Experimental Techiques in Particle Physics

Sources of Radiation

Lecture 2, 2020-11-03

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Who am I

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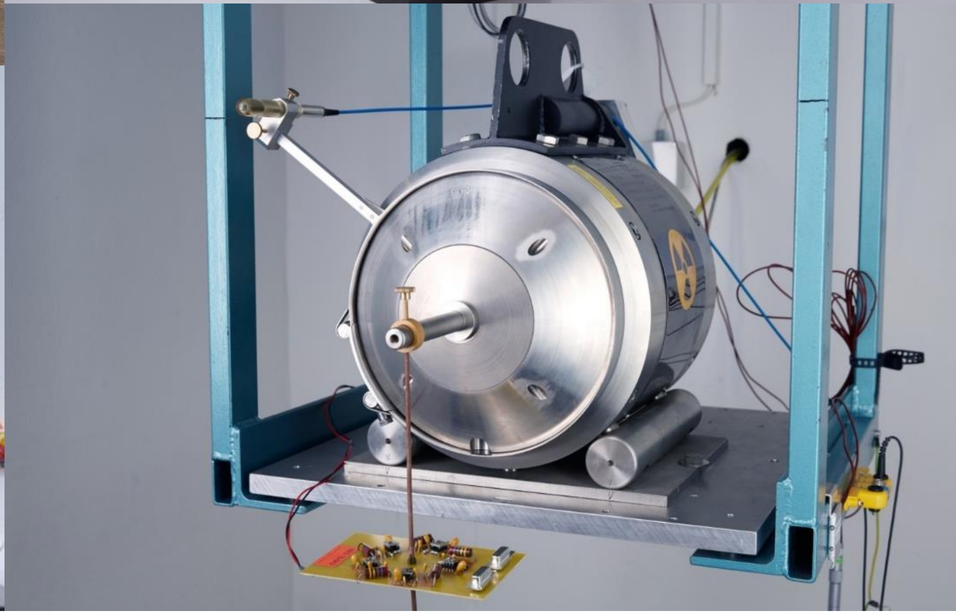
INT/NE - Profile

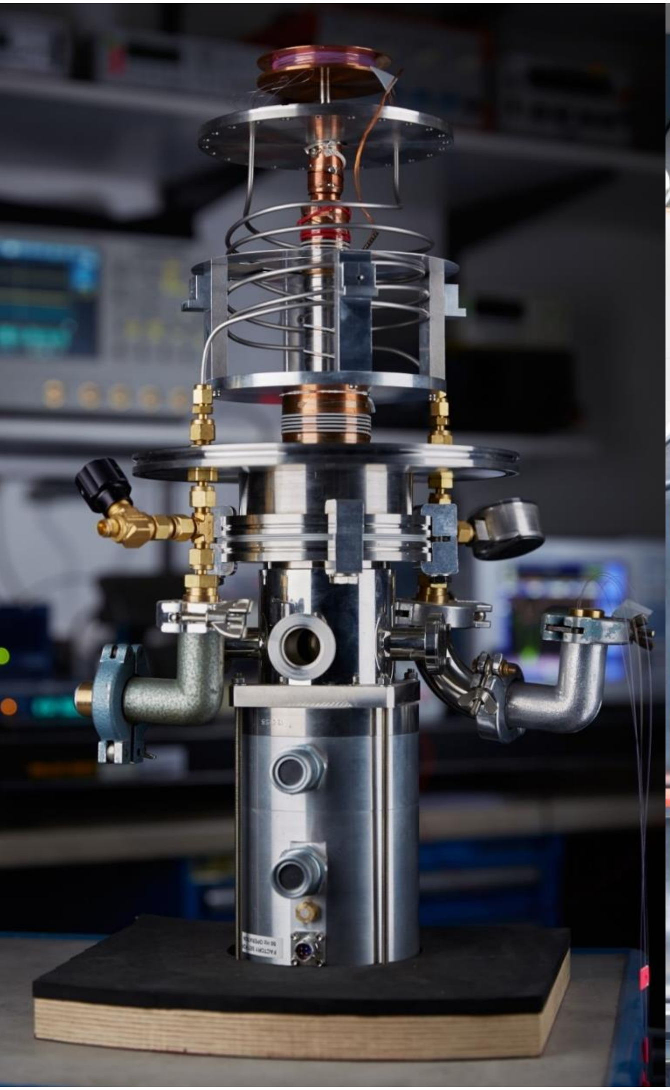
- Experimental and theoretical investigations of the sensitivity of electronic components and systems to ionizing radiation and high energy particles
- Qualification of electronic components and systems for use in radiation environments such as space, high energy accelerators, nuclear power plants or medicine
- Development of sensor systems for ionising radiation and high-power microwaves and for the detection of radioactive sources and nuclear material
- Operation and development of radiation facilities

INT/NE – Experimental Facilities (I)



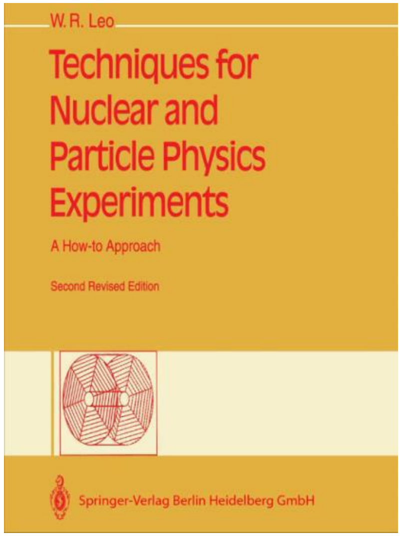



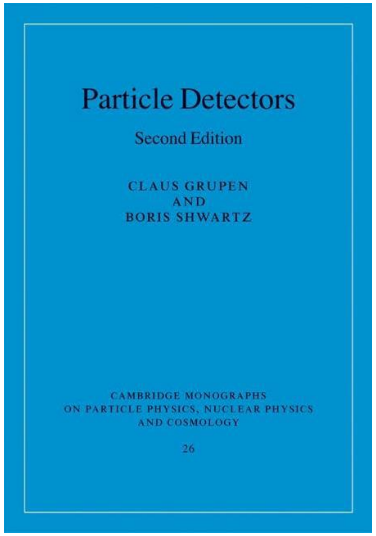
INT/NE – Experimental Facilities (II)

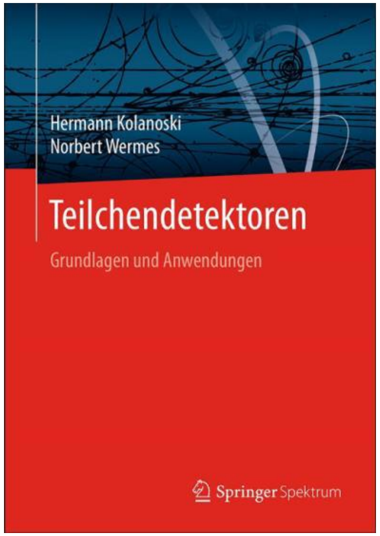


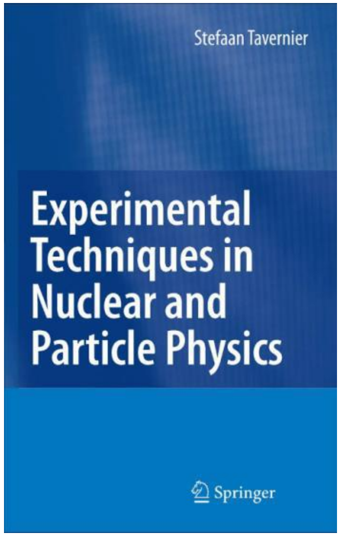
Literature

- W.R. LEO, Techniques for Nuclear and Particle Physics Experiments
- C. GRUPEN and B. SCHWARTZ, Particle Detectors
- H. KOLANOSKI und N. WERMES, Teilchendetektoren
- S. TAVERNIER, Experimental Techniques in Nuclear and Particle Physics
- PARTICLE DATA GROUP, Review of Particle Physics









Outline

- Radioactive Sources
  - Risks of Ionizing Radiation
- Cosmic Rays
- Accelerators

“Every effect of particles or radiation can be used as a working principle for a particle detector.”

Claus Grupen

Precise understanding of the interactions inducing effects and the knowledge of the processes leading to subsequent signals in particle detectors is key.

- **Detection** is the counting of particles
  in other words: “Is there a particle?”

- **Identification** is the measurement of its **mass** and **charge**
  therefore often the **momentum** or the **energy** of the particle
  must be measured.

Radioactive Sources

Radioactive Sources

Type	Process	Particle	Charge [e]	Mass [MeV/c2]	Energy
α	Nucl. decay	${}^{4}_{2}He$	+2	3727	~MeV (discrete)
β^-	Nucl. decay	e^-	-1	0.511	keV – MeV (continous)
β^+	Nucl. decay	e^+	+1	0.511	keV – MeV (continous)
γ	Nucl. de-excitation	γ	0	0	~MeV (discrete)
Internal Conversion	Nucl. de-excitation	e^-	-1	0.511	~MeV (discrete)
X-ray	Nucl. de-excitation	γ	0	0	~keV (discrete)
Neutrons	Nucl. decay / reaction	n	0	940	keV – MeV

Commonly used Radioactive Sources

Nuclide	Half-life	Type of decay	Particle Energy (MeV)	Particle Emission prob.	Photon Energy (MeV)	Photon Emission prob.
$^{22}_{11}$Na	2.603 y	β^+, EC	0.545	90%	0.511	Annih.
					1.275	100%
$^{54}_{25}$Mn	0.855 y	EC			0.835	100%
					Cr K x rays	26%
$^{55}_{26}$Fe	2.73 y	EC			Mn K x rays:	
					0.00590	24.4%
					0.00649	2.86%
$^{57}_{27}$Co	0.744 y	EC			0.014	9%
					0.122	86%
					0.136	11%
					Fe K x rays	58%
$^{60}_{27}$Co	5.271 y	β^-	0.316	100%	1.173	100%
					1.333	100%
$^{68}_{32}$Ge	0.742 y	EC			Ga K x rays	44%
$\rightarrow$ $^{68}_{31}$Ga		β^+, EC	1.899	90%	0.511	Annih.
					1.077	3%
$^{90}_{38}$Sr	28.5 y	β^-	0.546	100%		
$\rightarrow$ $^{90}_{39}$Y		β^-	2.283	100%		
$^{106}_{44}$Ru	1.020 y	β^-	0.039	100%		
$\rightarrow$ $^{106}_{45}$Rh		β^-	3.541	79%	0.512	21%
					0.622	10%
$^{109}_{48}$Cd	1.267 y	EC	0.063 e^-	41%	0.088	3.6%
			0.084 e^-	45%	Ag K x rays	100%
			0.087 e^-	9%		
$^{113}_{50}$Sn	0.315 y	EC	0.364 e^-	29%	0.392	65%
			0.388 e^-	6%	In K x rays	97%
$^{137}_{55}$Cs	30.2 y	β^-	0.514	94%	0.662	85%
			1.176	6%		
$^{133}_{56}$Ba	10.54 y	EC	0.045 e^-	50%	0.081	34%
			0.075 e^-	6%	0.356	62%
					Cs K x rays	121%
$^{207}_{83}$Bi	31.8 y	EC	0.481 e^-	2%	0.569	98%
			0.975 e^-	7%	1.063	75%
			1.047 e^-	2%	1.770	7%
					Pb K x rays	78%
$^{228}_{90}$Th	1.912 y	6α:	5.341 to 8.785		0.239	44%
		3β^-:	0.334 to 2.246		0.583	31%
					2.614	36%
($\rightarrow$ $^{224}_{88}$Ra $\rightarrow$ $^{220}_{86}$Rn $\rightarrow$ $^{216}_{84}$Po $\rightarrow$ $^{212}_{82}$Pb $\rightarrow$ $^{212}_{83}$Bi $\rightarrow$ $^{212}_{84}$Po)						
$^{241}_{95}$Am	432.7 y	α	5.443	13%	0.060	36%
			5.486	85%	Np L x rays	38%
$^{241}_{95}$Am/Be	432.2 y	6×10^{-5} neutrons (4–8 MeV) and 4×10^{-5} γ's (4.43 MeV) per Am decay				
$^{244}_{96}$Cm	18.11 y	α	5.763	24%	Pu L x rays	$\sim$ 9%
			5.805	76%		
$^{252}_{98}$Cf	2.645 y	α (97%)	6.076	15%		
			6.118	82%		
		Fission (3.1%)				
		$\approx$ 20 γ's/fission; 80% $<$ 1 MeV				
		$\approx$ 4 neutrons/fission; $\langle E_n \rangle = 2.14$ MeV				

Source: Particle Data Group

Acitivity and Radioactive Decay

- **Activity $\boldsymbol{A}$**: $[A]$ = 1 Bq = 1 decay per second

  $\boldsymbol{A = \lambda \cdot N}$, N = number of nuclei

- **Decay constant $\boldsymbol{\lambda}$**: $[\lambda]$ = 1/s = decay probability per nucleus per second

  $-dN/dt = \lambda \cdot N$ => $\boldsymbol{N(t) = N_0 e^{-\lambda t}}$

Activity and Radioactive Decay

- **Mean live time τ** : $[\tau]$ = s = mean live time for a nucleus

$$\boldsymbol{\tau} = \frac{1}{N_0}\int_0^\infty A(t) t\, dt = \frac{1}{N_0}\int_0^\infty \lambda N_0 e^{-\lambda t}\, t\, dt = \lambda \int_0^\infty e^{-\lambda t}\, t\, dt = \frac{\mathbf{1}}{\boldsymbol{\lambda}}$$

$$\boldsymbol{A(\tau)} = A(0)e^{-\lambda t} = A_0 e^{-1} = \frac{\boldsymbol{A_0}}{\boldsymbol{e}}$$

