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 Gerard ’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.
## Invitations to Stockholm: Physics above 1 MeV

41 of 112 years saw prizes to Nuclear and Particle Physics – mostly Physics, few Chemistry.

<table>
<thead>
<tr>
<th>Year</th>
<th>Discovery</th>
<th>Contributors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1903</td>
<td>Radioactivity (C)</td>
<td>Becquerel, P&amp;M Curie</td>
</tr>
<tr>
<td>1908</td>
<td>Nucleus (C)</td>
<td>Rutherford, M Curie</td>
</tr>
<tr>
<td>1911</td>
<td>Ra, Po (C)</td>
<td></td>
</tr>
<tr>
<td>1927</td>
<td>Cloud chamber</td>
<td>CRT Wilson</td>
</tr>
<tr>
<td>1935</td>
<td>Neutron</td>
<td>Chadwick</td>
</tr>
<tr>
<td>1935</td>
<td>Transmutation (C)</td>
<td>Joliot, Joliot-Curie</td>
</tr>
<tr>
<td>1936</td>
<td>Cosmic rays, positron</td>
<td>Hess, CD Anderson</td>
</tr>
<tr>
<td>1938</td>
<td>Transmutation by neutrons</td>
<td>Fermi, Lawrence</td>
</tr>
<tr>
<td>1944</td>
<td>Fission (C)</td>
<td>Yukawa</td>
</tr>
<tr>
<td>1948</td>
<td>More cloud chamber</td>
<td>Blackett</td>
</tr>
<tr>
<td>1949</td>
<td>Pion as Nuclear Force (th)</td>
<td>Hahn, Rabi</td>
</tr>
<tr>
<td>1950</td>
<td>Pion (discovery)</td>
<td>Powell</td>
</tr>
<tr>
<td>1951</td>
<td>Transmutation by accelerators (C)</td>
<td>Cockcroft, Walton</td>
</tr>
<tr>
<td>1952</td>
<td>Nuclear Magnetic Resonance</td>
<td>Bloch, Purcell</td>
</tr>
<tr>
<td>1957</td>
<td>Parity violation (th)</td>
<td>Lee, Yang</td>
</tr>
<tr>
<td>1958</td>
<td>Čerenkov radiation</td>
<td>Čerenkov, Frank, Tamm</td>
</tr>
<tr>
<td>1959</td>
<td>Antiproton</td>
<td>Segrè, Chamberlain</td>
</tr>
<tr>
<td>1960</td>
<td>Bubble chamber</td>
<td>Glaser</td>
</tr>
<tr>
<td>1961</td>
<td>Proton form factor</td>
<td>Hofstadter</td>
</tr>
<tr>
<td>1963</td>
<td>Nuclear shell structure</td>
<td>Wigner, Goeppert-Mayer, Jensen</td>
</tr>
<tr>
<td>1965</td>
<td>QED</td>
<td>Feynman, Schwinger, Tomonaga</td>
</tr>
<tr>
<td>1967</td>
<td>Stellar nucleosynthesis</td>
<td>Bethe</td>
</tr>
<tr>
<td>1968</td>
<td>Nucleon resonances (exp)</td>
<td>Alvarez</td>
</tr>
<tr>
<td>1969</td>
<td>Classify particle zoo (th)</td>
<td>Gell-Mann</td>
</tr>
<tr>
<td>1975</td>
<td>Collective motion in nuclei</td>
<td>A Bohr, Mottelson, Rainwater</td>
</tr>
<tr>
<td>1976</td>
<td>J/Ψ meson</td>
<td>Richter, Ting</td>
</tr>
<tr>
<td>1979</td>
<td>Electroweak unification</td>
<td>Glashow, Salam, Weinberg</td>
</tr>
<tr>
<td>1980</td>
<td>CP-violation (exp)</td>
<td>Cronin, Fitch</td>
</tr>
<tr>
<td>1982</td>
<td>Renormalisation group</td>
<td>KG Wilson</td>
</tr>
<tr>
<td>1983</td>
<td>Nucleosynthesis</td>
<td>Chandrasekhar, Fowler</td>
</tr>
<tr>
<td>1984</td>
<td>W, Z bosons</td>
<td>Rubbia, van der Meer</td>
</tr>
<tr>
<td>1988</td>
<td>Neutrino beam, (v_\mu)</td>
<td>Lederman, Schwartz, Steinberger</td>
</tr>
<tr>
<td>1990</td>
<td>Deep inelastic scattering</td>
<td>Friedman, Kendall, Taylor</td>
</tr>
<tr>
<td>1995</td>
<td>Neutrino discovery, (\tau) lepton</td>
<td>Perl, Reines</td>
</tr>
<tr>
<td>1999</td>
<td>Renormalisability</td>
<td>’t Hooft, Veltman</td>
</tr>
<tr>
<td>2002</td>
<td>Cosmic neutrinos</td>
<td>Davis, Koshiba, Giacconi</td>
</tr>
<tr>
<td>2004</td>
<td>Asymptotic freedom</td>
<td>Gross, Politzer, Wilczek</td>
</tr>
<tr>
<td>2008</td>
<td>Spontaneous symmetry breaking, CKM</td>
<td>Kobayashi, Maskawa, Nambu</td>
</tr>
<tr>
<td>2013</td>
<td>Higgs mechanism (th)</td>
<td>Englert, Higgs</td>
</tr>
<tr>
<td>2015</td>
<td>Neutrino oscillation</td>
<td>Kajita, McDonald</td>
</tr>
</tbody>
</table>

