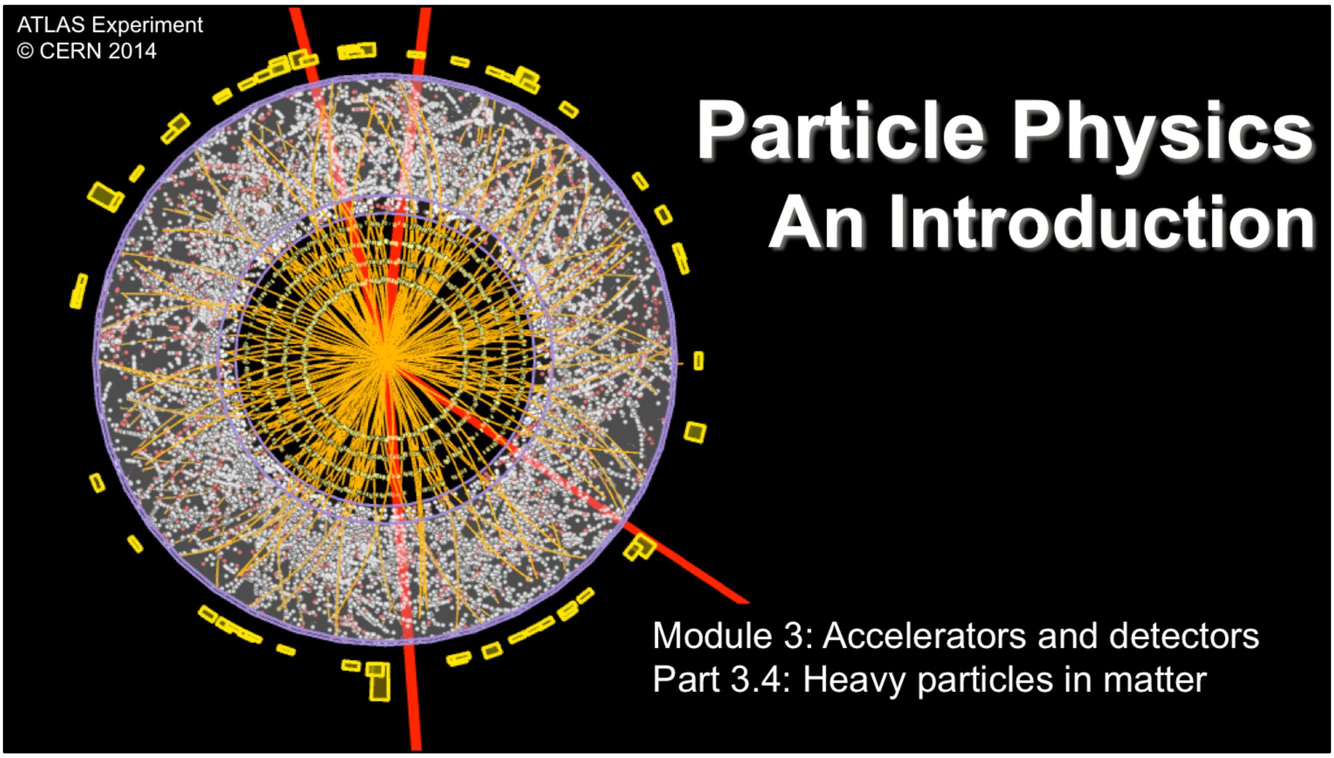


In this module, we will touch the basics of particle acceleration and detection methods.

In this fourth video we will show how heavy charged particles interact with matter. These interaction mechanisms are used to detect them.

At the end of this video you will know:

- The energy loss by ionization and excitation for heavy charged particles;
- The distribution of the energy loss for these particles and their angular deviation when traversing a slice of material.