- **Half life $\mathbf{T_{1/2}}$**: $[T_{1/2}] = s$ = time after which half of initial nuclei decayed

$$A(T_{1/2}) = \frac{1}{2} A(0) = A(0)e^{-\lambda T_{1/2}}$$

$$\frac{1}{2} = e^{-\lambda T_{1/2}} \quad => \quad \mathbf{T_{1/2}} = \frac{\boldsymbol{ln2}}{\boldsymbol{\lambda}} = \tau\, \boldsymbol{ln2}$$

From Activity to Dose

Activity

$$A = \frac{Decays}{Time}$$

Unit: Bq = s^{-1}

Energy dose

$$D_{T,R} = \frac{Energy\ deposited\ through\ Radiation\ R}{Mass\ of\ Tissue\ T}$$

Unit: Gy = J kg^{-1}

Equivalent dose
(Organ dose)

$$H_{T,R} = w_R \cdot D_{T,R}$$

Unit: Sv = J kg^{-1}

Effective dose

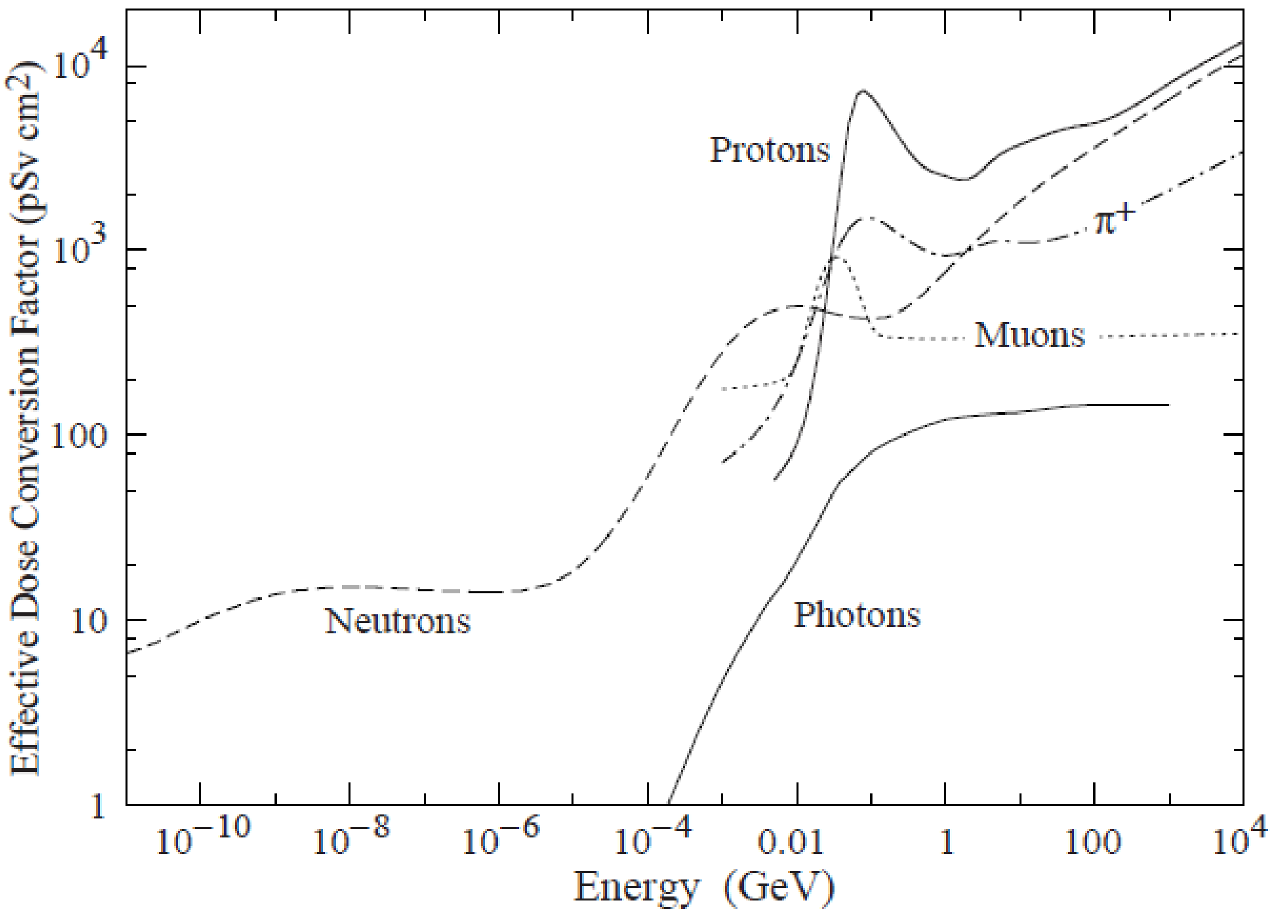
$$\mathrm{E} = \sum_T w_T \sum_R w_R \cdot D_{T,R}$$

Radiation Quality Factors w_R

- Same as **quality factor Q** or **Relative Biological Effectiveness RBE**

  - X-rays, Gammas: 1
  - Electrons, Muons: 1
  - Protons (> 2 MeV), charged Pions: 2 - 5
  - Alphas, fission products, heavy nuclei: 20
  - Neutrons
    - < 10 keV: 5
    - 10 keV – 100 keV: 10
    - > 100 keV – 2 MeV: 20
    - > 2 MeV – 20 MeV: 10
    - > 20 MeV: 5

Dose Conversion Coefficient: From Flux to Dose



Source: Particle Data Group

Level of Natural Radiation Exposure in Germany

- Total annual natural exposure for the public is on average 2.1 mSv.
- Depending on the place of residence, life habits etc. it sometimes adds between 1 and 10 mSv.

- External exposure: 0.7 mSv/a
  - Cosmic rays: 0.3 mSv/a
  - Terrestrial radiation (rocks and soil etc.): 0.4 mSv/a
- Internal exposure through inhalation or ingestion of natural substances
  - Potassium-40, Carbon-14, Thorium and Uranium: 0.3 mSv/a
  - Inhalation of Radon-222: 1.1 mSv/a

- Man-made exposure by medical or technical applications: 1.8 mSv/a
  - Ranging from 0.01 mSv for an dental X-ray diagnostic up to 10 mSv for a tomography

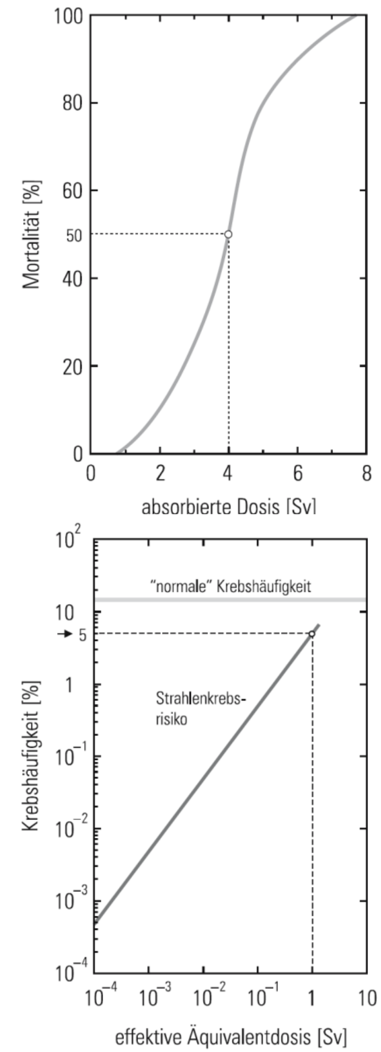
Risks of Ionizing Radiation (cont'd)

Deleterious effects of ionizing radiation

- **Deterministic** or **stochastic** effects
  - Deterministic only occur once a threshold has been exceeded
    - **Threshold := 1 Sv** for acute radiation syndrome (sickness)
    - **LD 50/30** value: **4 – 5 Sv**

    - The main stochastic effect is cancer (also on subsequent generations)
    - Additional risk for cancer **1% per 100 mSv**

  - No dose-rate dependency



Source: C.Grupen, „Grundkurs Strahlenschutz"

Risks of Ionizing Radiation (cont’d)

Limits given by the German „Strahlenschutzverordung“

(Additional) **occupational** radiation exposure

- Max **20 mSv/a** for radiation workers (class A)
  - > 6 mSV/a class B
- Max 1 mSv/a for normal population
- Monitored area: > 0.5 µSv/h equiv. 1 mSv/a
- Controlled area: > 3 µSv/h equiv. 6 mSv/a
- Closed, restricted area: > 3 mSv/h   (e.g. accelerator in operation)

- Radiation safety is a risk-benefit analysis
  - **ALARA:** As low as reasonable achievable

Risks of Ionizing Radiation (cont'd)

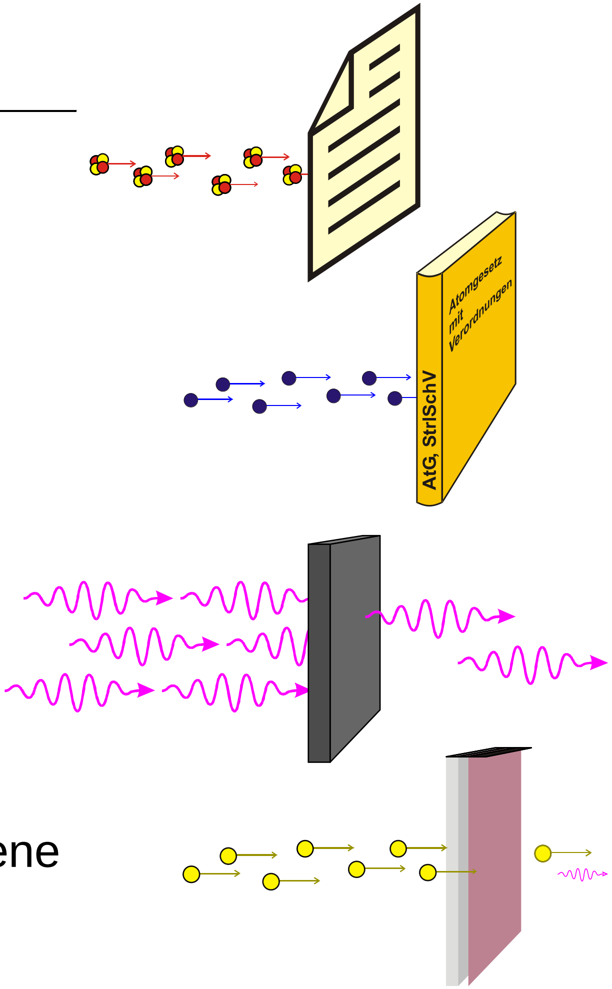
Shielding against radiation to reduce/minimize exposure

Effectiveness depends on type of radiation and shielding material

- Gammas: high Z (cross section for photo effect ~ Z^5) => Lead walls
- Betas: low Z (avoid bremsstrahlung) => aluminum or plastic shields
- Neutrons: high protonic content (elastic scatter) => water, paraffin
- Due to costs: Concrete as shielding at accelerators

Practical Aspects of Radiation Shielding

Type	Range in Air	Shielding
α	Less than 10 cm	A sheet of paper
β	Up to 10 m	1 cm Alu 2 - 5 cm acrylic glass
γ	several 100 m	at 2 MeV: 4.4 cm Lead down to 1/10
n	several 100 m	e.g. Am/Be-source with 18.6 cm Polyethylene down to 1/10



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Basic Rules in Radiation Protection

activity
(as low as possible)

high linear
attenuation coefficient

$$D_\gamma = \Gamma_H \cdot \frac{A}{r^2} \cdot t \cdot e^{-\mu d}$$

use thick
shielding

increase **distance**

shorten
Time closed to source

Risks of Ionizing Radiation (cont'd)

Laboratory rules especially where radioactivity is used or contamination is expected

- Follow the advice of the radiation protection officer
- Always wear your personal dosimeter
- Never touch radioactive sources or contaminated surfaces without cloves, wash your hands when leaving the area
- You must not eat, drink or smoke inside any laboratory

- Last is valid in any lab

Cosmic Rays

Why to Study Cosmic Rays

They propagate through universe and can give information on properties of cosmic environment (magnetic fields, matter densities…)

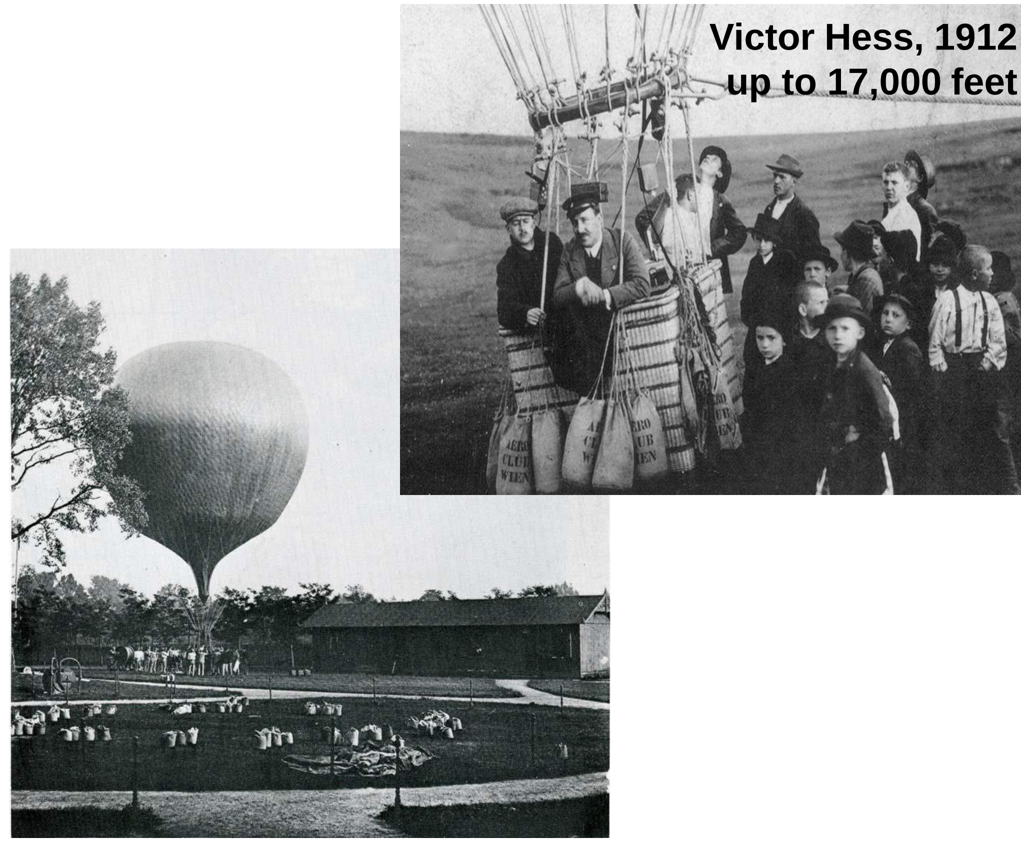
- Their chemical composition, modulated by propagation, reflects the nucleo-synthetic processes occurring at their origin and can also be used to measure the age of astrophysical objects
- They can be used to study the validity of physical laws in extreme conditions (e.g. violation of Lorentz invariance?)
- They can be messengers of « new physics » or yet unknown particles

Up to the Sky

1912 and 1913: Hess and Kolhörster made manned balloon flights to measure the ionization in the atmosphere with increasing altitude

They found that the average of the ionization increased with increasing altitude.