**Future (safe bets):**

- Higgs (exp), DIS (th), lattice-QCD, EFT, ?
The steering tools on which the US Department of Energy (DOE), the US National Science Foundation (NSF) and their European counterparts base their funding priorities.
Handout: Conventions and Bare Essentials for HW and Beyond

You will find much of what we will do today here (link).

Department of Physics, The George Washington University

H.W. GRIESSHAMMER  1

Nuclear Physics: Conventions
The Natural System of Units is particularly popular in Nuclear and High-Energy Physics since as many fundamental constants as possible have a simple value as possible (see [MM]).

Set the speed of light and Planck’s quantum to c = h = 1. This expresses velocities in units of c, and actions and angular moments in units of ħ. Then, only one fundamental unit remains, namely either an energy- or a length-scale. Time-scales have the same units as length-scales. We also set Boltzmann’s constant k_B = 1, so energy and temperature have the same units. Now one only memorises a handful of numbers. Setting Newton’s gravitational constant G_N = 1 eliminates any dimensionful unit – only String Theorists Do that.

Electrodynamic Units: The Rationalised Heaviside-Lorentz system will be used throughout. Formally, it can be obtained from the SI system by setting the dielectric constant and permeability of the vacuum to ε_0 = 1/ε = 1. The system is uniquely determined by any two of the fundamental equations which contain ħ and a combination of ħ and β. More on systems, units and dimensions e.g. in [MM].

Charges Q = Ze are measured in units Z of the elementary charge e = 0; electron charge e = 0 < 0.

Lagrangian: \( \mathcal{L}_{\text{Elastic}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \) ⇒ Maxwell’s equations: \( \partial_{\mu} F^{\mu\nu} = j^{\nu} \).

“Restoring” SI units from “natural units”: Multiply by \( \pi^2 \hbar^2 / c_0^2 \) and determine the exponents such that the proper SI unit remains, using: [e]: [m s^{-1}], |β| = [kg m s^{-1}], |k|= [m^2 s^{-2} K^{-1}] and [ε_0]: [C m^{-1}].

Example: \( E_\text{max} = \gamma E = m c^2 \hbar^2 / k_B \) and you have to convert kg m^2 s^2 into kg, i.e. add two powers of m/s, so that \( \alpha = 2, \beta = \gamma = 0 \).

Conventions Relativity: Einstein Summation Convention; “East-coast” metric (+−−−);
\( A^2 = \alpha A^\mu A_\mu \) = \( \alpha (A^\mu)^2 \). Velocity, Lorentz factor \( \gamma = (1 - \beta^2)^{-1/2} \).

Conventions QFT: “Bjørken/Drell” [HM, PS]: close to [HH], but fermion norms different:
Quantised complex scalar: \( \Phi(x) = \int \frac{d^4k}{(2\pi)^4} \left[ \frac{1}{\sqrt{2E_k}} \left( a_E e^{iE_kt} + \text{adj.} \right) e^{i\vec{k}\cdot\vec{x}} \right] \) with \( E_k = \sqrt{\vec{k}^2 + m^2} \).

