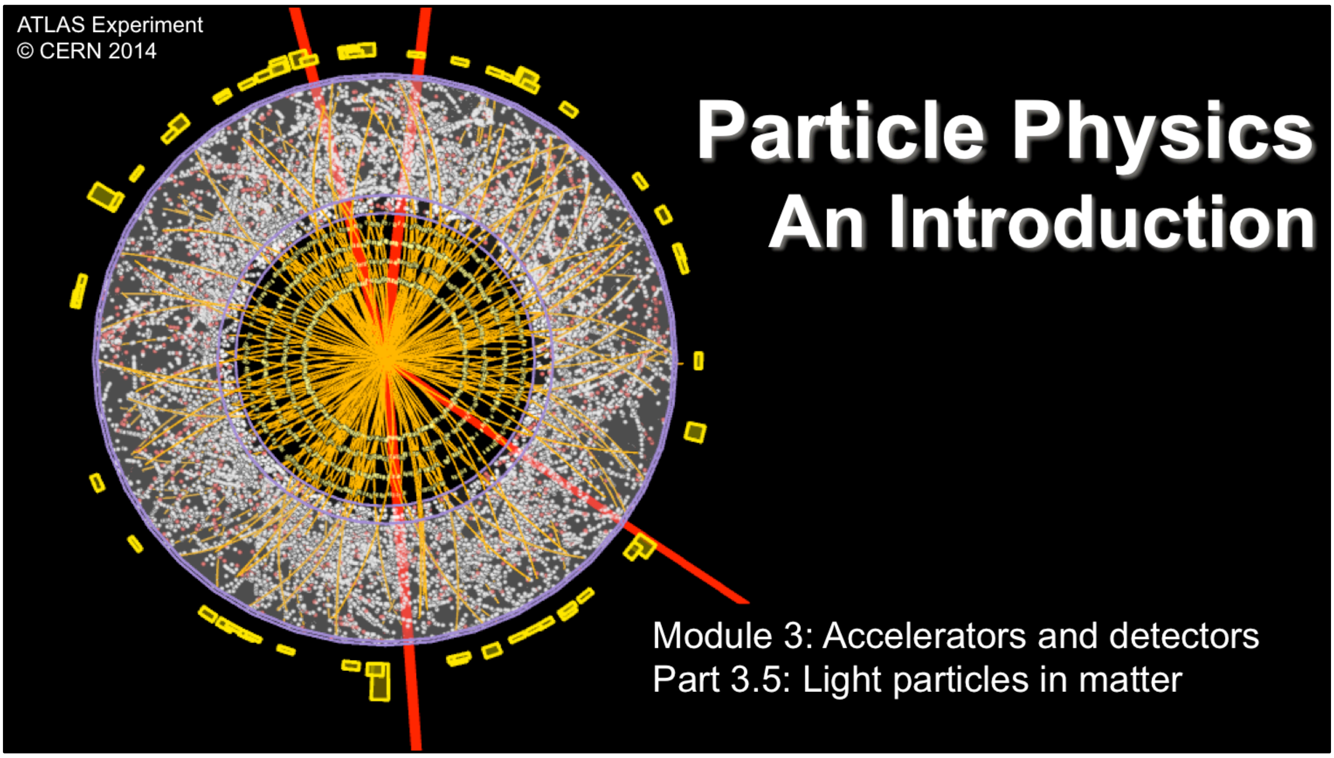


In this module, we will touch the basics of particle acceleration and detection methods.

In this video we show how light charged particles interact with matter. They are detected via these interactions.

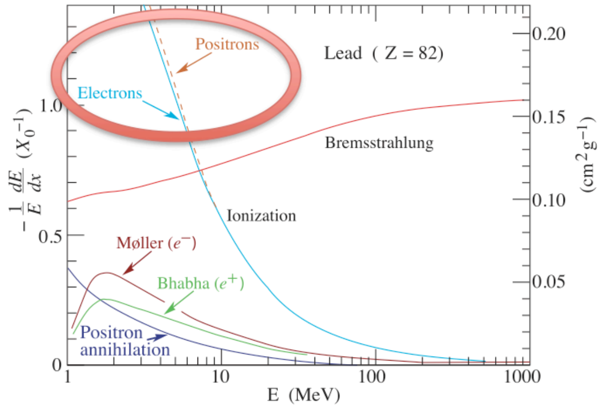
At the end of this video you will know:

- The energy loss by ionization and excitation for electrons
- The energy loss by radiation specific to light particles, called bremsstrahlung.

Bethe-Bloch formula for electrons and positrons:

$$-\frac{dE}{\rho\, dx}\bigg|_{ion} = K\frac{1}{\beta^2}\frac{Z}{A}\left[\ln\left(\frac{m_e\tau\sqrt{\tau+2}}{\sqrt{2}I}\right) + \frac{F(\tau)}{2} - \frac{\delta}{2}\right]$$

- τ: kinetic energy of the electron (positron) in units of m_e
- $F(\tau)$: function differentiating between electron and positron



For **light particles** like the electron and positron, things complicate slightly:

- The formula for *dE/dx* is similar to that for heavy particles, but the special properties of scattering between electrons **(Møller scattering)** and between electrons and positrons (**Bhabha scattering)** come in.
- The difference between the *dE/dx* for electrons and positrons is, however, not very large.