« The result of these observations seems to be explained in the easiest way by assuming that an extremely penetrating radiation enters the atmosphere from above » (V. Hess)



Source: V. F. Hess Society, Schloss Pöllau

Counting Improves

1929 The Geiger-Müller detector was invented

- The fast response time allowed to count individual cosmic rays and also to determine their arrival time precisely.
- 1929 Bothe and Kolhörster performed the first coincidence experiment (to about 0.01 s) by using two counters one placed above the other and introducing a thick absorber between these two.
- The coincident events indicated that the cosmic rays were charged, very penetrating particles as the gamma rays were stopped in the absorber.

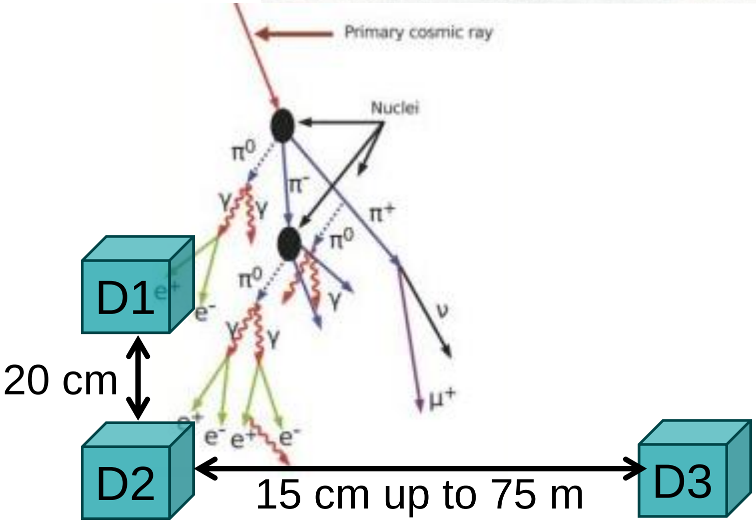
Extensive Air Showers

1938: Pierre Auger and P. Ehrenfest, Jr Measurements in the Alps

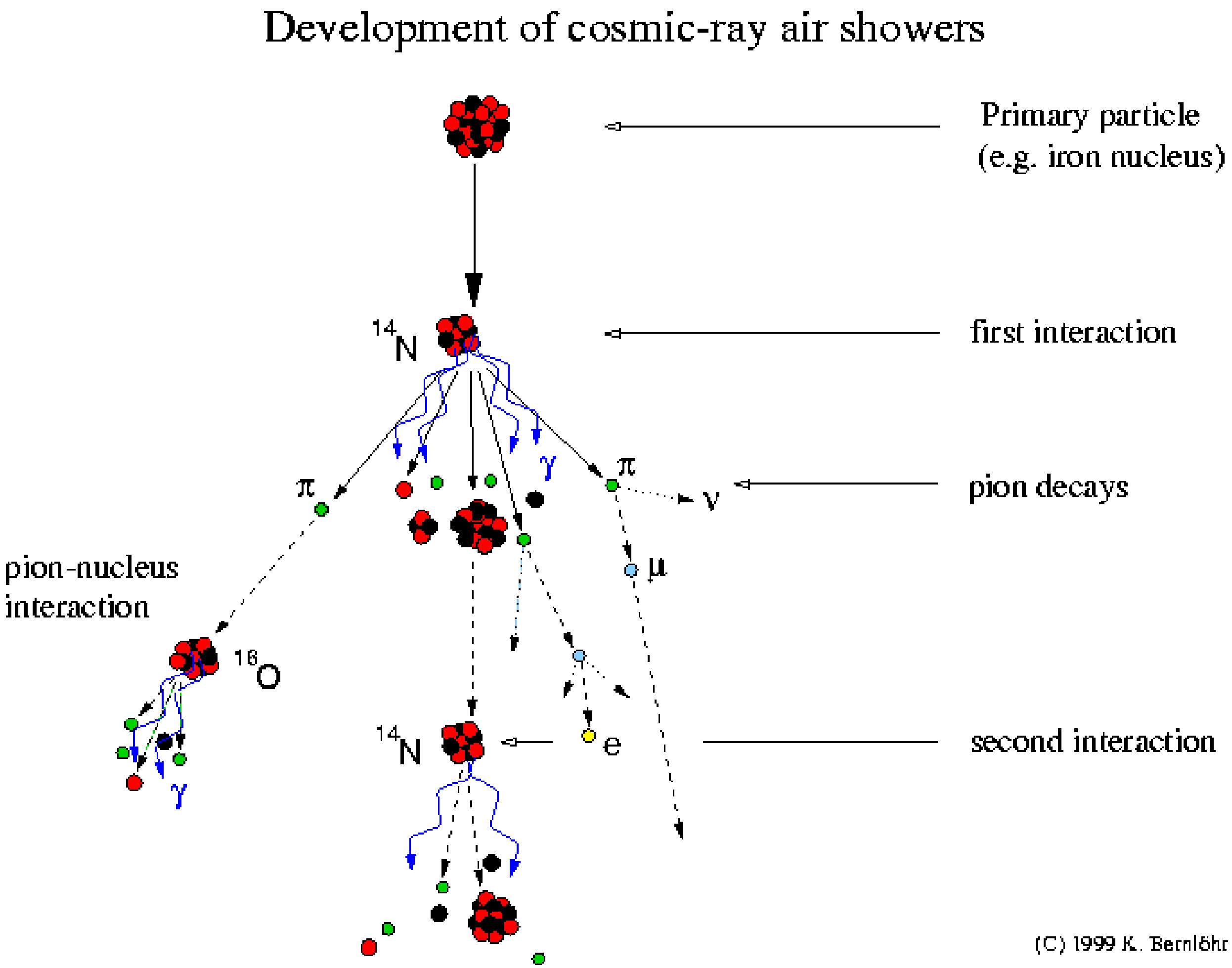
MEASURING COSMIC RAYS IN THE SWISS ALPS
The author (*left*) and his collaborator, P. Ehrenfest, set up their apparatus in the Jungfraujoch.

- Particle detectors positioned at 3500 m height on the “Jungfraujoch” in the Suisse Alps signaled the arrival of particles exactly at the same time.

- Explanation: Cosmic radiation events that are coincident in time are associated with a single event, an **air shower**.
  They estimated that the energy of the incoming particle that creates large air showers must be at least **10^{15} eV**, i.e.
  10^6 particles of 10^8 eV (critical energy in air) and a factor of ten for energy loss from traversing the atmosphere (Auger et al., 1939).



Primary and Secondary Cosmic Rays, Extended Air Shower



EAS = Mix of different processes, e.g.

$$\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu_e}$$

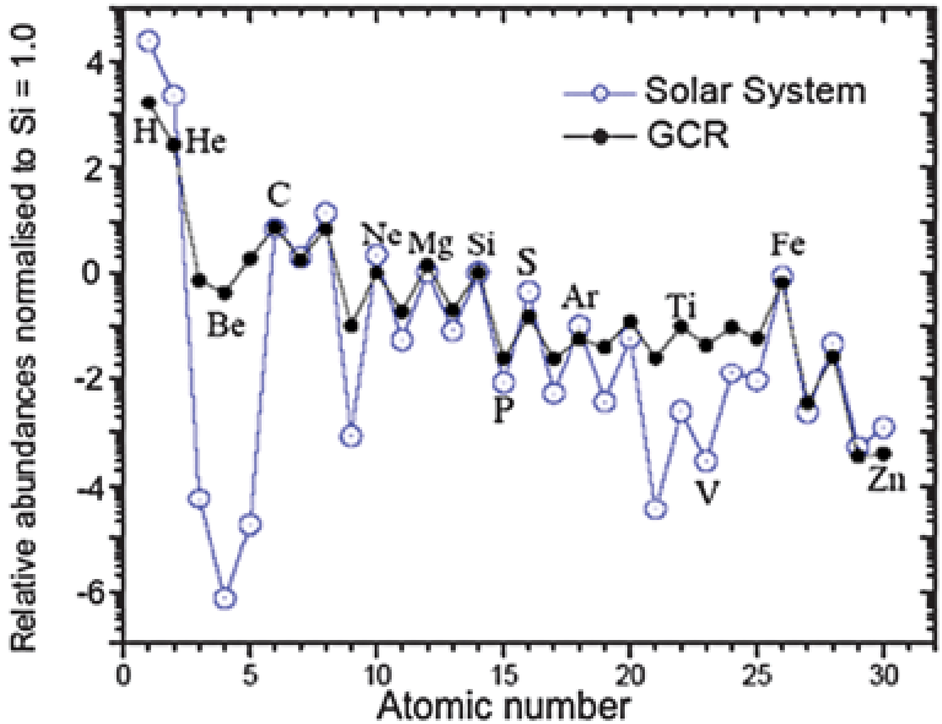
- Except for protons and electrons, all particles are produced in the atmosphere
- At ground level the main signal for primary cosmic rays is a flux of muons

Primary Cosmic Rays

- Flux of stable (>10^6 years) charged particles and nuclei
- Primary Cosmic Rays: accelerated at astrophysical sources
  - Protons ~ 87 %
  - He ~ 12 %
  - 1 % heavier nuclei: C, O, Fe and other ionized nuclei synthesized in stars
  - 2 % electrons
  - γ-rays, neutrinos
  - ~ 10^{-4} anti-p and e+, but no anti-nuclei are found
- But composition varies with energy (bulk of CR is at 1 GeV).
- Secondary Cosmic Rays: particles produced in interactions of primaries with interstellar gas
  - Also particles produced in atmospheric showers (Li, Be, B, anti-p, e+)
- Aside from particles produced in solar flares, they come from outside the solar system

Composition of CRs in the Solar System and in the Galaxy

- All stable elements of periodic table are found in CRs and abundances are very similar to solar system one.
- Taking Silicon abundance as reference (by definition its abundance is assumed equal for both) the relative abundances of the elements in the solar system and in galactic CRs are compared:
  - Less H and He in CRs than in solar system
  - More light elements (Li, Be, B) in GCRs than in the solar system CRs
  - The abundances of odd Z elements are larger
  - More sub-Fe elements in CRs



Source: Astrophysical Journal

Composition of CRs in the Solar System and in the Galaxy (cont'd)

- H and He: since Z = 1 is difficult to ionize and accelerate them
- Li, B, Be are not produced in star nucleosynthesis but are the result of spallation of heavier elements (such as C and O from interstellar matter).
- Sub-Fe come from fragmentation of Fe that is relatively abundant.
- The odd/even effect is due to the fact that nuclei with odd Z and/or A are weaker bound and more frequent products in thermonuclear reactions.
  - Extremely stable nuclei occur for filled shells ('magic nuclei') corresponding to magic numbers (2,8,20,50,82,126) that refer separately to n and p.
  - Double magic nuclei like He and O are particularly stable and hence abundant

Composition vs Energy: Heavy Ions

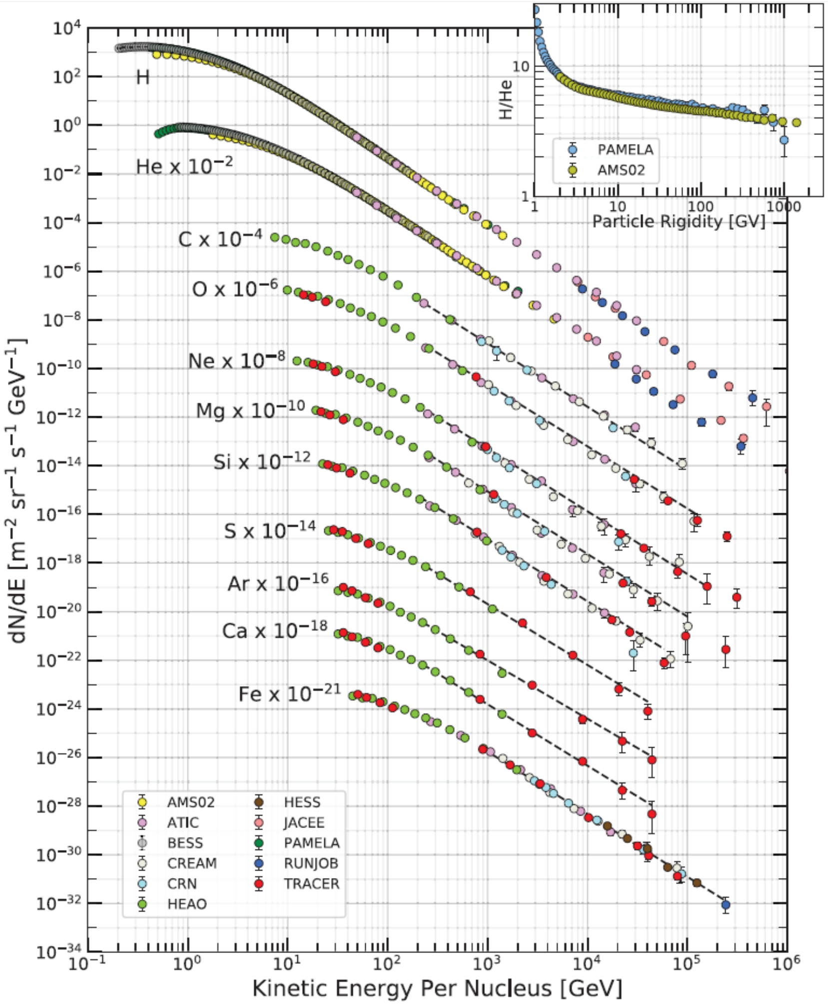


Figure 30.1: Fluxes of nuclei of the primary cosmic radiation in particles per energy-per-nucleus are plotted vs energy-per-nucleus using data from Refs. [2–13]. The inset shows the H/He ratio at constant rigidity [2,4].