Energy loss by dominant interaction:

Charged leptons (electron, muon, tau)	electromagnetic
Neutral leptons (neutrinos)	weak
Hadrons (nucleons, $\pi^{\pm}, \pi^{0} \ldots$)	electromagnetic, strong
Photons	electromagnetic

Electromagnetic interactions:

- between charged particles and atomic e^-: excitation, ionization, multiple Coulomb scattering
- between charged particles and nuclei: elastic and inelastic scattering, bremsstrahlung
- between photons and atomic e^-: photoelectric effect, Compton scattering
- between photons and nuclei: e^+e^- pair production
- coherent radiation by charged particles: Cherenkov and transition radiation

- To detect particles, one must make them **interact with matter**. With the exception of neutrinos, all particles interact in one way or another via the electromagnetic force. Hadrons interact also via the strong force.
- **Electromagnetic interactions** thus play a predominant role among the mechanisms of interaction and particle detection. Its **different reactions** are listed here. We will discuss them in this video and the one that follows.

Bethe-Bloch formula:

$$-\frac{dE}{dx}\bigg|_{ion} = \frac{e^4}{m_e 4\pi}\frac{n_e z^2}{\beta^2}\left[\ln\left(\frac{2m_e\beta^2\gamma^2}{I}\right) - \beta^2 - \frac{\delta}{2}\right]$$

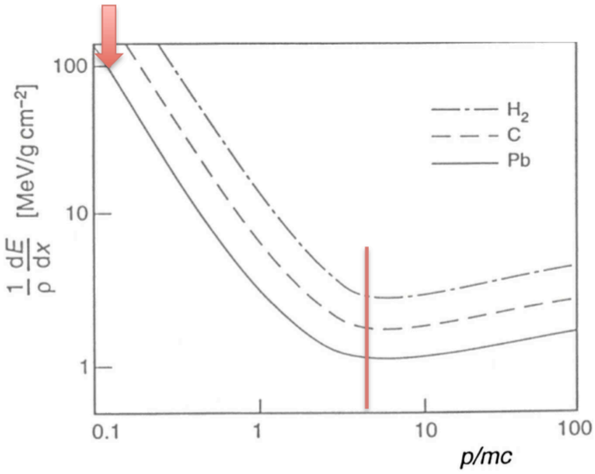
- m_e, e: electron mass and charge
- n_e: volume density of atomic electrons in the target material
- z, β, γ: charge, velocity and relativistic factor of the incident particle
- δ: correction due to polarization of the material, depends on $\beta\gamma = p/m$
- I = ionization constant:

$$\frac{I}{Z} = \begin{cases} 12 + 7/Z \text{ eV}; & Z < 13 \\ 9.76 + 58.8\, Z^{-1.19} \text{ eV}; & Z \geq 13 \end{cases}$$

- When a charged particle passes through a slice of material with thickness *dx,* it ionizes or excites the atoms it meets. By this, the particle loses a part *dE* of its energy.
- **The energy loss per unit length, *dE/dx*,** plays a central role in the detection of stable charged particles. It depends on both the **properties of the particle,** such as its charge *z* and its velocity *β*, as well as the **properties of the material crossed,** like the **volume density n_e of its electrons**, which is proportional to its atomic charge, and its **ionization constant *I***, which describes how easy it is to ionize the atom.
- The dependence of *dE/dx* on these factors is described by the **Bethe-Bloch formula**.

Energy loss per surface density of the material:

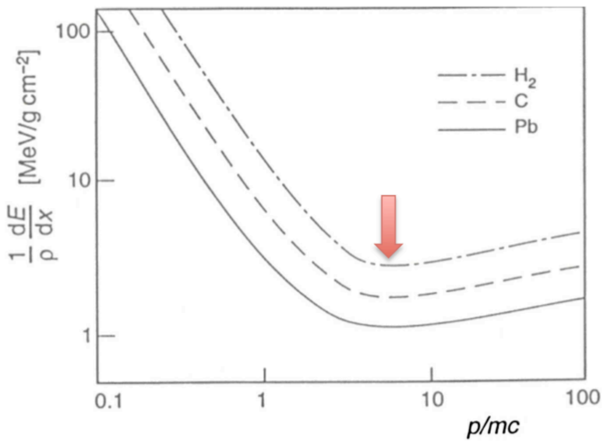
$$-\frac{dE}{\rho\,dx}\bigg|_{ion} = K\frac{z^2}{\beta^2}\frac{Z}{A}\left[\ln\left(\frac{2m_e\beta^2\gamma^2}{I}\right) - \beta^2 - \frac{\delta}{2}\right] \quad ; \quad K = 0.307\ \text{MeV cm}^2/\text{mol}$$



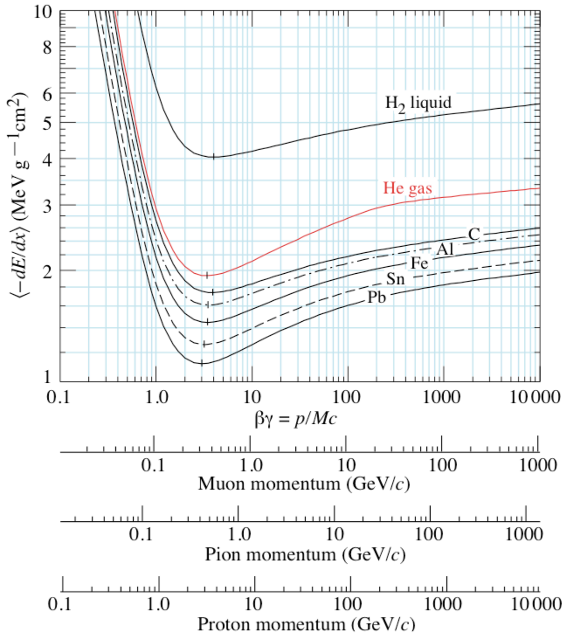
- One can combine many of the constants into a single one *K*. Thus it can be seen, that at low velocity, *dE/dx* is proportional to the **charge** of the particle **squared** and inversely proportional to the **square of its velocity.**
- The energy loss goes through a **shallow minimum** located approximately at the same velocity for all particles. In this minimum, particles are called **minimum ionizing.** Because of the strong dependence on the square of the charge, we can identify the charge of the incident particle by measuring its *dE/dx*.

Energy loss per surface density of the material:

$$-\frac{dE}{\rho\, dx}\bigg|_{ion} = K\frac{z^2}{\beta^2}\frac{Z}{A}\left[\ln\left(\frac{2m_e\beta^2\gamma^2}{I}\right) - \beta^2 - \frac{\delta}{2}\right] \quad ; \quad K = 0.307 \text{ MeV cm}^2\text{/mol}$$



Beyond the minimum, the ionization energy loss *dE/dx* increases slightly with the logarithm of $\beta\gamma = p/m$.



http://www-pdg.lbl.gov/2016/reviews/rpp2016-rev-passage-particles-matter.pdf

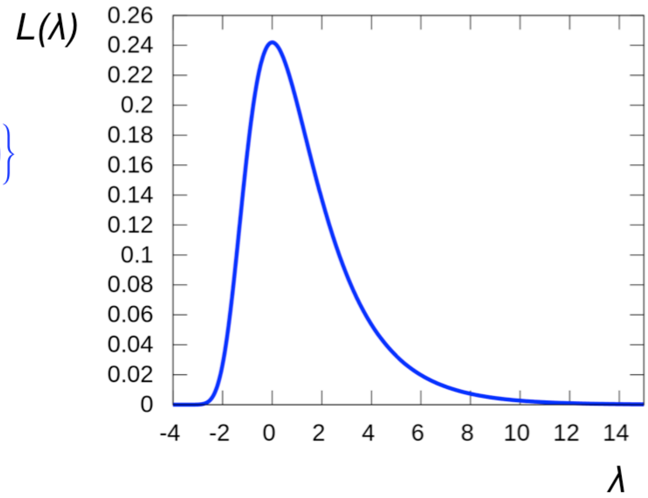
- Here is a **summary of *dE/dx*** in typical gases, liquids and metals, as presented by the **Particle Data** Group. The **minimum of the curves** is approximately at the same velocity for all the materials.
- It is surprising that the **curves for solids** are below those for gas. But do not forget that the energy loss is given here **with respect to the surface density**. To find *dE/dx* in units of **penetrated depth**, one must multiply by **the volume density,** which is 150 times greater for lead than for hydrogen.
- The *βγ* scale is converted to **momentum** for muons, charged pions and protons to simplify the use of the graph.

