spinor algebra
   4. Negative energy solutions etc.

G. Interactions of Particles with Matter

One should be able to explain the mechanisms of the following phenomena and derive or make plausible the cross-sections or probabilities thereof and how these depend on the energy, charge, mass of the interacting particles.

   1. Collision loss (dE/dx)
   2. Coulomb scattering: both single and multiple
   3. Bremsstrahlung: radiation length
   4. Absorption of gamma rays: Photoelectric effect, Compton effect, Pair production
   5. Cherenkov light
   6. Transition radiation
   7. Showers: EM and hadronic

H. Experimental techniques; detectors & facilities

The student should be familiar with these devices and their principle of operation.

   1. Magnets
      a) principles of design
      b) types: deflecting, quadruples, solenoids, etc.
      c) superconductors
   2. Accelerators and their milieu

a) Synchrotrons: focusing, acceleration
b) storage rings
c) linear accelerators: linear colliders
d) beam lines and beam optics
e) existing accelerators — SLAC, Fermilab, KEK, LHC, RHIC, JLab
f) future accelerators: EIC, ILC

3. Electronics
   a) Amplifiers
   b) Digital circuits
   c) Computers and interfaces
4. Particle detectors
   a) Wire chambers: electron multiplication, quenching
      (1) proportional chambers
      (2) drift chambers
   b) Scintillation detectors
      (1) photomultipliers
      (2) scintillation materials
   c) Visual detectors
      (1) bubble chambers
      (2) streamer chambers
   d) Cherenkov counters
      (1) threshold type
      (2) differential type
      (3) Ring imaging type
   e) Shower detectors/calorimeters
      (1) electromagnetic (E-M): total absorption and segmented
      (2) hadronic

I. Data Reduction and Analysis
   1. Monte-Carlo methods
      a) Random Number generation
      b) Sampling
      c) Phase Space
   2. Fitting
      a) Chi-squared minimization
      b) Likelihood method, estimation of uncertainties, correlations, covariance matrix
   3. C. Treatment of Uncertainties
      a) Propagation of uncertainties
      b) Treatment of statistical and systematic uncertainties
      c) Confidence level limits

II. Introductory Particle and Nuclear Physics

A. Fundamental fields and particles: the Standard Model
   1. Fields-one should know the fields, their relative strengths, their ranges, interpretation in terms of particle exchange.

a) E-M
b) Weak
c) Gluonic-color; range limits from colorless sources
d) Gravity

2. Particles: their names, charge, spins, approximate masses
   a) leptons
   b) quarks
   c) mesons, baryons
3. Gauge bosons
4. Interactions: what particles interact with what fields, the form of the interaction.
5. Cross-sections and lifetimes: you should be able to get rough magnitudes for these from simple arguments.

B. Transformations, invariance, conserved quantities, quantum numbers (QN)

The student should understand: the meaning of these and their relationship; when are QN are conserved and not conserved? how are these QN measured? The student should be able to provide examples of conservation and non-conservation. The examples are meant as a guide and are not exhaustive.

1. 4-space transformations and conservation of:
   a) Energy, momentum, angular momentum
   b) Parity
      (1) Intrinsic particle parity and how it is measured. Examples: $\pi^{\pm}$, π^0, positronium, _/_, _ states
      (2) Manifestation of non-conservation
      (3) Examples: handedness of neutrinos, _ decay, manifestation in scattering, $K^{\pm}$ decay.
2. Charge conservation and gauge invariance.
3. Charge conjugation C: the meaning of the operation
4. Intrinsic C-dependence on L and S in p $\overline{p}$ states
   a) Examples: photon, π^0, positronium
   b) Non-conservation of C
   c) Examples: weak decays, how it would appear in π^0 or _ decay.
5. CP conservation – meaning
   a) Conservation in weak interactions - explain
   b) Manifestation of CP non-invariance in K^0 decay. Decay oscillations.
   c) CP in K^0 decay — relation of K_1^0 and K_2^0 to K^0 and $\overline{K^\circ}$.
   d) Strangeness oscillations, K_s^0 - K_L^0 mass difference, K^0 regeneration.
6. Time reversal invariance
   a) Tests in scattering reactions.
   b) Neutron dipole moment.
   c) Use in measuring particle spin
   d) Example: measurement of pion spin
7. CPT invariance: CPT theorem, experimental tests
8. Flavor conservation: S(strangeness), B, C. Also in leptons
9. Baryon number and lepton number conservation