Source: Particle Data Group

Energy Spectrum

$$\boldsymbol{\Phi(E) \cong KE^{-\alpha} \quad \alpha \approx 2.7}$$

Knee (steepening of the spectrum): α: 2.7 → 3
Ankle (hardening of the spectrum): α: 3 → 2.7
$E_{Knee} \cong 3 \cdot 10^{15} eV$
$E_{Ankle} \cong 10^{19} eV$

CR energies are laboratory energies!
The corresponding CM energy in the collision of two particles of masses m_1 and m_2:

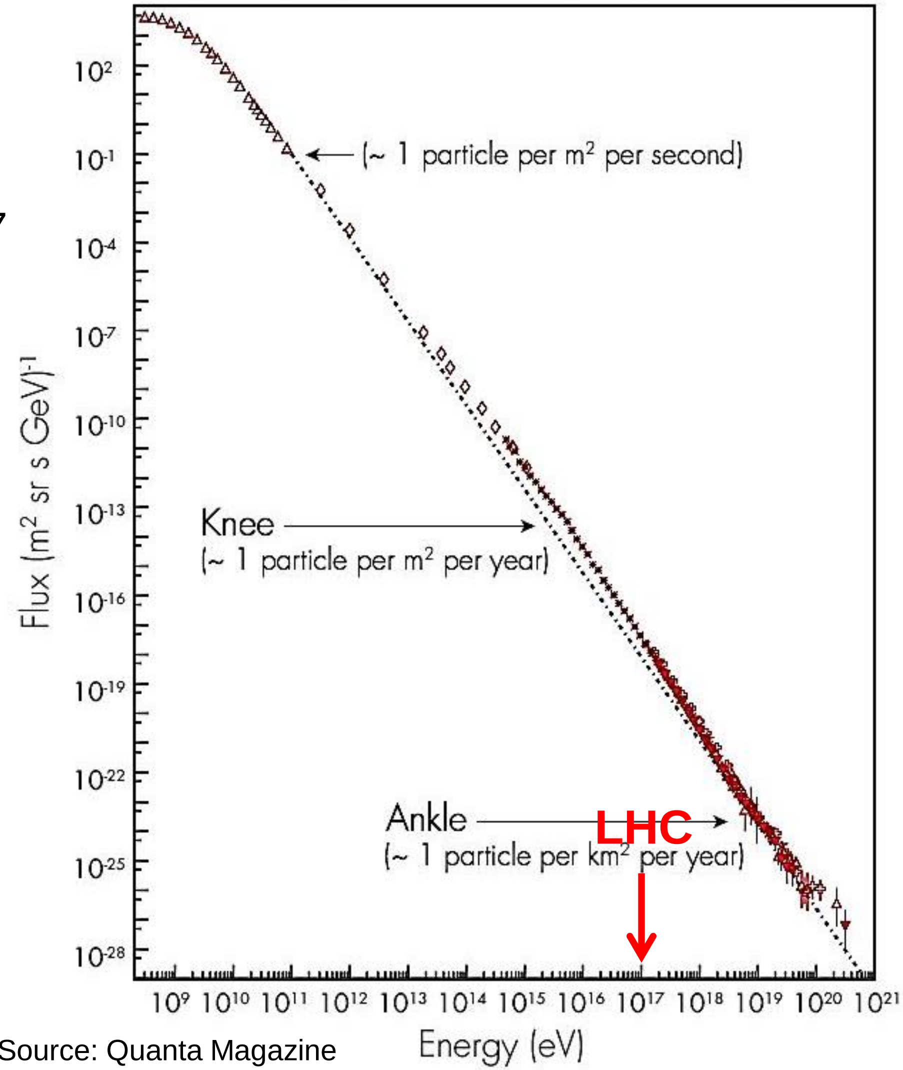
$$E_{cm}{}^2 = m_1{}^2 + m_2{}^2 + 2E_1E_2(1 - \beta_1\beta_2 cos\theta)$$

$$m_2 \; at \; rest \; and \; m_{1,2} \ll E_{1,2}$$

$$E_{cm} \cong 2m_2E_{1,lab}$$

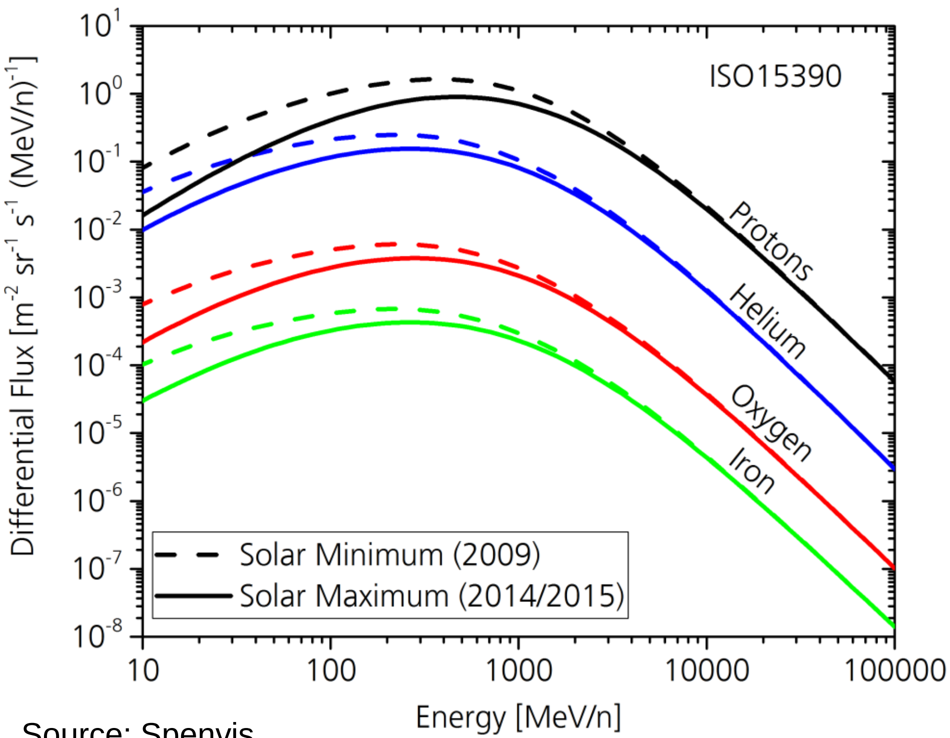
$$for \; m_2 = 1GeV \; and \; E_{cm} = 14TeV \; (LHC)$$