Landau distribution:

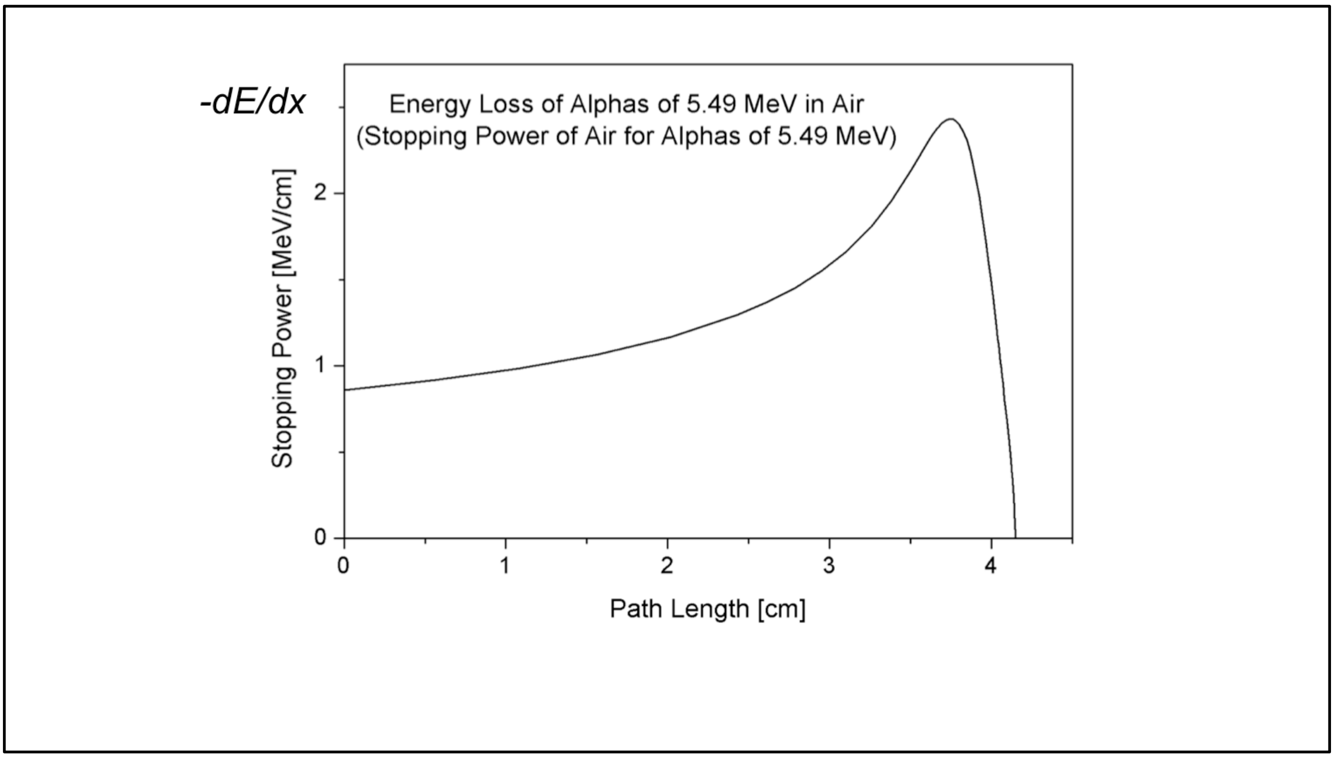
$$L(\lambda) = \frac{1}{\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left(\lambda + e^{-\lambda}\right)\right\}$$