10. Isospin
    a) Meaning and applicability, Examples: π, _, nucleon systems, nuclear states
    b) Isospin conservation, charge state ratios
    c) G-parity and its conservation
    d) _I = 1/2 rule in weak decays
    e) Isospin non conservation: when does it occur?
    f) Quark models of mesons and baryons

C. SU(3) groups for particles with *u, d, s* quarks.
  1. Singlets, octets, and decuplets.
  2. Quark compositions of mesons and baryons.
  3. Mixing between states.
  4. Baryon magnetic moments
  5. Mass relations
  6. States of general quark systems (*u, d, c, s, b, t*)
     a) discovery
     b) properties
     c) Zweig rule
     d) Other charmed and bottom mesons-comparison with positronium
     e) Strong decays of the above
     f) Charmed baryons
  7. Potential models
     a) Quark binding via gluons: approximate short and long distance behavior
     b) Dependence of masses on: $\vec{L}\cdot\vec{S}, \vec{S}\cdot\vec{S}$ (color hyperfine splitting)
  8. Principles of other models (qualitative)
     a) Bag model
     b) Lattice gauge calculations
  9. Glueballs
     a) Expected properties
     b) Candidates

III. Advanced Nuclear Physics

A. Properties of nuclei and nuclear matter
  1. Density, radii, Z/A, stability, lifetimes
  2. Binding energies, Q - values, Weizsäcker mass formula
  3. Characteristics of the strong force and saturation
  4. Nuclear shapes and radial-distribution, form factors; measurement of charge and matter distributions
  5. Mean free path of nucleons in nuclei; experimental measurements and qualitative explanations

B. Basic concepts of reaction theory
  1. Fermi's Golden Rule and calculation of cross sections
  2. S-matrix and optical theorem

3. Elastic scattering and phase shifts
4. Born approximation, regime of validity, plane wave impulse approximation, distorted waves

C. The nucleon-nucleon interaction
1. General forms allowed by conservation principles (spin, parity, isospin, angular momentum)
2. The deuteron
3. Nucleon-nucleon scattering
4. Phenomenological potentials and relation to meson exchange,
5. Assumptions involved, non-locality, experimental sensitivity to aspects of potentials

D. Independent particle models
1. Fermi Gas model
2. Hartree-Fock model (self-consistency)
3. Evidence for and tests of validity of the shell model
4. Ground state spins, magnetic moments, electric quadrupole moments, islands of isomerism, (e,e'p) reactions
5. Compatibility of the shell model with strong 2-body forces
6. Basis for the spin-orbit potential
7. Level ordering up to $1f_{7/2}$
8. Interacting boson model

E. Collective phenomena
1. Experimental evidence for collective phenomena (e.g. systematics)
2. 2+ states, vibrational and rotational spectra, enhanced quadrupole moments
3. Definition of and experimental evidence for deformed intrinsic states
4. Nilsson model
5. Energy level sequence of vibrational and rotational states, selection rules for electromagnetic transitions
6. Giant resonances: sum rules, widths, collective vs. particle-hole description

F. Decays
1. Role of decays in delineating boundaries of the chart of the nuclide
2. Alpha-decay (barrier penetration)
3. Electromagnetic transitions: collective vs. single-particle
4. Transition rates (Weisskopf units), measurement of multipolarity, definition of B(E2)
5. Beta decay, electron capture (parity violation, helicity of neutrino, selection rules); Fermi and Gamow-Teller matrix elements
6. Fission: physical effects contributing to shape of fission barrier, measurement of barrier heights

G. Electro-weak interactions
1. General features of electron scattering as a function of energy transfer and momentum transfer; qualitative behavior of elastic, inelastic, quasielastic scattering; Rosenbuth separation; physics contained in

longitudinal and transverse form factors; structure functions
2. Deep inelastic scattering and the parton model
3. Bjorken scaling and the EMC effect
4. Electromagnetic structure of few-nucleon systems
5. y-scaling and the momentum distribution of nucleons in nuclei
6. Weak interactions at high energy; charged and neutral currents