$$E_{lab} = 10^{17} eV$$

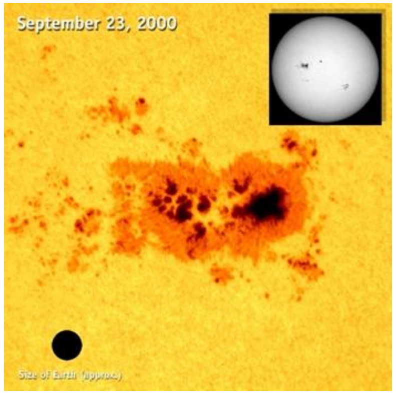


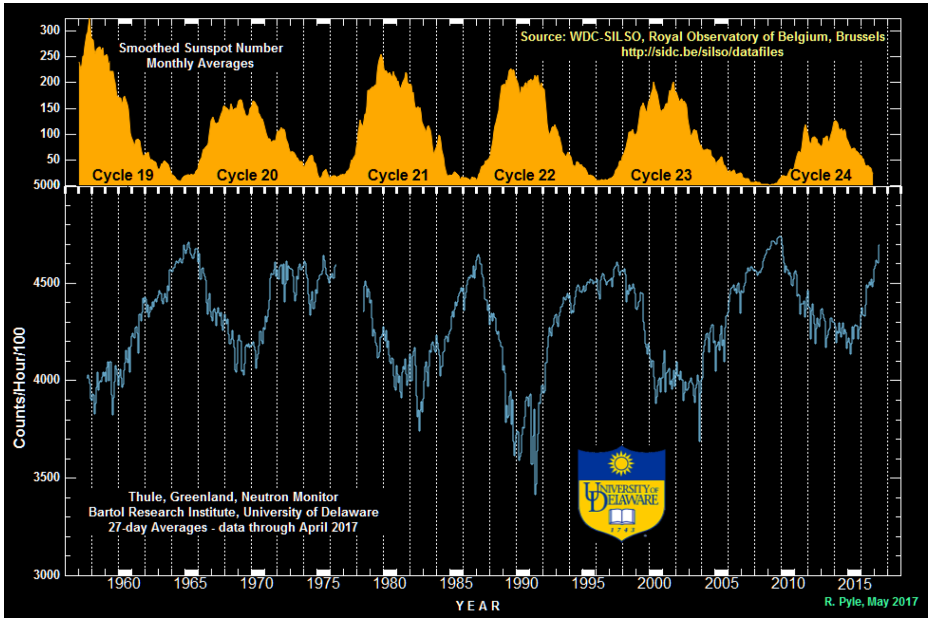
Source: Quanta Magazine

Low Energy Cosmic Rays and the Influence of the Sun @ 1AU

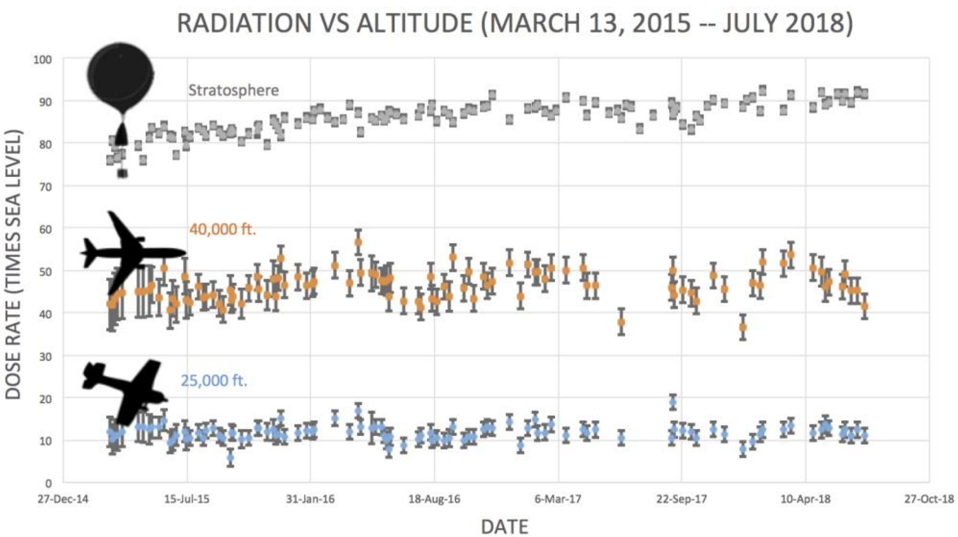


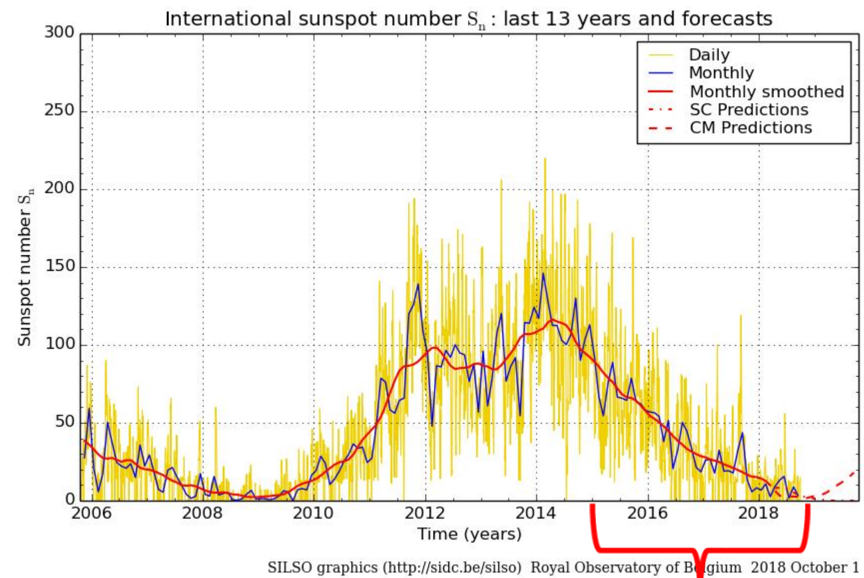
Source: Spenvis

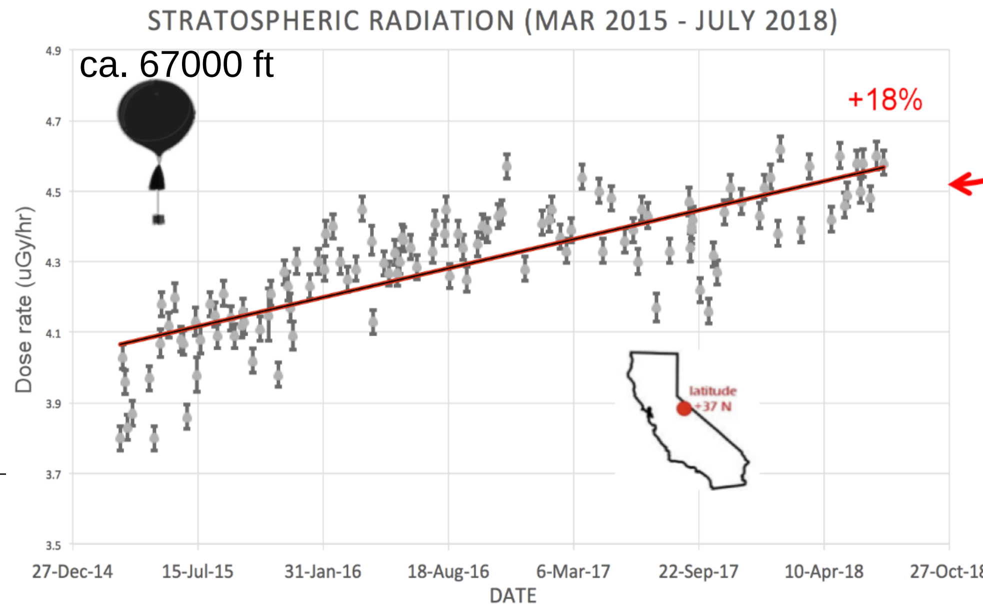




Source: University of Delaware, Bartol Research Institute



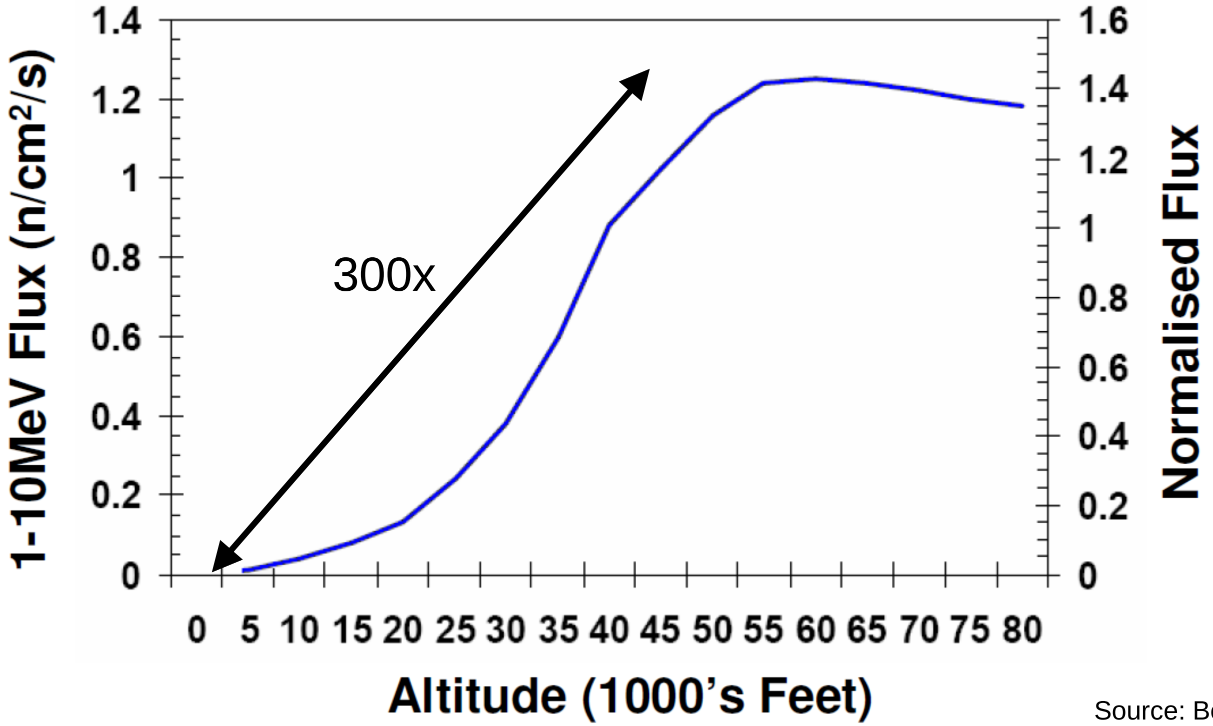




Source: Spaceweather.com

Atmospheric Neutron Flux

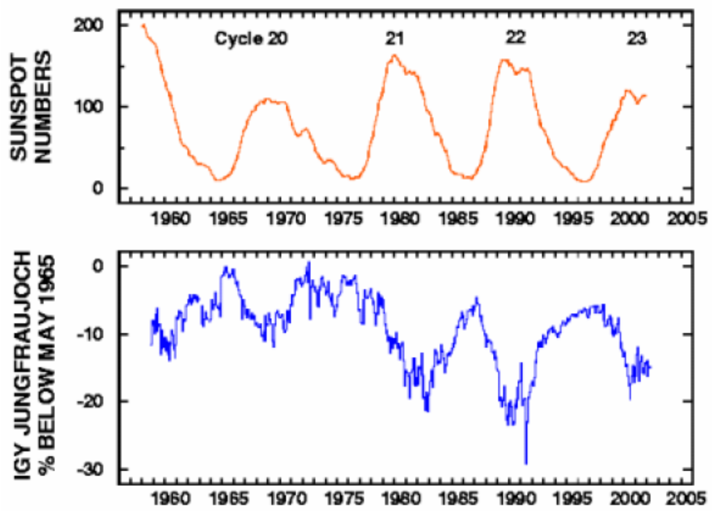
- Total neutron flux at sea height: ca. 20 $cm^{-2}\ h^{-1}$
  - Among those with energies > 10 MeV: ca. 2 $cm^{-2}\ h^{-1}$
- Neutron flux (E > 10 MeV) at 10 km altitude: ca. 6000 $cm^{-2}\ h^{-1}$