$$\lambda = \frac{\Delta E - \Delta E_W}{\xi}$$

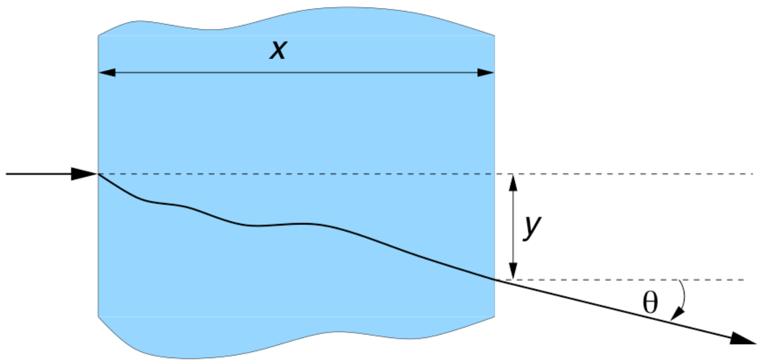
- ΔE: actual energy loss
- ΔE_W: most probable energy loss
- ξ: quantity determining the width of the distribution



- Obviously, the energy loss by ionization and excitation is a **random process,** which will not always yield the same result. Therefore, ***dE* in a given material thickness *dx*** follows a Landau distribution. This is an asymmetric distribution around the most probable value E_W, with a width characterized by ξ.
- The most probably energy loss is determined by the Bethe-Bloch formula.



- Since *dE/dx i*ncreases with decreasing velocity, the particles lose more and more energy while penetrating the material. The greatest loss happens immediately before the particle is stopped. This is called **the Bragg peak.**
- This effect may be beneficial in **medical applications**. When irradiating tissue by charged particles, one can adjust the initial momentum and thus the penetration, such that most of the energy is deposited where a cancerous tumor is located, preserving healthy tissue around.