Minimal substitution in QED: \( D^\mu = \partial^\mu + ie\overline{\Phi} A^\mu \); in non-Abelian gauge theories (QCD…): \( D^\mu = \partial^\mu - ig A^\mu \).

\( \gamma^a = \frac{\gamma \cdot \gamma^a}{\sqrt{\gamma \cdot \gamma}} = \gamma \), \( \gamma^a \gamma^b \gamma^{abc} = \gamma \), \( 2m a_{\mu}(p) a_{\nu}(p) = p + m, -2m a_{\mu}(p) \cdot a_{\nu}(p) = p - m = P^\mu + P_{\mu} = 1 \).

Elastic cross section (our convention) in cm: \( d\sigma / d\Omega = \frac{1}{64\pi^2} \left( E_k^2 / \sqrt{E_k^2 + m^2} \right)^2 \) [\( \text{in } \text{cm}^2/\text{sr} \) lab, \( m = 0 \) \( \text{in } \text{cm}^2/\text{sr} \) inlab, \( \text{in } \text{GeV}^2/\text{sr} \)].

Decay of particle with mass \( M \) (cm, our convention): \( \Gamma(\Phi) = \text{Int}[A \rightarrow B + \gamma] = \left| C_{AB} \right|^2 \).

More cross section formulae & conventions in “Summary Electron Scattering Cross Sections” below.

Nuclear Physics: Some Oft-Overlooked Bare Essentials
Know these by heart! Physicists spend a lot of time solving complicated problems, so we want to always start with an idea of the result. We have ideas when we are hiking, cycling, in the shower, etc., and usually not on our desk. We discuss them with our colleagues on the blackboard, and we cannot waste their time and our time with looking stuff up. Therefore, we need to be able to do calculations without computers, books or calculators, i.e. in our head or with a piece of scrap paper and a dull pencil.

We refer to the list of “Essentials” from Mathematical Methods [MM] (dimensional estimates, guesstimates, Natural System of Units). If you know more things worth remembering, let me know!

This is the list of often-looked numbers, not of the minimum necessary – the minimum is much larger (including names, spins, charges, masses of all fundamental particles, etc.).

Please turn over.

Department of Physics, The George Washington University

H.W. GRIESSHAMMER  2

Value

\( \epsilon := 2,997,924.58 \times 10^8 \text{ m s}^{-1} \) (def!)

\( 3 \times 10^8 \text{ m s}^{-1} \)

1 electron Volt (eV) \( \equiv 1.6 \times 10^{-19} \text{ Joule} = \frac{1}{\sqrt{2}} \text{ eV} \)

1 J = 6 \times 10^19 eV

1 fermi (femtometre, fm) \( = 10^{-15} \text{ m} \)

\( 1.97 \times 10^2 \text{ MeV} \text{ fm} \approx 200 \text{ MeV} \text{ fm} \)

1 fm \( = \frac{1}{3} \times 10^{-23} \text{ s} \)

\( a = \frac{\pi^2}{6} \text{ fm} \) (nat. units), \( \text{SL} = \frac{\pi^2}{6} \approx \frac{1}{12 \pi} \) (no units!)

1 eV \( \approx 11,600 \text{ KeV} \text{ cm} \)

\( 300 \text{ K} \approx 1 \text{ eV} \)

\( n_r = \frac{e^2}{\hbar^2} = 4.8 \times 10^{-10} \text{ nat. units} \)

\( \approx 3 \text{ fm} \)

\( m_e = 110 \text{ MeV} \text{ c}^{-2} \text{ } \)

\( m_{\mu} = 106 \text{ MeV} \text{ c}^{-2} \text{ } \)

\( m_{\pi} = 140 \text{ MeV} \text{ c}^{-2} \text{ } \)

\( m_{\text{nucleon}} = 1000 \text{ MeV} \text{ c}^{-2} \text{ } \)

\( 800 \text{ MeV} \text{ c}^{-2} \text{ } \)

\( m_{\text{meson}} = 800 \text{ MeV} \text{ c}^{-2} \text{ } \)

\( m_{\text{boson}} = 100 \text{ GeV} \text{ c}^{-2} \text{ } \)

Translating:

1 barn = 100 fm^2 = (10 fm^2) x 10^{-28} m^2 = 10^{-40} m^2

“geometric” scattering: \( n_{\text{geom}} = 4 \pi a^2 \).