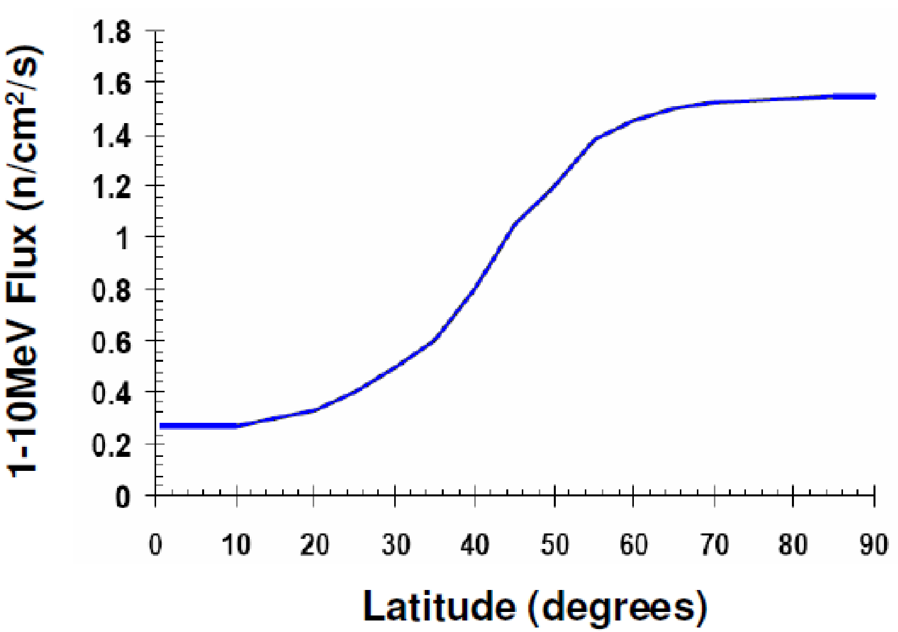
Source: Boeing Radiation Effects Lab

Atmospheric Neutron Flux – Other Dependencies

Day time	< 2 %
Season	< 5 %
Solar cycle	< 20 %
Geographical latitude	400 - 600 %

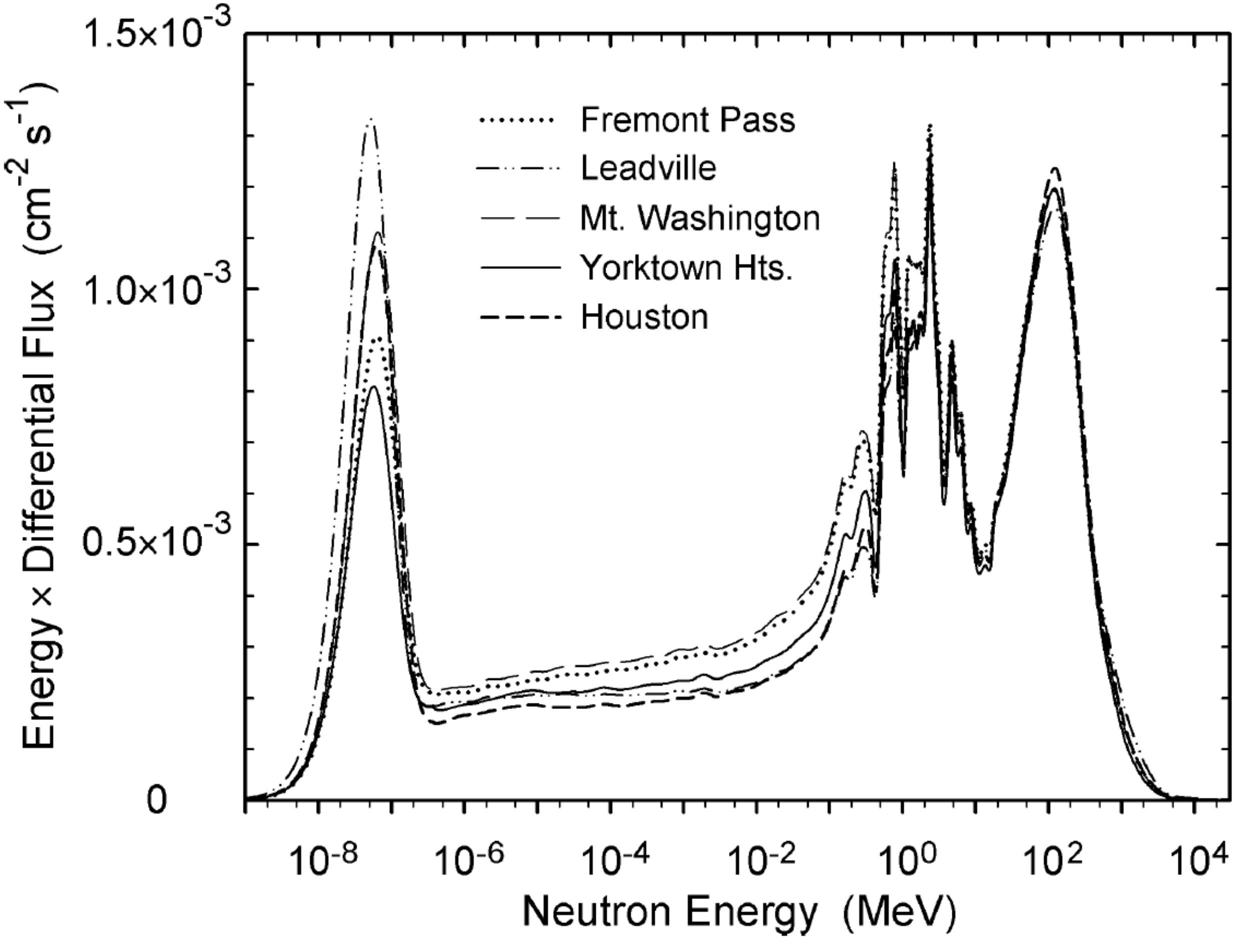


Source: Jungfraujoch Neutron Monitor



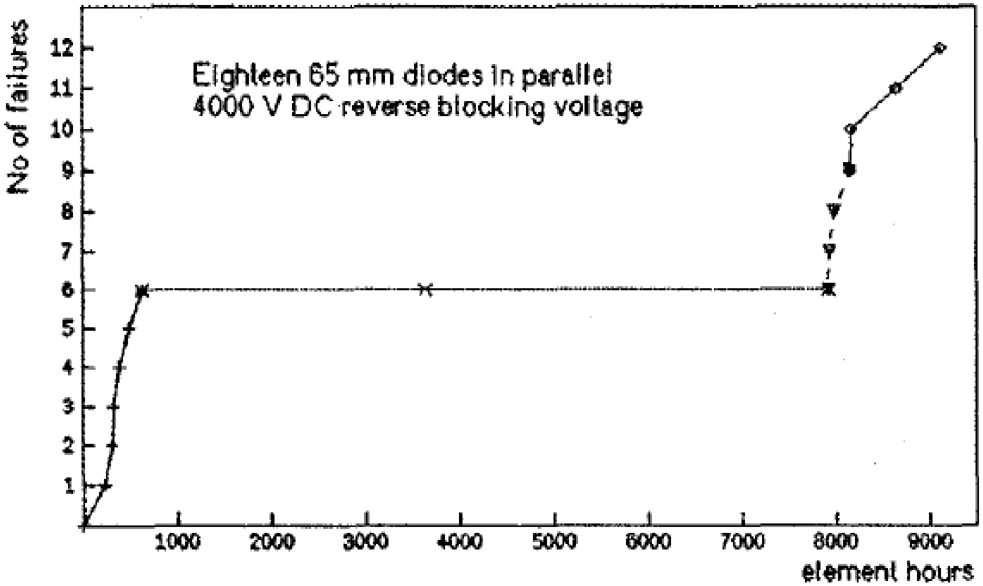
Source: Boeing Radiation Effects Lab

Atmospheric Neutrons – Energies



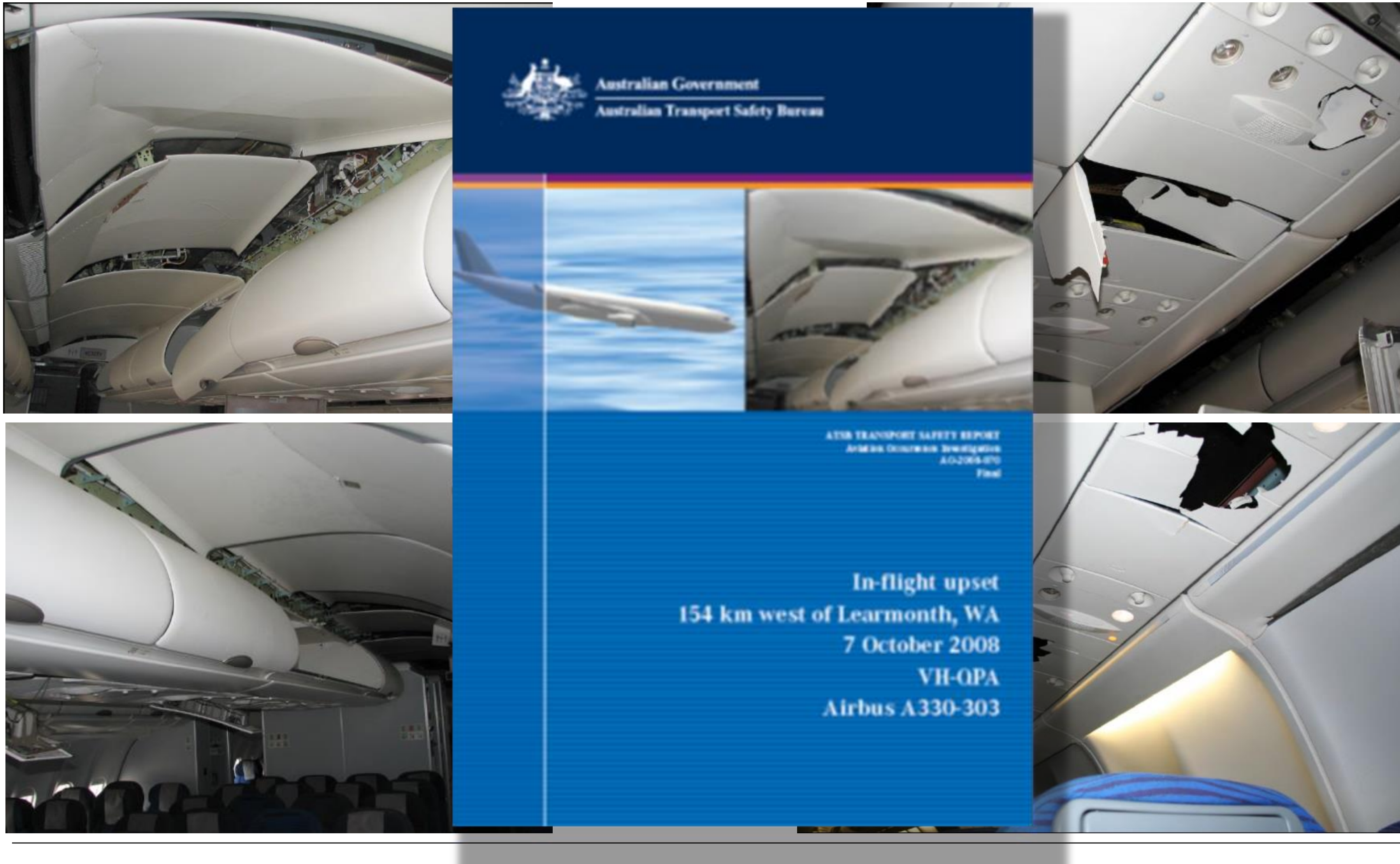
Source: IEEE Trans. Nucl. Sci., vol.51, no.6, Dec. 2004

Effects of Atmospheric Neutrons (I)



Source: Proc. 6th Internat. Symp. Power Semiconductor Devices & IC's, Davos, Switzerland, May 3 1 - June 2 1994.

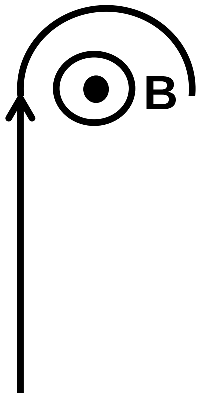
Effects of Atmospheric Neutrons (II) – Quantas 72



Angular Distribution

The angular distribution of cosmic rays is isotropic

- Galactic magnetic fields are in the order of a few µG (1µG = 10^{-10} T)
- Assume Gyroradius to be
  - ca 1 pc (e.g. Supernova remnant) => $E_{CR} \cong 10^{15} eV$
  - ca 1 kpc (e.g. galaxy) => $E_{CR} \cong 10^{18} eV$
  - ca 1 Mpc (large galaxy clusters) => $E_{CR} \cong 10^{21} eV$



=> Cosmic Rays with energies above ca.
10^{18} eV are of **extra-galactic origin**

Accelerators

Why do we need accelerators?

Accelerators

Technical Applications
- TV-tubes
- Electron beam welding
- keV

Particle Physics
- Production of heavy particles
- Collider experiments
- Search for new or exotic matter
- GeV - TeV

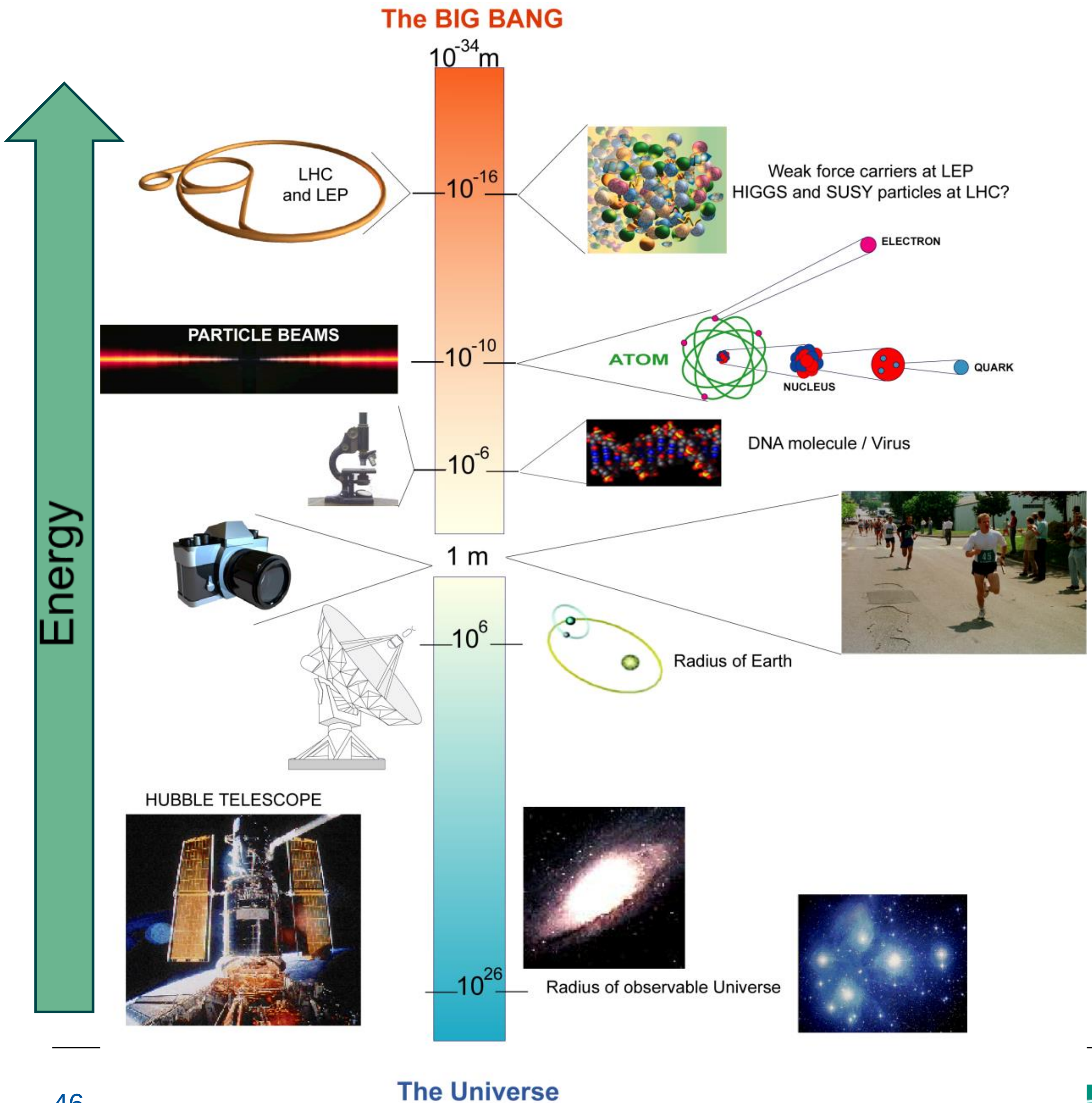
Nuclear Physics
- Binding energies
- Nuclear reaction
- Radioactivity
- keV – MeV/nucl

Material Science
- Synchrotron radiation
- Implanting
- Ion beam analysis
- keV – GeV

Medical Applications
- Production of isotopes
- Therapy
- keV – GeV

Chemistry
- Mass spectrometry
- keV

The right energy for a given size

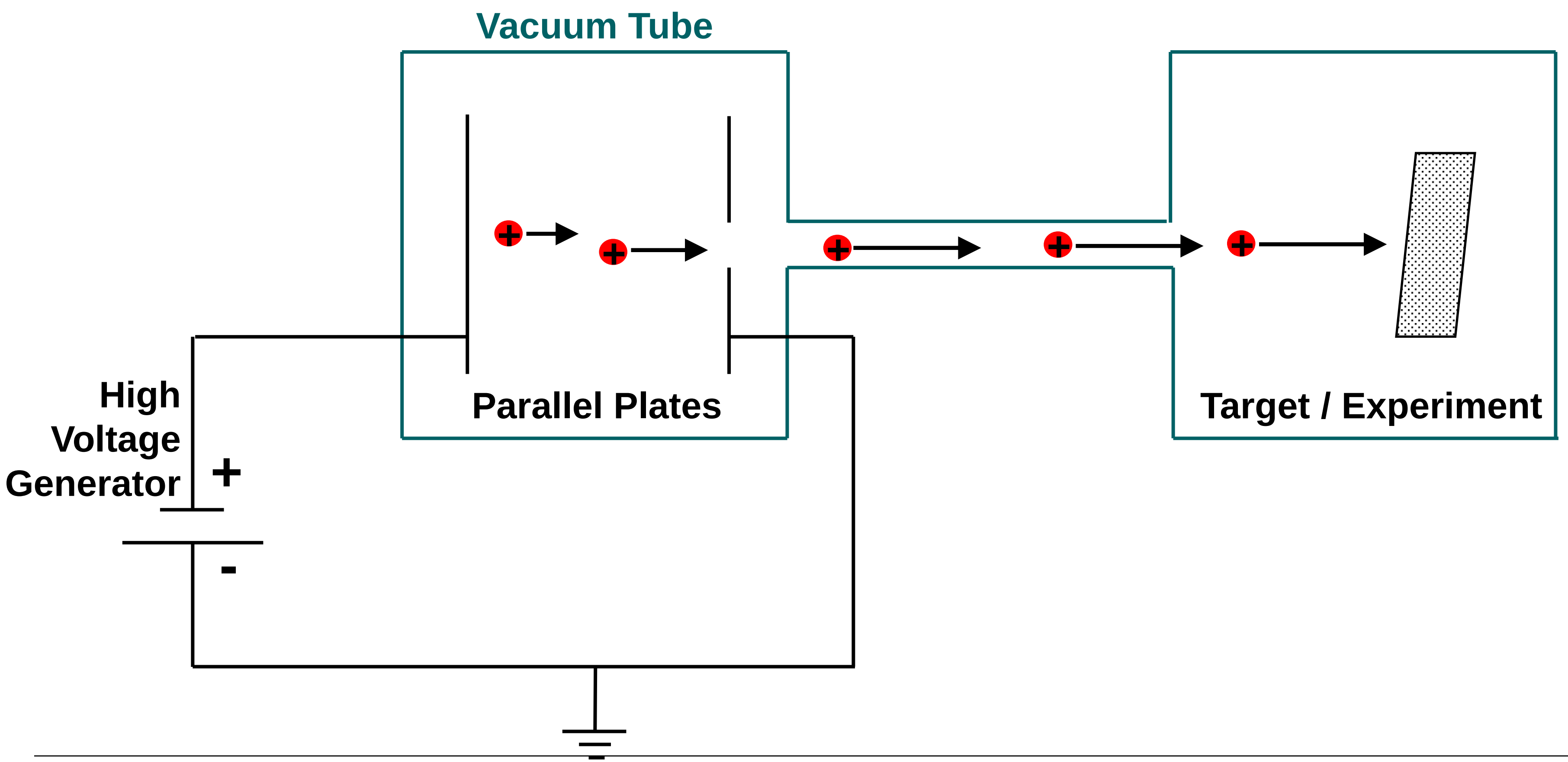


Wavelength of the probe must be shorter than the size of the object to be measured