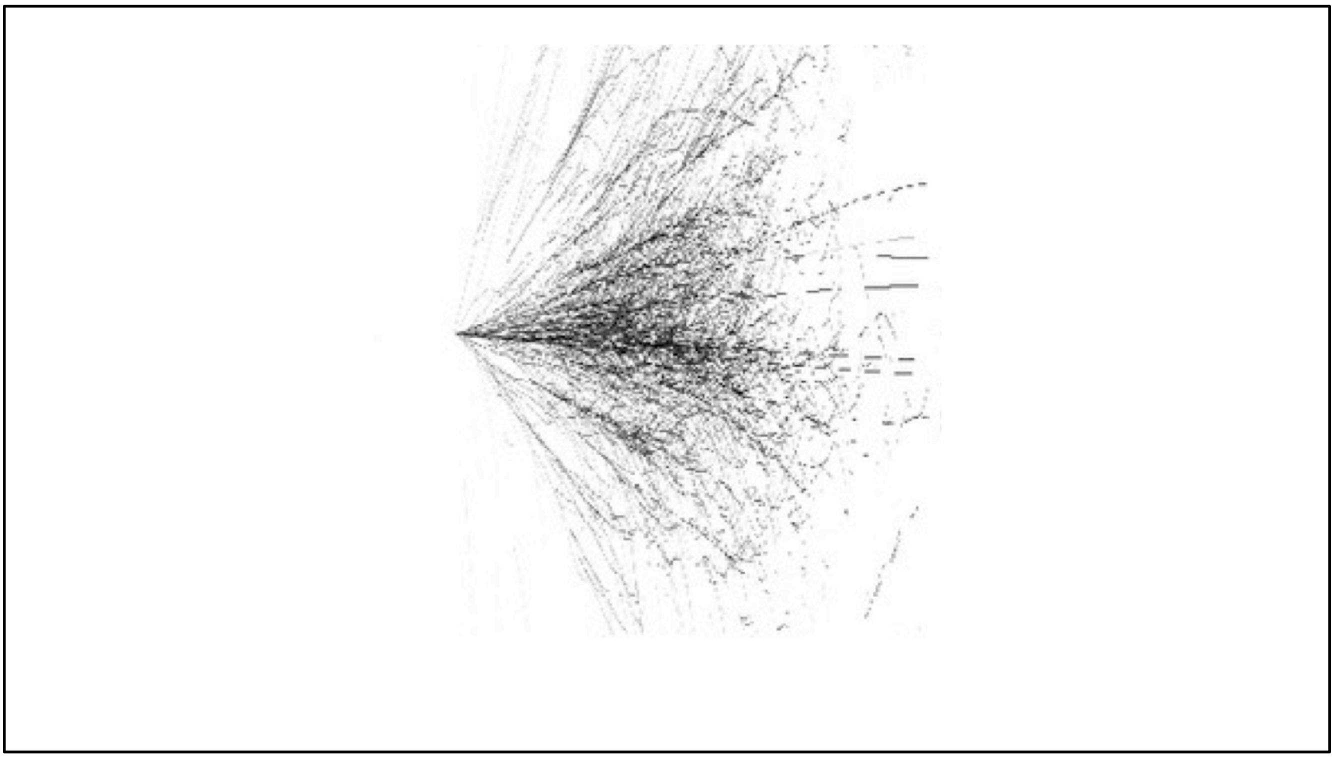
Gaussian distribution :

$$\frac{dN}{d\theta} = \frac{1}{\sqrt{2\pi}\sigma_\theta} \exp\left(\frac{\theta^2}{2\sigma_\theta^2}\right)$$

$$\sigma_\theta = \frac{13.6\,\text{MeV}}{\beta p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \log \frac{x}{X_0}\right]$$

- θ: angular deviation (projection on a plane)
- σ_θ: quantity determining the width of the distribution
- X_0: radiation length

- Multiple scattering off atomic electrons also deflects the incident particle from its **initial direction** and **displaces its path**.
- The distribution of **angular deflection** follows a Gaussian around zero, the width depends on particle and material properties. The latter can be combined into the **radiation length X_0**, which we will introduce later in this module.



- **Hadrons** of course also belong to the class of heavy particles. In addition to electromagnetic interactions, they can interact with matter nuclei through strong interactions.
- **Elastic scattering** makes them lose energy to a lesser extent, because nuclei are typically heavy and recoil little.
- **Inelastic interactions** occur at high energies and create additional particles. These deposit energy by *dE/*dx, but can also in turn produce more particles. At sufficient energy, typically a few GeV, this will generate a cascade process, called a **hadron shower.** You see in this image a simulation of such a process. Each black dot represents a unit of energy loss by a charged particle .