Interpretation: (1) class. point particle on sphere, radius \( a \), any energy; (2) QM zero-energy, scatt. length \( a \).
(b) Units & Conventions

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

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

- **Natural System of Units:** $\hbar = c = k_B = 1 \implies$ velocity in units of $c$. [MM 1]

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

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

Set base-unit to match Nuclear/Particle scales:

<table>
<thead>
<tr>
<th>Typ. length scale:</th>
<th>$1 \text{fm} := 1 \text{fermi} := 1 \text{femtometre} = 1 \times 10^{-15} \text{m} \approx \text{N size} $</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typ. time scale:</td>
<td>$\frac{1 \text{fm}}{c} \approx \frac{1}{3} \times 10^{-23} \text{s} \quad \text{time for light to traverse N}$</td>
</tr>
<tr>
<td>Typ. energy &amp; momentum:</td>
<td>$1 \text{GeV} = 1000 \text{MeV} = 10^9 \text{eV} \approx \text{N mass} $</td>
</tr>
<tr>
<td>Typ. nuclear cross section:</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:

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

- **Electrodynamics**: Rationalised Heaviside-Lorentz units, electron charge \(-e < 0\)

\[
\epsilon_0 = \frac{1}{\mu_0 c^2} := 1
\]

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

Maxwell

\[
\partial_\mu F^{\mu\nu} = j^\nu
\]

Lorentz

\[
\vec{F}_L = Ze[\vec{E} + \vec{\beta} \times \vec{B}]
\]

Coulomb

\[
\Phi(r) = \frac{Ze}{4\pi r}
\]

fine structure constant \(\alpha := \frac{e^2}{4\pi\epsilon_0 \hbar c} = \frac{e^2}{4\pi} = \frac{1}{137} \rightarrow e \approx 0.30\) dimension-less

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

- **Restoring SI Units**: Throw in \(\hbar^\alpha c^\beta k_B^\gamma \epsilon_0^\delta\) until SI units match: \(E = mc^\alpha \hbar^\beta k_B^\gamma \epsilon_0^\delta \rightarrow \alpha = 2\).

- **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

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

- $100,000,000$ m: "Atomic Physics"
- $10,000$ m: "Nuclear Physics"
- $1,000$ m: "Nuclear Structure"
- $100$ m: "Nuclear Physics"
- $10$ m: "Hadron Physics"
- $1$ m: "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 (∼²³⁵U size)</td>
</tr>
<tr>
<td>few-nucleon</td>
<td>binding: 2.2MeV deuteron 24MeV ⁴He</td>
<td>mₚ ∼ 140MeV</td>
<td>1/mₚ ≃ 1.5fm (Yukawa)</td>
</tr>
<tr>
<td>hadronic</td>
<td>Mₜ, mₚ ∼ 1GeV</td>
<td>1GeV (relativistic)</td>
<td>1/Mₜ ≃ 0.2fm</td>
</tr>
<tr>
<td>particle</td>
<td>100GeV Z, W masses</td>
<td>100GeV (relativistic)</td>
<td>1/100GeV ≃ 2 × 10⁻³fm</td>
</tr>
</tbody>
</table>

---

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

---

**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 γ-emission accompanying proton-neutron, proton-proton, neutron-neutron collisions have been derived. Numerical results are given for an incident nucleonic energy of 250 Mev.
Lepton Quark Universality Hypothesis: Leptons Quarks couple with same form & strengths.
Standard Model mass hierarchy not understood

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.
Some Important Particles, Their Masses and Contents

**Fermions**

- **electron** ($J^P = \frac{1}{2}^+$) \( m_e \approx 511\text{keV} \)
- **muon** ($\frac{1}{2}^+$) \( m_\mu \approx 110\text{MeV} \approx 200 m_e \)
- **nucleon** ($\frac{1}{2}^+$) \( M_N \approx 940\text{MeV} \approx 1800 m_e \approx 1\text{GeV} \approx 1\text{u} \)
- **proton** ($\frac{1}{2}^+$) \( M_p \approx 938\text{MeV} \approx 6\pi^5 m_e \quad (uud) \)
- **neutron** ($\frac{1}{2}^+$) \( M_n \approx 940\text{MeV} \quad (udd) \)

\[ \implies \text{p-n mass difference} \quad 1.3\text{MeV} \approx 3m_e \]

