I. Tools

2. Particle Sources

Or: Where Your Bullets Come From

References: [HG 2, 19.5; PDG 29, 30, 37]
(a) Non-Accelerator Sources: Radioactive Sources

**Radiative Material**

- $\alpha$ ($^4\text{He}$) source (discrete): e.g. $^{226}\text{Ra}$: $E_{\text{kin}} = 4.78, 4.60\text{MeV}$  
  Rutherford’s Gold Foil exp. 1909

- $\beta$ ($e^\pm$) source ($\text{keV} - \text{MeV}$, continuous): e.g. $^{90}\text{Sr}$: $0.55\text{MeV}$  
  PET scans, cancer treatment, …

- $\gamma$ source ($0.1 - 3\text{ MeV}$, discrete):

- …

**Reactor Neutrons** mean neutron life-time $[881.5 \pm 1.5]\text{s}$ (15 minutes)

produced by fission: $E_{\text{kin}} \sim 8\text{MeV}$  
  (typ. single-n binding energy)

scattering on low-$A$ material (paraffin, carbon,… ) moderates down to arbitrary energy

no elmag. interaction $\implies$ large penetration

tune de-Broglie-wavelength $\lambda = \frac{1}{\text{momentum}}$ to resolution

thermal neutrons $E_{\text{kin}} \approx 0.025\text{eV} = 300\text{K} \implies \lambda = 2\text{ Ångstrom}$:

  condensed matter, biology, in-time analysis,…

ultra-cold neutrons $E_{\text{kin}} \approx 10^{-7}\text{eV} = 10^{-4}\text{K} \implies$ speed $\approx 10\text{ m s}^{-1}$:

  can be trapped $\implies$ neutron lifetime, subject to gravity, beyond-SM,…
**Non-Accelerator Sources: Cosmic Rays**

Cosmic rays: primary shower

\[ \approx 1.8 \times 10^4 \left( \frac{E}{\text{GeV}} \right)^{-2.7} \text{nucleons m}^2\text{ssrGeV} \text{ for GeV – 100 TeV} \]

produced by supernovae, black holes, cosmic events, . . .

Any particle with life-time

\[ > 10^6 \text{ years,} \]

energies well beyond LHC

fight tiny rates

\[ \rightarrow \text{Alpha Magnetic Spectrometer on ISS since 2011:} \]

search for exotics, dark matter, . . .
Primary shower: nuclear abundances

Figure 19.10: Composition of the nuclear component of the primary cosmic rays. Shown for comparison are the solar abundances. [From T.K. Gaisser and T. Stanev, *Nucl. Phys. A777*, 98 (2006).]
Cosmic rays: secondary shower

used to discover positron (1932),
muon (1939), pion (1947), . . .

hadron core
most produced: $e^\pm$ pair-production
most at sea level: $\mu^\pm$ time-dilatation
all other trapped above

typ. energy $2\text{GeV}$
typ. rate $\frac{1 \text{ event}}{\text{cm}^2 \text{ minute}}$

Application cargo scanning [Tav 4.22]
Cosmic rays: examples of secondary shower usage today

Neutrinos (via muons), High-Energy Astrophysics,… → isolated, shielded

IceCube Neutrino Observatory
(ice at South Pole)

ANTARES (2.5 km under Mediterranean, France)

Pierre Auger Observatory (Chilean Pampa)
(c) Accelerator Principle

⊕: controlled environment, beam delivered on-target, any energy up to $13\text{TeV}$ (LHC)

$\implies$ match to desired resolution $\lambda = \frac{1}{p}$

⊖: only charged particles, energies beyond reach, financial resources limited

**Ingredients**: accelerator physicists, source (cathode, vaporiser, ...), vacuum pipes
accelerating & beam-focusing units use **relativistic Lorentz-force** law

$$m\gamma(\beta) \frac{d}{dt} \vec{\beta} = Ze \left[ \vec{E} + \vec{\beta} \times \vec{B} \right]$$

Lorentz-factor $\gamma$ depends on magnitude of velocity $\beta$!

$\implies$ In potential difference, charge gains kinetic energy $\Delta E = Q\Delta \Phi$.