Material	Z	A	$\langle Z/A \rangle$	Nucl.coll. length λ_T {g cm^{-2}}	Nucl.inter. length λ_I {g cm^{-2}}	Rad.len. X_0 {g cm^{-2}}	$dE/dx\vert_{min}$ { MeV g^{-1}cm^2}	Density {g cm^{-3}} ({gℓ^{-1}})	Melting point (K)	Boiling point (K)	Refract. index @ Na D
H_2	1	1.008(7)	0.99212	42.8	52.0	63.04	(4.103)	0.071(0.084)	13.81	20.28	1.11[132.]
D_2	1	2.01410177803(8)	0.49650	51.3	71.8	125.97	(2.053)	0.169(0.168)	18.7	23.65	1.11[138.]
He	2	4.002602(2)	0.49967	51.8	71.0	94.32	(1.937)	0.125(0.166)		4.220	1.02[35.0]
Li	3	6.94(2)	0.43221	52.2	71.3	82.78	1.639	0.534	453.6	1615.	
Be	4	9.0121831(5)	0.44384	55.3	77.8	65.19	1.595	1.848	1560.	2744.	
C diamond	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.725	3.520			2.42
C graphite	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.742	2.210			
N_2	7	14.007(2)	0.49976	61.1	89.7	37.99	(1.825)	0.807(1.165)	63.15	77.29	1.20[298.]
O_2	8	15.999(3)	0.50002	61.3	90.2	34.24	(1.801)	1.141(1.332)	54.36	90.20	1.22[271.]
F_2	9	18.998403163(6)	0.47372	65.0	97.4	32.93	(1.676)	1.507(1.580)	53.53	85.03	[195.]
Ne	10	20.1797(6)	0.49555	65.7	99.0	28.93	(1.724)	1.204(0.839)	24.56	27.07	1.09[67.1]
Al	13	26.9815385(7)	0.48181	69.7	107.2	24.01	1.615	2.699	933.5	2792.	
Si	14	28.0855(3)	0.49848	70.2	108.4	21.82	1.664	2.329	1687.	3538.	3.95
Cl_2	17	35.453(2)	0.47951	73.8	115.7	19.28	(1.630)	1.574(2.980)	171.6	239.1	[773.]
Ar	18	39.948(1)	0.45059	75.7	119.7	19.55	(1.519)	1.396(1.662)	83.81	87.26	1.23[281.]
Ti	22	47.867(1)	0.45961	78.8	126.2	16.16	1.477	4.540	1941.	3560.	
Fe	26	55.845(2)	0.46557	81.7	132.1	13.84	1.451	7.874	1811.	3134.	
Cu	29	63.546(3)	0.45636	84.2	137.3	12.86	1.403	8.960	1358.	2835.	
Ge	32	72.630(1)	0.44053	86.9	143.0	12.25	1.370	5.323	1211.	3106.	
Sn	50	118.710(7)	0.42119	98.2	166.7	8.82	1.263	7.310	505.1	2875.	
Xe	54	131.293(6)	0.41129	100.8	172.1	8.48	(1.255)	2.953(5.483)	161.4	165.1	1.39[701.]
W	74	183.84(1)	0.40252	110.4	191.9	6.76	1.145	19.300	3695.	5828.	
Pt	78	195.084(9)	0.39983	112.2	195.7	6.54	1.128	21.450	2042.	4098.	
Au	79	196.966569(5)	0.40108	112.5	196.3	6.46	1.134	19.320	1337.	3129.	
Pb	82	207.2(1)	0.39575	114.1	199.6	6.37	1.122	11.350	600.6	2022.	
U	92	[238.02891(3)]	0.38651	118.6	209.0	6.00	1.081	18.950	1408.	4404.	
Air (dry, 1 atm)			0.49919	61.3	90.1	36.62	(1.815)	(1.205)		78.80	[289]
Shielding concrete			0.50274	65.1	97.5	26.57	1.711	2.300			
Borosilicate glass (Pyrex)			0.49707	64.6	96.5	28.17	1.696	2.230			
Lead glass			0.42101	95.9	158.0	7.87	1.255	6.220			
Standard rock			0.50000	66.8	101.3	26.54	1.688	2.650			

http://www-pdg.lbl.gov/2016/reviews/rpp2016-rev-atomic-nuclear-prop.pdf

- The characteristic lengths of these processes are the **nuclear collision length** (applying to elastic interactions) and the **nuclear interaction length** (applying to inelastic interactions). Both can be found in the tables of the **Particle Data Group**. They are typically much larger than the radiation length of a material.

In the next video, we talk about the interactions of **light particles** in general, and **bremsstrahlung** in particular.