**Bosons/Mesons**

- **pion** ($0^-$) \( m_\pi \approx 140\text{MeV} \)
  \[ \approx \frac{1}{7} M_N \]
  \[ \pi^+ (\bar{u}\bar{d}) \]
  \[ \pi^- (\bar{u}\bar{d}) \]
  \[ \pi^0 (u\bar{u}, d\bar{d}) \]
- **kaon** ($0^-$) \( m_K \approx 500\text{MeV} \)
  \[ K^+ (\bar{u}\bar{s}) \]
  \[ K^- (\bar{u}s) \]
  \[ K^0 (d\bar{s}, \bar{d}s) \]
- **$\rho^0, \pm$, $\omega^0$** ($1^-$) \( m_\rho \approx m_\omega \approx 800\text{MeV} \quad (\bar{u}d, ud, \bar{u}u, dd) \)
- **Higgs** ($0^+$) \( M_H \approx 125\text{GeV} \)
- **W boson** ($1^-$) \( M_W \approx 80\text{GeV} \)
- **Z boson** ($1^-$) \( M_Z \approx 90\text{GeV} \)
Valence Quarks determine charge,

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

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

\[ \Delta(1232), S_{11}(1535) \]

\[ \gamma p \rightarrow X, \gamma p \rightarrow \eta p \]

atom

nucleon

<table>
<thead>
<tr>
<th>P</th>
<th>+</th>
<th>+</th>
<th>+</th>
<th>+</th>
<th>+</th>
<th>+</th>
<th>+</th>
<th>+</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1/2</td>
<td>3/2</td>
<td>0</td>
<td>1</td>
<td>1/2</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>-2</td>
<td>-3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Flavour

Energie/MeV

Ba Ca
Results of the Standard Model: Meson Resonances

Vacuum Excitation Spectrum of the Standard Model
NucleAR Excitation Spectrum: Not Like H-Atom!

[HG fig. 5.37]
Results of the Standard Model: Nuclear Landscape

- Mean Field Models
- Shell Model(s)
- Microscopic
- Ab Initio
- Effective Interactions
- Quark-Gluon Interaction

QCD Vacuum

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

⇒ \( \frac{A}{Z} \) Name: \( ^{235}_{92} \) U

- black: stable
- red: \( \beta^+ \) emitter
- blue: \( \beta^- \) emitter
- yellow: \( \alpha \) emitter
- green: spont. fission

PN: \( B = 2.2246 \text{MeV} \)

PN: \( B = 7.7 \text{MeV} \)

PPNN: \( B = 28.3 \text{MeV} \)
Know \(< 3000\) nuclei \(< 300\) stable\) – \(\rightarrow 7000\) unknown

neutron star: \(N = 10^{57}\)

need to account for gravity!
Explain Abundances of the Solar System!

**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 ($= 10^6$).
(f) Interactions: Patterns Emerging

Typical decay scales

Strong

Electromagnetic

Weak

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

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

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

NN scattering at 1MeV: 70 b

- $10^{-24}$ b
- $10^{-28}$ b
- $10^{-32}$ b
- $10^{-36}$ b
- $10^{-40}$ b

$\sigma_{\text{geom}}$ (cm$^2$)

$\sigma_{\text{tot}}$ (cm$^2$)

- 1 b
- 1 mb
- 1 $\mu$b
- 1 nb = $10^{-9}$ b
- 1 pb = $10^{-12}$ b
- 1 fb = $10^{-15}$ b

$K_{\text{lab}}$ (MeV, GeV, TeV)

- Hadronic
- Electromagnetic
- Weak

$\sim$ constant

decreases

increases

[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

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!

[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.**

![Galaxy rotation curve](wikipedia: Galaxy rotation curve)

**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-Robertson-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 wish to identify a Superluminal Cure for Long-Distance Communication found that 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, but the connection was indeed [Science 335 (2 Mar 2012) 1027]

---

**xkcd**
But hope springs eternal: a bump in $p\bar{p} \rightarrow \gamma\gamma$ at $M_X \approx 1.5$ TeV?

- **In the NWA search**, an excess of 3.6$\sigma$ (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 $\implies$ fluctuations may mimic rare events.

**Sagan’s Rule:** *Extraordinary claims require extraordinary evidence.*
But hope springs eternal: a bump in $\bar{p}p \rightarrow \gamma\gamma$ 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]

**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 30, 31, 38]