**Electrostatic accelerators**: cathode ray tubes
Breaking voltage of vacuum limits $\Delta \Phi \lesssim 15\text{MV}$

cheap, enough for nuclear structure reactions

**continuous beam**
Pulsed beam: particle bunches $\Rightarrow$ Reverse polarity while charges inside “drift tubes” (field-free)

**Synchronise** acceleration steps by common frequency $\omega_{RF} \sim \text{MHz}$ for all tubes

[PRSZR A.2]

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**Fig. A.2.** Sketch of the fundamentals of a (Wideröe type) linear accelerator. The potentials of the tubes shown are for one particular moment in time. The particles are accelerated from the source to the first drift tube. The lengths $L_i$ of the tubes and the generator frequency $\omega$ must be adjusted to each other so that we have $L_i = v_i \pi/\omega$ where $v_i$ is the particle velocity at the $i$th tube. This depends both upon the generator voltage and the type of particle being accelerated.

$\Rightarrow$ Length of $i$'th tube dictated by RF frequency: $L_i = \frac{\pi \beta_i}{\omega_{RF}}$ grows until $v \approx c$:

$M_p \gg 15\text{MeV} \Rightarrow$ many steps until $\beta \approx c$

$m_e \ll 15\text{MeV} \Rightarrow \beta \approx c$ after 1 step
Linacs at CERN
Standford Linear Accelerator SLAC

Largest Linac: electrons to **50 GeV** in 3km, **60Hz**. **Problem:** single shot, no recycling.
(e) Making Things Round

Cyclotron

Circular orbit: Lorentz $Ze \beta B = \gamma m \omega \beta$ centrifugal (relativistic!!)

\[ \omega_C = \frac{Ze B}{\gamma m} \]

$\beta \ll 1 \implies \gamma \approx 1 \implies \omega_C$ independent of particle velocity \implies can synchronise $\omega_C = \omega_{RF}$ fixed!

\[ 2 \text{ accelerations per orbit inside “dees” add } \approx Z \times 15 \text{MeV, } R = \frac{p}{Ze B} \text{ increases, still pulsed beam} \]

$\beta \to 1$: $\omega_C$ depends on $\beta$ \implies no synchronisation with $\omega_{RF}$ \implies good for ions, bad for electrons.
Largest cyclotron: TRIUMF’s 500 MeV for protons (Vancouver BC)

Isotope production, radioactive (secondary) beams, . . . Click for URL
Synchrotrons: Fixed orbit $\Rightarrow$ ramp up $B$ in sync with $\omega_{RF}$: Pulsed

Several RF Cavities around ring: accelerate particle by applying high-frequency $\vec{E}$ at right timing

$$\omega_{RF} = \text{integer} \times \omega_C = \frac{\text{integer}}{R} \text{ for } \beta \to 1.$$ 

Spatial focussing into bunches by quadrupole magnets (cf. optical lenses) & waning part of RF-wave:

- too early $\Rightarrow$ larger $\vec{E}$ $\Rightarrow$ more accel. $\Rightarrow$ larger orbit at same $\beta = 1$ $\Rightarrow$ fall back
- too late $\Rightarrow$ smaller $\vec{E}$ $\Rightarrow$ less accel. $\Rightarrow$ smaller orbit at same $\beta = 1$ $\Rightarrow$ catch up

[HG 2.10]
Storage Rings typically accelerate one bunch per second

accelerate + store + collide at interaction points + recycle if unused

CERN Large Hadron Collider LHC-II: 2 rings, p on p (soon U on U) \( \leq 13\text{TeV} \), 27km circumference
Some Other “Real-Life” Accelerators

Thomas Jefferson National Accelerator Facility

Continuous Electron Beam Accelerator Facility

Click for URL; Newport News VA;

electron “race-track”: stretched beam $\lesssim 200\mu A$

12 GeV upgrade for US$310M completed in 2015
≤ 100μA electrons up to 1.5GeV
energy resolution $\Delta E = 0.1$MeV
100% duty cycle: continuous beam
~ 7000 beam hrs per year
snugged into existing building
accelerated charges radiate \implies ultra-relativistic energy loss of single particle per orbit on circle:

\[-\Delta E = \frac{4\pi Z^2 \alpha}{3} \frac{1}{R} \left( \frac{E}{m} \right)^4 \quad \text{Larmor's formula (relativistic)}\]

HW: Very narrowly peaked in direction of \( \vec{v} \), not of acceleration!

LEP-II (electron-positron, same tunnel as LHC): \( E = 85 \text{GeV} \implies 2\% \text{ energy loss} \)

Compensate by increasing \( R \)??: 4th power vs 1st power \implies $$$!

at same energy, radiation loss for proton smaller by

\[
\left( \frac{m_e}{M_p} \right)^4 \approx \left( \frac{1}{1800} \right)^4 \approx 10^{-13}
\]

\implies LHC-proton energy up to 14 TeV (limit is strength of mag. holding field for same orbit!)
(h) Produce Photon Beams by Accelerating Charges

Tagged Photon Facility: “Glasgow Tagger” (A2@MAMI) upgraded 2017

$e^-$ on diamond (polarised $\gamma$ at MAMI) or foil (unpolarised) $\implies$ continuous Bremsstrahlung spectrum

**Tagging**: detect momentum of deflected electron event-by-event $\implies$ photon energy $\omega = E_0 - E'_e$

Event-selector is excellent trigger to reduce background for small-rate experiments (Compton: nanobarn $\equiv$ events/hour).