H. Heavy-ion reactions
1. General features of nucleus-nucleus reactions from below barrier to 100 GeV/A: Coulomb excitation, fusion, deep-inelastic, fireball, ultra-relativistic colisions
2. Evidence for new states of matter, elliptic flow
3. Jet quenching

I. Nuclear astrophysics
1. Big Bang and stellar nucleosynthesis
2. The abundances of the elements
3. The age of the universe
4. Nuclei far from stability

J. Hadronic physics
1. Longitudinal and transverse spin structure of the nucleon
2. Chiral perturbation theory
3. Hypernuclei
4. Generalized parton distributions

IV. Advanced Particle Physics

A. Calculations with Feynman Diagrams

Sometime one should have gone through a complete derivation of a scattering cross-section and a decay lifetime for elementary particles (quarks and leptons). Such a calculation, in all detail, is not a suitable orals question; but a familiarity with the methodology is.

1. The general interaction between particle and field-weak ($Z^0$and *W*) and E-M. A qualitative knowledge of gluon interactions.
2. The propagator, Tracery.
3. The general form for cross-sections and lifetimes-dimensional analysis.

B. Electromagnetic Interactions, QED

One should be familiar with the interactions listed below, their dependence on scattering angle, energy, particle masses. One should know how these phenomena are measured.

1. Classical EM interactions (Essentially Section A-II)
2. Elastic electron scattering from hadrons-hadron sizes
3. Lepton-lepton scattering and annihilation-relation between the two.
4. Examples: e^+e^-_ e^+e^- ; e^+e- _ _+ _- ; e^+e^- _q$\overline{q}$
5. Elastic e (or _) — nucleon scattering: general form, the elastic form factors-F's and G's.
6. Tests of QED

a) g - 2 experiments and comparison with theory
b) In e^+e experiments: how measured and parametrized

C. Strong Interactions, QCD
1. Inelastic lepton nucleon scattering.
2. The general equation with structure functions
   a) y (v / E) dependence
   b) Dependence of Fs on x and Q^2
   c) Callan - Gross relation
   d) Quark models of the structure functions
   e) Scaling
   f) General character of quark distributions
   g) x ($=-Q^2/ 2Mv$) as a measure of quark momentum.
   h) The quark (valence and sea) and gluon distributions.
   i) The scattering cross-section in terms of quarks and their charges. How are these distribution obtained from data?
3. Violation of scaling — how is this seen? secondary QCD effects

D. C. e^+e^- annihilation to hadrons (through virtual gamma)
1. discovery of jets-their angular distribution
2. production of heavy mesons
   a) detection of heavy quark states
   b) measurement of heavy meson lifetimes
3. Discovery of the top
4. QCD effects
   a) gluonic radiation
   b) measurements of $\_{s}$
   c) measurements of the running of the coupling
   d) constant
5. Elastic scattering — e.g. meson-nucleon, nucleon-nucleon
6. Diffractive scattering
7. Regge theory — an idea of the general principles
8. Highly inelastic collisions
   a) Phenomenology
   b) Leading particle effects
   c) Spectator model
9. Hadronization:
   a) Phenomenology
   b) Independent (Field-Feynman)
   c) String
   d) Cluster
   e) Gluonic hadronization
   f) Peterson
   g) Correlations; Bose-Einstein effect
   h) Fragmentation variables:
      (1) Multiplicities
      (2) x_F distributions
      (3) Charge ratios

(4) Heavy meson production
(5) P_T distributions

E. Weak Interactions

A knowledge of the basic interaction (the appropriate Feynman diagram), a measure of the lifetimes or cross-sections, a knowledge of the experiments to make these measurements. An understanding of the degree to which theory can predict quantitatively these interactions.

1. Elementary particle decays
   a) neutron decay, beta decay in nuclei; π decay
   b) *K* decay
      (1) leptonic and non-leptonic channels
      (2) Cabbibo angle
2. Kobayashi-Maskawa matrix: implication for flavor changing decays and T-invariance
3. *B* and *D* meson weak decays

F. Neutrino scattering

1. _- *e* scattering — relation to _ decay
2. _-nucleon scattering
   a) cross-section with structure functions; relation between _ and $\overline{v}$ scattering
   b) quark model of scattering, relation to E-M scattering
   c) relation of neutral-current to charged current scattering
   d) measurement of Weinberg angle
   e) production of higher mass flavors
3. GIM mechanism
4. Neutrino masses
   a) Direct measurement-what are the difficulties?
   b) Neutrino oscillations-how measured? mixing angle, experimental status
5. Double beta decay
   a) Conventional
   b) Unconventional

