I. Tools

1. Introduction

Or: What NOVA Covered

See pdf: Handout Conventions, Essentials, Scattering

References: [HM1; HG 1; cursorily HG 5; PRSZ 1]
Many excellent accounts – see e.g. [Per, App. B]

1894 Henri Becquerel ruins a photographic plate by leaving uranium salt on top of it.
1898 Pierre and Marie Curie isolate the first radioactive elements and coin the term radioactivity.
1909 Ernest Rutherford, Hans Geiger and Ernest Marsden: Atoms mostly empty, with small, heavy core.
1930 Wolfgang Pauli makes up the neutrino to save energy: “Dear Radioactive Ladies and Gentlemen”.
1932 James Chadwick discovers the neutron, Carl David Anderson finds Dirac's positron (first antiparticle, first (?) lost-and-found): Theorists move from just explaining to predicting.
1938 Otto Hahn and Fritz Strassmann split the nucleus but need their exiled collaborator Lise Meitner and her nephew Otto Fritsch to explain to them what they did. The latter do not get The Prize.
1945 Three nuclear fission bombs change the world.
1947 Powell et al. find Yukawa's pion (nucleon-nucleon force particle).
1960's Quip that the Nobel Prize should be awarded to the Physicist who does not discover a particle.
1961/2 Murray Gell-Mann, Yuvrai Ne’eman and others tame the particle zoo: flavours.
1964 Reading too much Joyce, Murray Gell-Mann and George Zweig hypothesize and baptise “quarks”.
1967/70 Stephen Weinberg, Abdus Salam and Sheldon Glashow unify electromagnetic and weak theory.
1973 Murray Gell-Mann, Harald Fritsch and Heiri Leutwyler formulate QCD.
1970's Gerhard 't Hooft and many others: The Standard Model can be used to calculate & explain Nature.
1990 Stephen Weinberg suggests to describe Nuclear Physics as Effective Field Theory of QCD.
2012 CERN finds a boson right where Peter Higgs, Tom Kibble and François Englert left it.
41 of 112 years saw prizes to Nuclear and Particle Physics – mostly Physics, few Chemistry.

1903 Radioactivity (C) Becquerel, P & M Curie
1908 Nucleus (C) Rutherford
1911 Ra, Po (C) M Curie
1927 Cloud chamber CRT Wilson
1935 Neutron Chadwick
1935 Transmutation (C) Joliot, Joliot-Curie
1936 Cosmic rays, positron Hess, CD Anderson
1938 Transmutation by neutrons Fermi
1939 Cyclotron Lawrence
1944 Fission (C) Hahn
1948 More cloud chamber Blackett
1949 Pion as Nuclear Force (th) Yukawa
1950 Pion (discovery) Powell
1951 Transmutation by accelerators (C) Cockcroft, Walton
1952 Nuclear Magnetic Resonance Bloch, Purcell
1957 Parity violation (th) Lee, Yang
1958 Čerenkov radiation Čerenkov, Frank, Tamm
1959 Antiproton Segrè, Chamberlain
1960 Bubble chamber Glaser
1961 Proton form factor Hofstadter
1963 Nuclear shell structure Wigner, Goeppert-Mayer, Jensen
1965 QED Feynman, Schwinger, Tomonaga
1967 Stellar nucleosynthesis Bethe
1968 Nucleon resonances (exp) Alvarez
1969 Classify particle zoo (th) Gell-Mann
1970 J/Ψ meson Richter, Ting
1975 Collective motion in nuclei A Bohr, Mottelson, Rainwater
1980 CP-violation (exp) Cronin, Fitch
1982 Renormalisation group KG Wilson
1983 Nucleosynthesis Chandrasekhar, Fowler
1984 W, Z bosons Rubbia, van der Meer
1985 Neutrino beam, νμ Lederman, Schwartz, Steinberger
1988 Neutrino beam, νμ Lederman, Schwartz, Steinberger
1990 Deep inelastic scattering Friedman, Kendall, Taylor
1991 Deep inelastic scattering Friedman, Kendall, Taylor
1992 Multiwire proportional chamber Charpak
1995 Neutrino discovery, τ lepton Perl, Reines
1999 Renormalisability 't Hooft, Veltman
2002 Cosmic neutrinos Davis, Koshiba, Giacconi
2004 Asymptotic freedom Gross, Politzer, Wilczek
2008 Spontaneous symmetry breaking, CKM Kobayashi, Maskawa, Nambu
2013 Higgs mechanism (th) Englert, Higgs
2015 Neutrino oscillation Kajita, McDonald
2018 Higgs (exp), DIS (th), lattice-QCD, EFT, ?