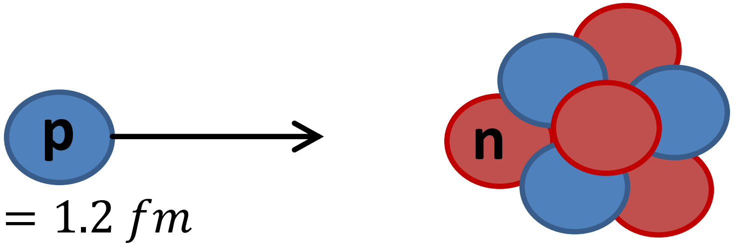
$$\lambda \ll \frac{h}{p} = \frac{hc}{E}$$

Object	Size	Energy
Atom	10^{-10} m	10 keV
Nucleus	10^{-14} m	10 MeV
Nucleon	10^{-15} m	100 MeV
Quarks		> 1 GeV

Simple DC (electrostatic) accelerator



Energy needed for reaching the nucleus



- Radius of nuclei: $r_{nucl} = r_0 A^{1/3}$ with $r_0 = 1.2\ fm$
- For enabling nuclear reactions the repulsive force of the positive charged nucleus must be compensated

$$U_{repulsive} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r} \quad \text{with } k = \frac{e^2}{4\pi\varepsilon_0} = 1.44\ \text{MeV fm}$$

$$U_{repulsive} = \frac{kZ_1Z_2}{r_0 A^{1/3}} = 1.2\frac{Z_1Z_2}{A^{1/3}}\ [MeV]$$

- Example first nuclear reaction measured by Cockroft and Walton

$$p^+ + {}^7_3Li \rightarrow \alpha + \alpha$$

$$U_{repulsive} = 1.2\frac{1\cdot 3}{7^{1/3}} = 1.88\ \text{MeV}$$

Convenient Units

- 1 eV = 1.602 x 10^{-19} C x 1 V = 1.602 x 10^{-19} J

  1 MeV = 1.602 x 10^{-13} J

  1 GeV = 1.602 x 10^{-10} J
- LHC at CERN in the TeV range

  this is the energy to lift 1 g about $\mathbf{16\ \mu m}$ on Earth

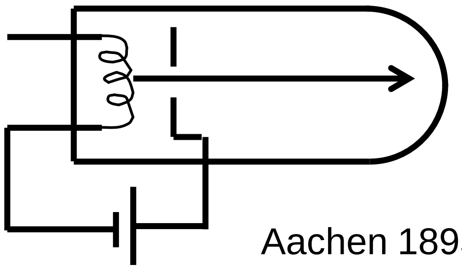
  or the light a 100 W lamp for about $\mathbf{1.6}$ **ns**

Rigidity: Bending Radius vs Momentum

- Correlation between beam parameters and accelerator features
- **Rigidity:** $\boldsymbol{\frac{p}{q} = B\ \rho}$
- This expression is called rigidity (important quantity for accelerators)
- Ration of momentum to charge
- Expresses how difficult or easy it is to deflect or bend a particle
- The typical unit is [T m]
- For q = e: $p\left[\frac{GeV}{c}\right] \approx 0.3B[T] \cdot \rho[m]$

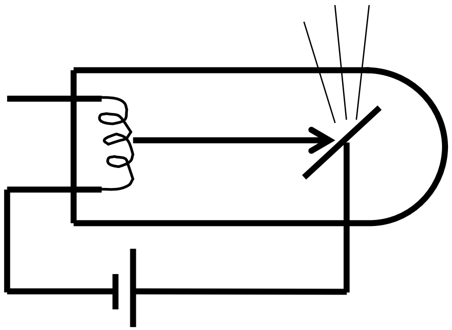
History of Accelerators

1894: P. Lenard develops discharge tube
→ „Channel rays“

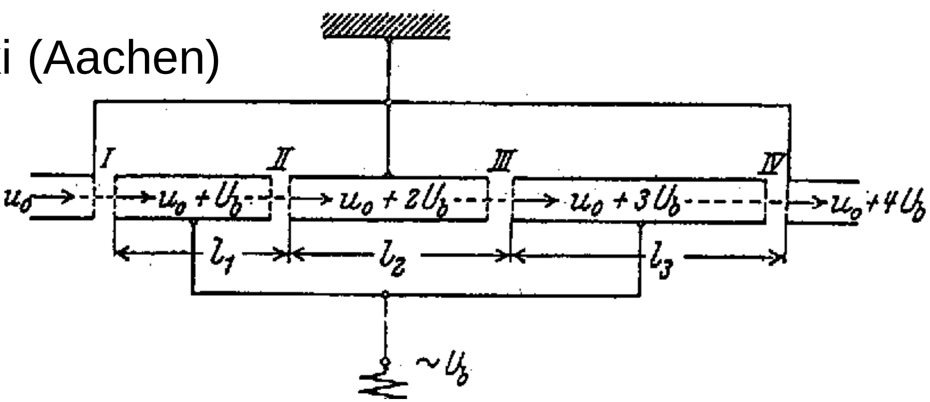


Aachen 1895

1895: W. Röntgen used such discharge tubes
→ Discovery of „X-rays“

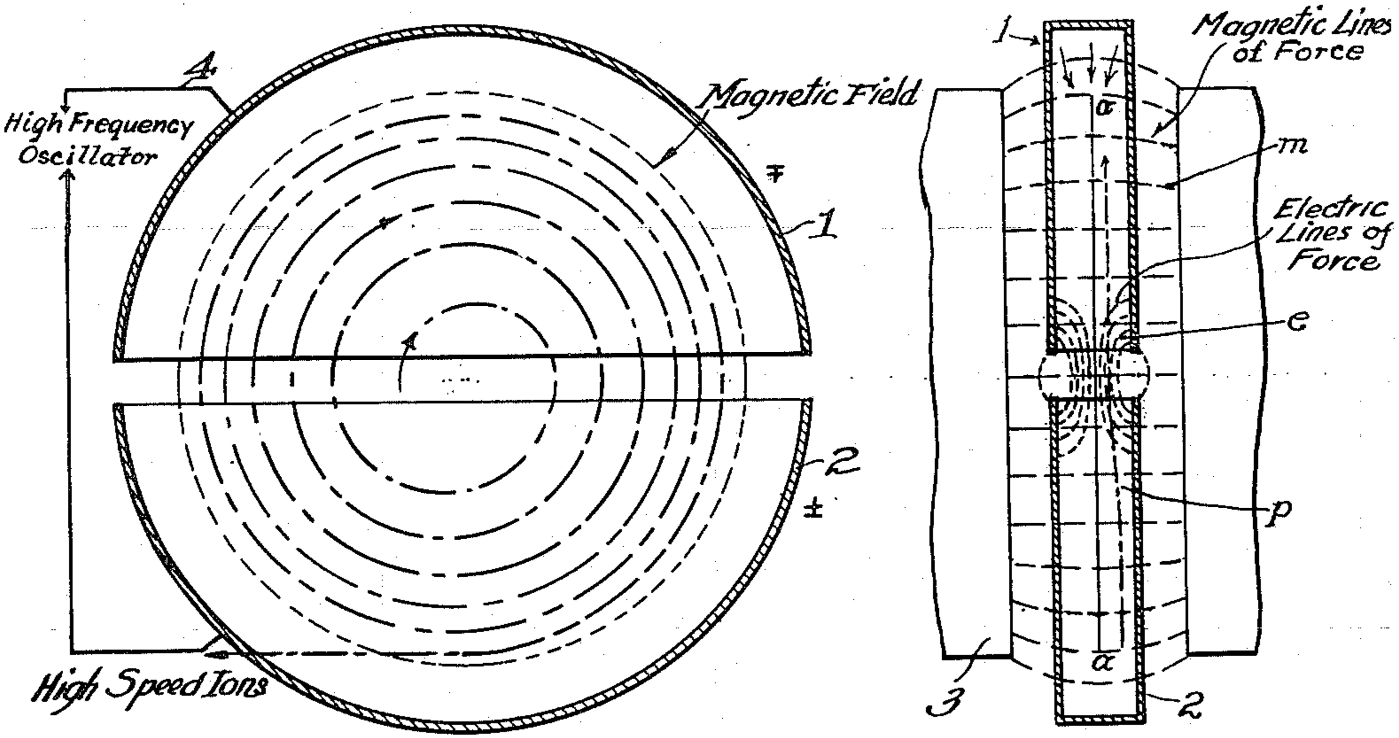


1928: R. Wideröe develops first linear accelarator using an idea of G. Ising
→ Acceleration of Na ions to 50 keV
using 25 kV Voltage
→ PhD thesis at Prof. Rogowski (Aachen)



History of Accelerators (cont'd)

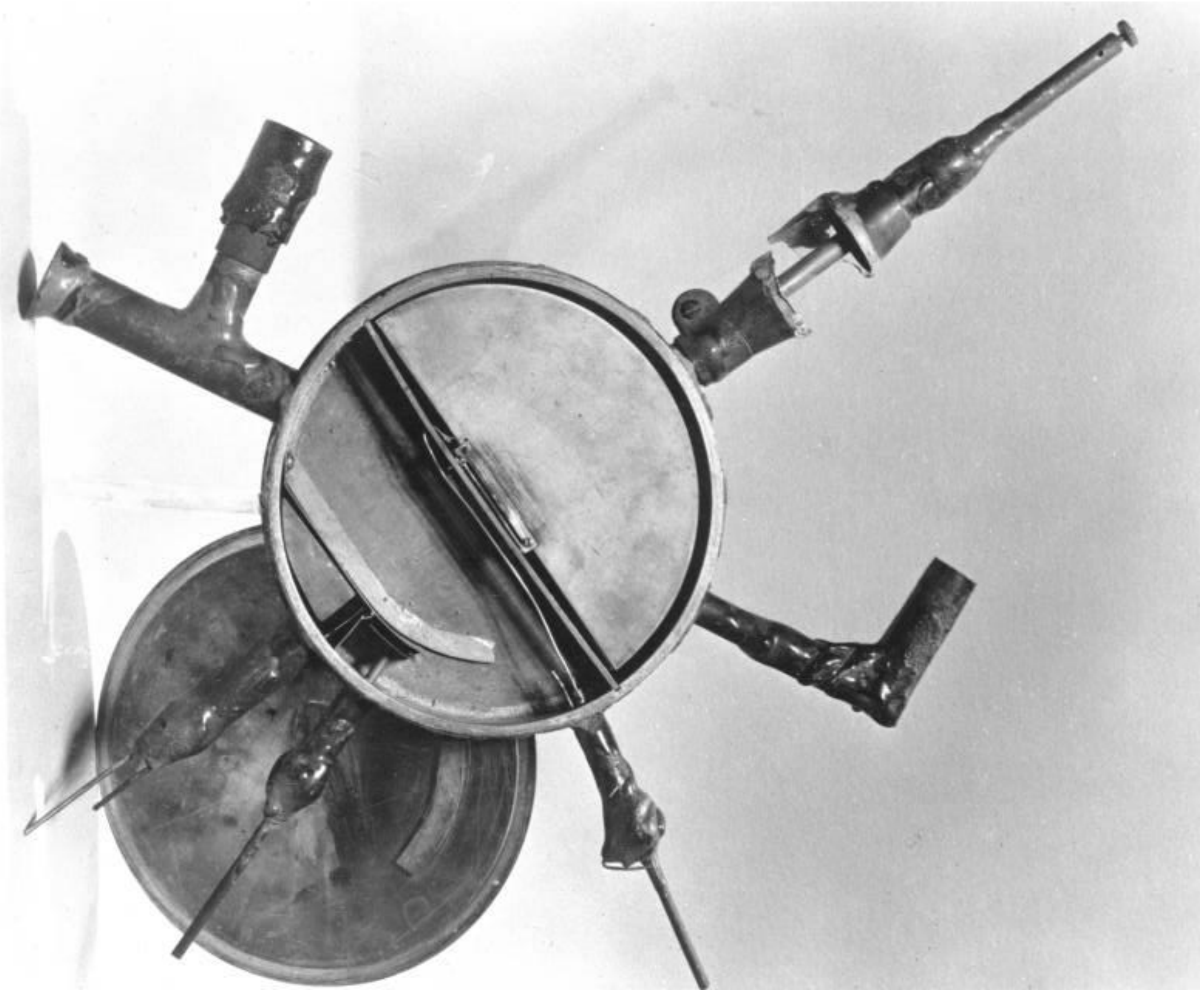
1932: E. Lawrence develops cyclotron (Nobel prize 1939)
→ Acceleration of protons up to 9 MeV