G. Electroweak Unification and Gauge Theories

1. Weinberg-Salam Model
2. Weinberg angle and vector boson mixing
3. *W* and Z^0 masses at tree level; _ parameter, experimental status
4. Higgs mechanism: how could such a particle be detected; what are other alternatives? e.g. technicolor.
5. Gauge theories and renormalization — what is meant by this?
6. Running coupling constant

H. Jet Physics

One should have a descriptive knowledge of the nature of e^+e^- and *pp* collisions and an understanding of the phenomenology used for these phenomena.

1. Parton-parton collisions: a quantitative understanding

    a) General parton-parton collisions e.g. *qq, qg, gg* scattering
    b) Drell-Yan effect
    c) W and Z production
2. Jets
    a) Definition of jets. Sterman-Weinberg jets.
    b) Discovery of jet structure in e+e-; in p $\overline{p}$ (previous ISR failure)
    c) Two, three and four jet production in e^+e^-, p $\overline{p}$
3. Multijet cross-sections
    a) Jet algorithms (JADE, UA1); dependence on cone, prescription
    b) Problems with infinities
    c) Axigluons, excited quarks, compositeness
4. Running coupling constant in QCD
    a) Gluon Propagator
    b) Calculation of _(e^+e^-_ hadrons) to order $\_{s}$
    c) Extraction of $\_{s}$, from jet ratios. Photon + jet production.

I. Deep Inelastic Scattering within QCD
1. Altarelli-Parisi equation .
2. Structure function evolution with Q^2
3. QCD corrections to DIS
4. Experimental results (CDHS, NMC, HERA)

J. Heavy Flavor Physics
1. Production and Decay
    a) Photoproduction
    b) Hadroproduction
    c) Leptoproduction
    d) Hadronic decays; $B \to J/\psi X$ transitions;
    e) Lifetimes, of $\tau(D^{\pm})/\tau(\overline{D}^0)$. Extrapolate to $B^{\pm}, \overline{B}^0$, the unknown f_d, f_s
2. Models
    a) LBSW,ACCM Models;
    b) HQET
    c) V_{ub}, V_{cb} phases and measurement
3. B0-$\overline{B}^0$ mixing
    a) Discovery
    b) Time-integrated measurements; CKM matrix elements
    c) Time dependent measurements.
    d) CP violation

K. CP violation
1. Theory of CP violation
2. Rare decays
3. B factories; hadron machines

L. W&Z Physics
1. Lepton Interactions in the Standard Model

a) Inverse _ decay
b) Weak Mixing angle, expt results
c) Width of W&Z; expected final states, angular distribution of products.

2. Production &. Decay of IVBs
   a) e^+e^- ; signature
   b) Left-right asymmetry; Use of polarized electrons-why?
   c) p $\overline{p}$; signature
   d) Associated jet production

M. The Higgs
1. Renormalizability
2. Decay Modes
3. Diboson resonances in the absence of Higgs.
4. Searches at LEP

N. Beyond the Standard Model and Present Experiments

You should have a qualitative knowledge of the deficiencies of present theories, where one might expect new phenomena to occur, and how one could do experiments to reveal these.

1. Limitations of the standard model
2. GUTs
3. SU(5)
4. Proton Decay
5. Magnetic monopoles
6. Supersymmetry:
   a) Phenomenology
   b) Cascade decays
   c) Searches for SUSY at LEP, Sp $\overline{p}$ S, Tevatron
7. Cosmology and astrophysics
   a) The origin of the universe — baryon excess
   b) Baryon Number in the Universe
   c) Dark matter and its source as some kind of particle
   d) Neutrinos from supernova
   e) Solar neutrinos
8. Superstring theory
9. Higher energy experiments
   a) LHC
10. New accelerating mechanisms
11. Quark-gluon plasma-where might it-be seen?
12. Underground detectors
    a) Extent and future detectors
    b) The processes they do and hope to measure

V. References

The following is a short review of relevant books. They are ordered in increasing level of sophistication.