Future (safe bets):

Higgs (exp), DIS (th), lattice-QCD, EFT, ?
(b) Units & Conventions

- **Relativity:** Einstein Sum Convention; metric $(+−−−)$: $A^2 \equiv A^\mu A_\mu := (A^0)^2 − \vec{A}^2$

  velocity $\beta$, Lorentz factor $\gamma = (1 − \beta^2)^{-1/2}$

- **Natural System of Units:** $\hbar = c = k_B = 1$ $⇒$ velocity in units of $c$.

Resolution at given momentum: Uncertainty Relation $\Delta p \Delta x \geq \hbar = 1$ $⇒$ only one base unit

$$1 = \hbar c = 197.327 \text{MeVfm} \quad 11,605 \text{K} = 1 \text{eV}$$

Set base-unit to match Nuclear/Particle scales:

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$1 \text{fm} := 1 \text{fermi} := 1 \text{femtometre} = 1 \times 10^{-15} \text{m}$</td>
<td>$c \frac{1 \text{fm}}{c} \approx \frac{1}{3} \times 10^{-23} \text{s}$</td>
<td>$1 \text{GeV} = 1000 \text{MeV} = 10^9 \text{eV}$</td>
<td>$1 \text{b} := 1 \text{barn} := 1 \times 10^{-28} \text{m}^2 = (10 \text{fm})^2 \approx \frac{1}{400 \text{MeV}^2}$</td>
</tr>
</tbody>
</table>

"geometric" scatter: class. point particle on hard sphere (any energy)/QM zero-energy scatt. length:

$$\sigma_{\text{geom}} = 4\pi a^2 = 1 \text{b} = (10 \text{fm})^2 \quad \Rightarrow \quad a \approx 3 \text{fm} \quad \text{typ. heavy nucleus size (lead, Uranium)} \checkmark$$
More Units

- **Electrodynamics**: Rationalised Heaviside-Lorentz units, electron charge $-e < 0$

\[ \varepsilon_0 = \frac{1}{\mu_0 c^2} := 1 \]

\[ \Rightarrow \mathcal{L}_{\text{elmag}} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} \]

Maxwell \quad \text{Lorentz} \quad \text{Coulomb}

\[ \partial_{\mu} F^{\mu\nu} = j^{\nu} \quad \vec{F}_L = Ze[\vec{E} + \vec{\beta} \times \vec{B}] \quad \Phi(r) = \frac{Ze}{4\pi r} \]

fine structure constant $\alpha := \frac{e^2}{4\pi\varepsilon_0 \hbar c} = \frac{e^2}{4\pi} = \frac{1}{137} \Rightarrow e \approx 0.30$ dimension-less

- **QFT conventions**: “Bjørken/Drell”: [HM] – close to Haberzettl (fermion norms different)

- **Restoring SI Units**: Throw in $\hbar^\alpha c^\beta k_B^\gamma \varepsilon_0^\delta$ until SI units match: $E = mc^\alpha \hbar^\beta k_B^\gamma \varepsilon_0^\delta \Rightarrow \alpha = 2$.

- **Convenient mass conversion factor**:

\[ 1\text{u (atomic unit)} = \frac{\text{mass of } ^{12}\text{C atom}}{12} = \frac{1}{12} \times \frac{12\text{ g}}{6.022 \times 10^{23}\text{(Avogadro)}} \approx \frac{1}{6} \times 10^{-23}\text{ g} \]

\[ \Rightarrow \text{nucleon mass} \approx 1\text{GeV} \approx \frac{1}{12} ^{12}\text{C mass} \approx \frac{1}{6} \times 10^{-23}\text{ g} \]
Length Scales

Scale in m:

- $10^{-10}$ m: atom
- $10^{-14}$ m: nucleus
- $10^{-15}$ m: proton
- $\leq 10^{-18}$ m: quark, electron, quark

Scale in $10^{-18}$ m:

- $100,000,000$:
  - “Atomic Physics”
- $10,000$:
  - “Nuclear Physics”
  - “Nuclear Structure”
- $1,000$:
  - “Nuclear Physics”
  - “Hadron Physics”
- $\leq 1$:
  - “Particle Physics”