$E_e = 135.2$ MeV
3rd Generation Synchrotrons and Free Electron Lasers

Undulators, period $d$: $e^-$ wiggles $\Rightarrow$ emits radiation

Lasing: $e^-$ in bunches, tuning $\Rightarrow$ induced emission

Lorentz contraction: wavelength $\frac{d}{\gamma}$ in $e^-$ rest frame

"Radiation Always Forward" (HW): emit photon along $e^-$

Relativistic Doppler Effect into lab frame: $\hat{\lambda} = \frac{1}{\gamma} \left( \frac{d}{\gamma} \right)$

Example: electrons at $1\text{GeV}$ $\Rightarrow \gamma = \frac{E}{m} \approx 2000$

$\omega \approx \frac{2\pi (\gamma \sim 2000)^2}{d \sim 0.3\text{m}} \approx [1 \ldots 10]\text{eV}$: visible light, UV
Reflect photons back onto next bunch

Lorentz contraction: \( e^- \) sees \( \frac{1}{\gamma} \left( \frac{d}{\gamma^2} \right) \)

Head-on collision: \( e^- \) emits radiation, “forward”

Relativistic Doppler into lab frame:
\[
\lambda = \frac{1}{\gamma} \left( \frac{d}{\gamma^3} \right)
\]

Movie how HI\(\gamma\)S works

**High Intensity \(\gamma\)-Ray Facility HI\(\gamma\)S, Duke U. (NC)**

\(E < 100\text{MeV}\) tunable, \(\Delta E \lesssim 5\%\) quasi-monochromatic
\(10^7 \frac{\gamma}{s}\): most brilliant laser, \(100\%\) circ. or lin. polarisation
(i) Secondary Beams: neutral or short-lived particles

Some examples:

- **Neutrons**: cannot be accelerated \(\Rightarrow\) fission reactor or spallation (high-\(E\) proton on mercury), moderate down to desired \(E\). – e.g. NIST, SNS (Oak Ridge National Lab)

- **Antiprotons**: \(p\) at e.g. \(28\text{GeV}\) on 60-cm Be target produces \(10^{-3...4}\) \(\bar{p}\). Store, cool, use; – e.g. CERN SPS.

- **Pions** \(\pi^\pm\): as above, but much higher probability – mag. field separates & selects energy – e.g. \(500\text{MeV}\) \(p\) on C at Paul Scherer Institute PSI (Switzerland) (Briscoe, Downie)

- **Kaons** \(K^\pm\): as above, probability \(\approx 1/20\) of pion – e.g. CERN SPS.

- **Muons** \(\mu^\pm\): ternary beam: \(\pi \rightarrow \mu + \nu_\mu\); passage through several metres of steel. – e.g. PSI

- **High-energy neutrinos**: as muon, but shield by hundreds of metres – e.g. OPERA in the Alps.

Use time-dilatation for short-lived particles:

pion lifetime at rest: \(\approx 10^{-8}\text{s}\) at \(10\text{GeV}\): \[10^{-8}\text{s} \times \gamma = 10^{-8}\text{s} \times \frac{E}{m_\pi} = 10^{-6}\text{s}\]

\[\Rightarrow\] pion travels distance \(c \times 10^{-6}\text{s} = 100\text{'s of metres}.\)

secondary beams often contain several species

\[\Rightarrow\] separate by el. & mag. fields, passage through matter, good final-state ID.
Future Accelerators: Examples

US Department of Energy 2009: The Three Futures of Nuclear and Particle Physics

$e^\pm$ linear collider (ELC or CLIC): 1 – 3TeV, 2 linacs, each 15 – 20km cost?? when??

NSAC recommendation 2017: Electron Ion Collider: 20-200GeV, luminosity $> 10^{33}$ cm$^{-2}$s$^{-1}$

Supercond. energy recovery electron linacs, e.g. MESA (Mainz): 300 MeV, 10 mA, 100% polarised
(construction started)
Laser-Driven “Table-Top” Accelerators (Exawatt!)

Need to re-think “single-energy” & detector concepts!
Next: 3. Interaction of Particles and Matter; Detectors

Familiarise yourself with: [HG 3,4; PDG 33-35]