A. I. Experimental Techniques

1. Kleinknecht, "Detectors for Particle Radiation", Cambridge University Press (1986)

Just instrumentation, but very valuable for that. It includes measurement of ionization, position, and time, particle identification, particle and shower energy momentum, and an overview of detector systems. A very useful first step in understanding particle detectors.

2. Ferbel, "Experimental Techniques in High Energy Physics", Addison Wesley (1987)

A series of papers relating to instrumentation, containing an overview by Ferbel, and Sauli's classic monograph on proportional and drift chambers, as well as articles on calorimetry, Cerenkov and transition radiation detectors, ring imaging, liquid noble gas detectors, and a nice article on electronics by Radeka. Useful to someone who wants to understand how detectors work.

B. Experiment and Theory

1. G. Kane: "Modern Elementary Particle Physics", Addison-Wesley (1987)

A very basic book. It is really aimed at undergraduates. Covers a variety of topics. Its theory is simple (no long derivations). It has a good introduction to the Standard Model, emphasizing accelerator-induced processes. There's almost no discussion of instrumentation, or interactions of particles and radiation with matter.

2. D. Perkins: "Introduction to High Energy Physics", 4th edition, Addison-Wesley (2000)

An undergraduate level introduction. Unlike Griffiths, it has a short discussion of instrumentation. Topics include conservation laws, isospin, Dalitz plots, 8-Fold way, QED, QCD and weak interactions. It's a broad overview, but there's not enough depth for a graduate course.

3. Griffiths: "Introduction to Elementary Particles", John Wiley & Sons (1987)

This is a basic text on particle physics, containing a history overview of interactions, symmetries, Feynman rules, QED, QCD, weak interactions and Higgs phenomenology. The level is at the advanced undergraduate level. It's a good Introduction.

4. R. Cahn & G. Goldhaber, "The Experimental Foundations of Particle Physics", Cambridge University Press (1989)

A collection of papers that carry you through the main developments in Particle Physics. It also contains short overviews of each subject. The problems are hard. Overall, a "must read" before you get your PhD!

C. Mostly Theoretical

1. Halzen & Martin: "Quarks and Leptons", John Wiley & Sons (1984)

An advanced undergraduate or beginning graduate text. Unfortunately, it's weak in experiment and instrumentation. It is, however, a good foundation for the Standard Model. In addition to this text, you will likely need a book like Perkins or the first part of Segre in order to round out a beginning course in Particle Physics.

2. V. D. Barger & RJ.N. Philips: "Collider Physics", Addison-Wesley (1987)

The book is in monograph form with low quality Tex formatting. It has a good introduction to the Standard Model including heavy quark decays and lifetimes. It has basic discussions of lepton and neutrino processes and cross sections, including deep inelastic scattering. Other topics include QCD, including Altarelli-Parisi equations, decays of W and Z bosons, jets and jet rates and fragmentation models, heavy quark decays, and Monte Carlo simulation. There's a long section on the Higgs, and an overview of possible physics beyond the standard model, including heavy neutrinos, additional generations, GUTs, and SUSY. This is a good, but high level book, especially valuable after you have digested an introductory text like Haizen & Martin. It also has a few (inadvertent) mistakes.

3. P. Renton, "Electroweak Interactions", Cambridge University Press (1990)

More theory than experiment, this is a book on "phenomenology". Very nice discussions of caiculational techniques. It is relatively complete in covering the phenomena of interest in particle physics.

4. Commins & Bucksbaum, "Weak Interactions of Leptons & Quarks", Cambridge University Press (1983)

Covers the standard model with emphasis on the weak interactions. It has a good discussion of V-A, the GIM mechanism, and Kaon decays. It also has a good overview of B decays, a discussion of second class currents, and a good overview of CP violation in the Kaon system and expected CP violation in the B meson systems. Some discussion of possible neutrino mixing and implication to astrophysics. Highly recommended.

5. Cheng & Li, "Gauge Theory of Elementary Particle Physics", Oxford University Press (1984)

Good broad and deep overview of the gauge theoretical aspects of the Standard Model. Includes basics of field quantization, renormalization, .group theory, the quark model, current algebra, QCD, QED and weak interactions. It includes a good discussion of SU(5) GUTs, magnetic monopoles, and an overview of instantons. It's a graduate level text that assumes familiarity with Dirac algebra formalism. Highly recommended.