Elementary? Strings? Preons?
### (c) Hierarchy of Scales

<table>
<thead>
<tr>
<th></th>
<th>typ. energy</th>
<th>typ. momentum</th>
<th>typ. size</th>
</tr>
</thead>
<tbody>
<tr>
<td>nuclear structure</td>
<td>binding: 8MeV per nucleon</td>
<td>100 keV…1MeV</td>
<td>10fm (∼^{235}U size)</td>
</tr>
<tr>
<td>few-nucleon</td>
<td>binding: 2.2MeV deuteron</td>
<td>(m_\pi \approx 140\text{MeV})</td>
<td>(\frac{1}{m_\pi} \approx 1.5\text{fm}) (Yukawa)</td>
</tr>
<tr>
<td>hadronic</td>
<td>(M_N, m_\rho \approx 1\text{GeV})</td>
<td>1GeV (relativistic)</td>
<td>(\frac{1}{M_N} \approx 0.2\text{fm})</td>
</tr>
<tr>
<td>particle</td>
<td>100GeV (Z, W) masses</td>
<td>100GeV (relativistic)</td>
<td>(\frac{1}{100\text{GeV}} \approx 2 \times 10^{-3}\text{fm})</td>
</tr>
</tbody>
</table>

**Difference "Low" – "High" Energy Physics Is Time-Dependent!**

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**Physical Review**

**Volume 76, Number 1**

**July 1, 1949**

**Bremsstrahlung in High Energy Nucleon-Nucleon Collisions**

**J. Ashkin and R. E. Marshak**

*University of Rochester, Rochester, New York*

(Received March 22, 1949)

Formulas for the differential cross sections for the continuous \(\gamma\)-emission accompanying proton-neutron, proton-proton, neutron-neutron collisions have been derived. Numerical results are given for an incident nucleonic energy of 250 Mev.
The Standard Model

Lepton Quark

Universality Hypothesis: Leptons Quarks couple with same form & strengths.
Fig. 1.7. The mass spectrum of leptons and quarks. The values shown for neutrinos are upper limits from direct measurements, and the solar and atmospheric neutrino anomalies (see Chapter 9) suggest even smaller masses. Other important mass scales are also shown: the Fermi or electroweak scale at 100 GeV, typified by the $W^{\pm}$ and $Z^0$ boson masses; the Planck mass scale, of order $10^{19}$ GeV, at which gravitational interactions are expected to become strong (see Chapter 2); and the value, $kT \simeq 1$ meV, of the cosmic microwave radiation ($T = 2.7$ K) in the universe today.

[Per, modified]
Valence Quarks determine charge,…

Mesons: Valence Quark-Antiquark     Baryons: 3 Valence Quarks
Results of the Standard Model: Meson Resonances

Vacuum Excitation Spectrum of the Standard Model
Results of the Standard Model: Baryon Resonances

QCD Partial Wave Analysis
for Baryons (& Mesons):
GW Data Analysis Center DAC

GW Data Analysis Center DAC

Energie/MeV

Δ(1232) S_{11}(1535)

atom

nucleon

Flavour

<table>
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<tr>
<td>I</td>
<td>1/2</td>
<td>3/2</td>
</tr>
<tr>
<td>S</td>
<td>0</td>
<td>0</td>
</tr>
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</table>
Results of the Standard Model: Nuclear Landscape

- Black: stable
- Red: $\beta^+$ emitter
- Blue: $\beta^-$ emitter
- Yellow: $\alpha$ emitter
- Green: spont. fission

Z: proton number
N: neutron number
A = Z + N: mass n.

$\Rightarrow \frac{A}{Z}\text{Name: }^{235}_{92}\text{U}$
Know $< 3000$ nuclei ($< 300$ stable) – $7000$ unknown

neutron star: $N = 10^{57}$

need to account for gravity!
Fig. 2.2. Abundance of the elements in the solar system as a function of their mass number $A$, normalised to the abundance of silicon ($= 10^6$).
NucleAR Excitation Spectrum: Not Like H-Atom!

[HG fig. 5.37]
Typical decay scales

Minimum decay time for particle of size $R$: $\tau \geq \frac{R}{c}$: time to traverse object (“transmit signal to break up”).

$$\implies \tau_{\text{hadron}} \gtrsim \frac{1 \text{ fm} = 10^{-15} \text{ m}}{3 \times 10^8 \text{ m s}^{-1}} \approx 10^{-24} \text{ s}$$ for “typical strong decay”.