Lawrence

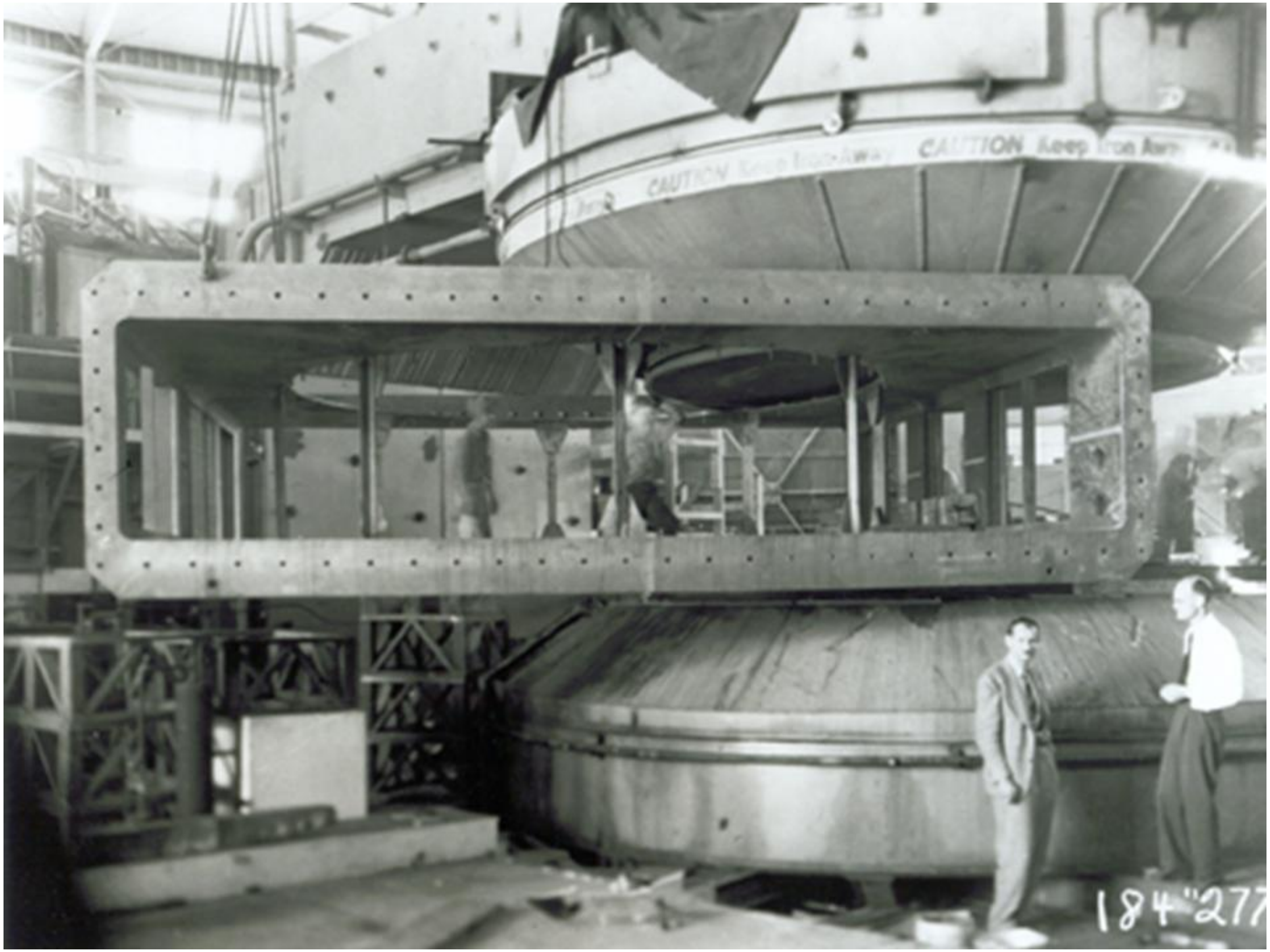
Fraunhofer INT RWTH AACHEN UNIVERSITY

First Cyclotron

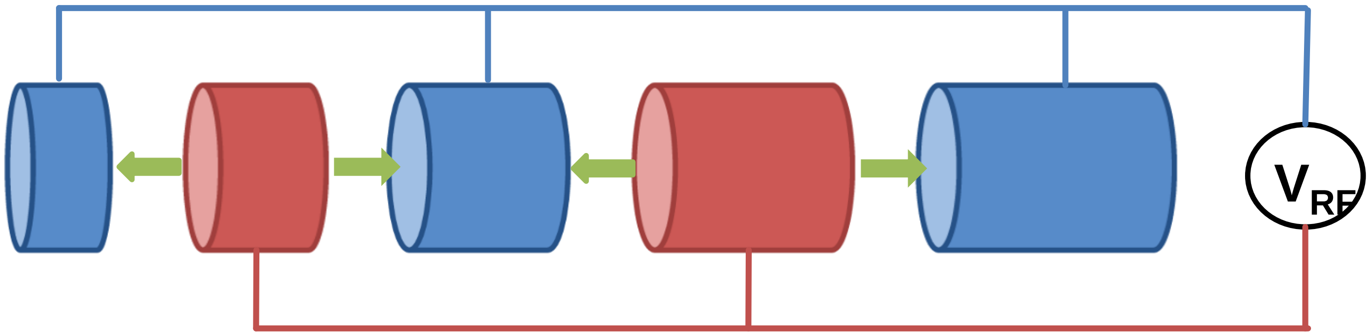


- 4 Inch Diameter
- 1 kV on the „D“
- 80 keV Protons

The 184“ Cyclotron at Berkley

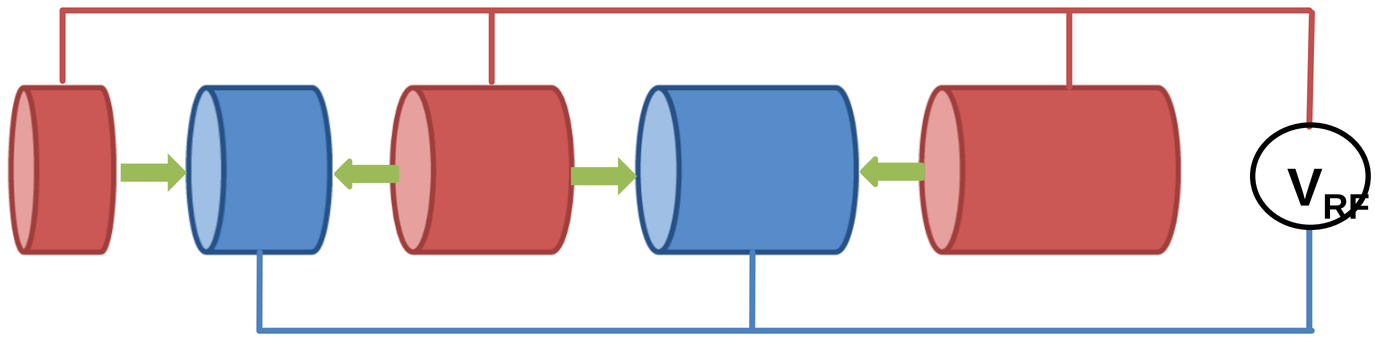


Wideroe linac: the first linear accelerating structure



25 kV
1 MHz oscillator

And half a period later:



Phase shift between drift tubes is 180°

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Wideroe linac: the first linear accelerating structure

- First linac composed by drift tubes interleaved by acceleration gaps powered by an RF generator. (1928, Wideroe PhD)

- Please note: the drift tube length has to increase as long as the particles are not yet relativistic.

- Each energy increase corresponds to a speed increase, and the particle has to travel more in the shielded region to be in phase with the accelerating field.

- Total energy: $(N_{Drifttube}-1) * V_{RF}$

- Main limitations:
  - After a certain energy, the length of the drift tube is too long.
  - The RF frequency has increase to some 10 MHz, need to enclose the structure in a resonator to avoid field losses.

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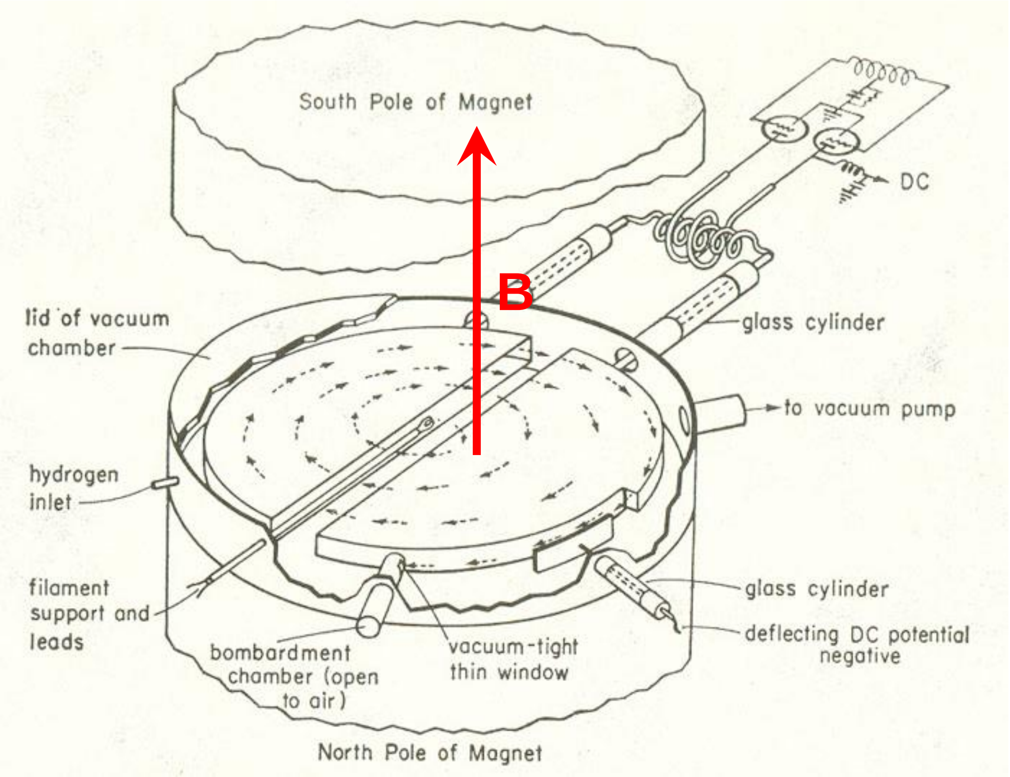
Cyclotron

- Particle source located in a vertical B field near the center of the ring.
- Electrical (E) RF field generated between two gaps with a fixed frequency.
- Particles spiral while accelerated by E field every time they go through the gap (“D”).
- The energy increases during each passage through the E-field between the „Ds“ with q U
- Max energy for protons: several tens of MeV



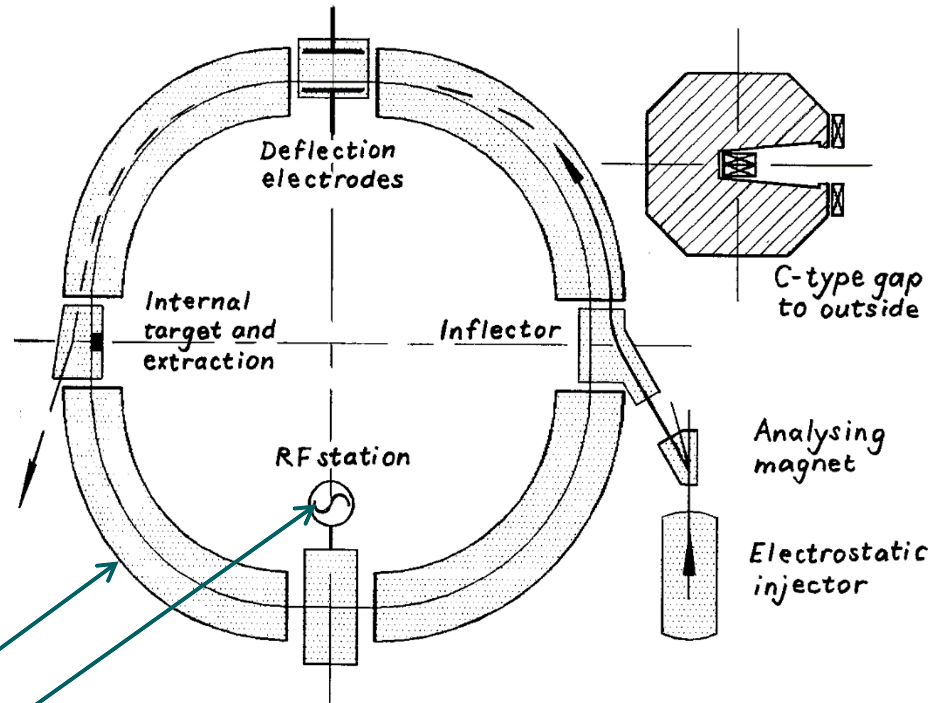
Main limitations:
1) not working for relativistic particles, either high energy or electrons
2) B field at large radii not vertical

Source: www.physics.rutgers.edu/cyclotron/

Synchrotron

- New concept of circular accelerator. The magnetic field of the bending magnet varies with time.
- As particles accelerate, the B field is increased proportionally.
- The frequency of the RF cavity, used to accelerate the particles has also to change.
- Bending strength limited by used technology to max ~ 1 T for room temperature conductors and several T for superconducting magnets
- Weak focusing machine: no quadrupoles
- Strong focusing machine, using quadrupoles,

- Rigidity: $\frac{p}{q} = B\,\rho$



B = B(t) magnetic field from the bending magnets
p = p(t) particle momentum varies by the RF cavity
q electric charge
ρ constant radius of curvature

Thank you for your attention

Next week Prof. Alexander Schmidt will continue with the derivation of the Bethe-Bloch-formula