Nuclei show much more spread: $10^{-22}$ s to $10^{10}$ years – still depends on interaction.
Typical hadron cross sections

- **Hadronic** cross sections are generally **constant**.
- **Electromagnetic** cross sections typically **decrease** with energy.
- **Weak** cross sections generally **increase** with energy.

[HG 14.2 modified]
There are four fundamental forces between particles:

1) Gravity, which obeys this inverse-square law:
   \[ F_{\text{gravity}} = G \frac{m_1 m_2}{d^2} \]

2) Electromagnetism, which obeys this inverse-square law:
   \[ F_{\text{static}} = k_e \frac{q_1 q_2}{d^2} \]

And also Maxwell’s equations

Also what?

3) The strong nuclear force, which obeys, uh...
   ...well, umm...
   ...it holds protons and neutrons together.

I see.

It’s strong.

4) The weak force. It [mumble mumble] radioactive decay [mumble mumble]

That’s not a sentence. You just said “radio--

--and those are the four fundamental forces!

[xkcd 20 Feb 2015]

(weblink)
(h) The Known Unknowns: It’s There, But What Is It?
**Evidence:** Velocity distribution of stars around galactic centres not explained by stars + gas

⇒ “dark halo” of non-luminous/non-absorbing matter: no interaction via electromagnetism.

More Evidence: Stronger in galactic clusters/superclusters; Cosmic Microwave Background Anisotropy

**Preferred Candidates:** “Cold Dark Matter CDM”: nonrelativistic (heavy!)

Some is baryonic (primordial black holes? Massive Compact Halo Objects MACHOs?);

≈ 80% non-hadronic: Weakly Interacting Massive Particles WIMPs (axions, SUSY, heavy neutrino,...)
**Evidence:** Redshift of type-Ia supernovae in Einstein-Friedman-Walker universe:

Unknown long-range repulsive force counters gravity’s pull. [Perlmutter/Schmidt/Riess 1998, Nobel 2011]

**More Evidence:** Cosmic Microwave Background Anisotropy.

**Preferred Candidates:** Modified gravity at very large distance scales?; Cosmological constant $\Lambda$ (positive vacuum energy $\Rightarrow$ negative pressure)?

**Dark matter + dark energy $\Rightarrow \Lambda$CDM scenario**
We do not understand the composition of 95% of the universe.

68.3% Dark Energy

26.8% Dark Matter

4.9% Ordinary Matter

mass generated by Higgs: $\lesssim 0.1\%$ (?)

[wikipedia: Dark energy]
Be wary of spectacular announcements

**TIME Science**

**PHYSICS**

**Was Einstein Wrong? A Faster-than-Light Neutrino Could Be Saying Yes**

By **MICHAEL D. LEMONICK**  Friday, Sept. 23, 2011

**SUPERLUMINAL NEUTRINOS**

**Loose Cable May Unravel Faster-Than-Light Result**

Anomalous data suggesting that neutrinos can travel faster than light probably resulted from a faulty connection in a GPS timing system, physicists from the OPERA collaboration revealed last week. Scientists who wished not to be identified say a connection in the coaxial fiber cable was plugged into a socket attached to a card inside the experiment’s master-clock computer. The card converts the light pulses into electronic signals. Any loose connection was supposed to stop the pulses from being registered, but instead...

[Science 335 (2 Mar 2012) 1027]
But hope springs eternal: a bump in $pp \rightarrow \gamma\gamma$ at $M_X \approx 1.5$ TeV?

- **In the NWA search**, an excess of 3.6σ (local) is observed at a mass hypothesis of minimal $p_0$ of 750 GeV

  [ATLAS collaboration: CERN seminar 15 Dec 2015]  
  [CMS collaboration: CERN seminar 15 Dec 2015]

**Statistics:** Huge event number $\Rightarrow$ fluctuations may mimic rare events.

**Sagan's Rule:** Extraordinary claims require extraordinary evidence.
But hope springs eternal: a bump in $p\bar{p} \rightarrow \gamma\gamma$ at $M_X \approx 1.5$ TeV?

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[CMS collaboration: CERN seminar 15 Dec 2015][ATLAS collaboration: CERN seminar 15 Dec 2015]

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**Wikipedia Jan 2018**: Analysis of a larger sample of data, collected by ATLAS and CMS in the first half 2016, indicates that the excess seen in 2015 was a **statistical fluctuation**.
Next: 2. Particle Sources

Familiarise yourself with: [HG 2, 19.5; PDG 29, 30, 37]