Energy loss by radiation in terms of radiation length X_0:

$$-\left.\frac{dE}{dx}\right|_{brem} = \frac{E}{X_0}$$

- $E(x) = E_0 \exp(-x/X_0)$: remaining energy
- $x = X_0$: particle energy reduced by a factor e through bremsstrahlung
- $X_0[\text{cm}] = \rho X_0[\text{g/cm}^2]$: radiation length in terms of surface density

But there is an important difference between light and heavy particles:

- Since light projectiles and atomic electrons are of comparable mass, interactions with atomic electrons cause **bremsstrahlung**.
- The energy loss *dE/dx* by this process is proportional to the energy of the projectile. The material properties that come into play can be combined into a single constant, the **radiation length X_0**.

By integrating the energy loss we can calculate the **remaining energy *E(x)*** of the electron. It is a function which **decreases exponentially** with the penetrated material depth *x*.

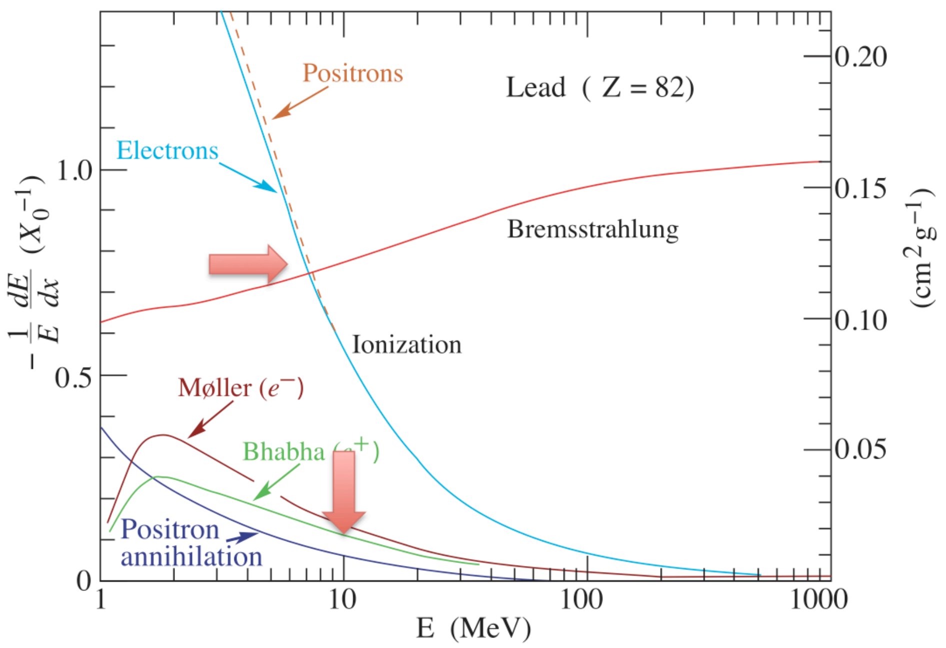
The radiation length is then given as the path length after which **the energy of the projectile is reduced by a factor *of e*.**

To obtain the energy loss *dE/dx* or the radiation length in terms of the target **surface density,** one must take into account the volume density ρ of the material.

Material	Z	A	$\langle Z/A \rangle$	Nucl.coll. length λ_T {g cm^{-2}}	Nucl.inte length λ {g cm^{-2}	Rad.len. X_0 {g cm^{-2}}	$dE/dx\|_{\rm min}$ { 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)	3.81	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	53.6	1615.	
Be	4	9.0121831(5)	0.44384	55.3	77.8	65.19	1.595	1.848	560.	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)	3.15	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)	4.36	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)	3.53	85.03	[195.]
Ne	10	20.1797(6)	0.49555	65.7	99.0	28.93	(1.724)	1.204(0.839)	4.56	27.07	1.09[67.1]
Al	13	26.9815385(7)	0.48181	69.7	107.2	24.01	1.615	2.699	33.5	2792.	
Si	14	28.0855(3)	0.49848	70.2	108.4	21.82	1.664	2.329	687.	3538.	3.95
Cl_2	17	35.453(2)	0.47951	73.8	115.7	19.28	(1.630)	1.574(2.980)	71.6	239.1	[773.]
Ar	18	39.948(1)	0.45059	75.7	119.7	19.55	(1.519)	1.396(1.662)	3.81	87.26	1.23[281.]
Ti	22	47.867(1)	0.45961	78.8	126.2	16.16	1.477	4.540	941.	3560.	
Fe	26	55.845(2)	0.46557	81.7	132.1	13.84	1.451	7.874	811.	3134.	
Cu	29	63.546(3)	0.45636	84.2	137.3	12.86	1.403	8.960	358.	2835.	
Ge	32	72.630(1)	0.44053	86.9	143.0	12.25	1.370	5.323	211.	3106.	
Sn	50	118.710(7)	0.42119	98.2	166.7	8.82	1.263	7.310	05.1	2875.	
Xe	54	131.293(6)	0.41129	100.8	172.1	8.48	(1.255)	2.953(5.483)	61.4	165.1	1.39[701.]
W	74	183.84(1)	0.40252	110.4	191.9	6.76	1.145	19.300	695.	5828.	
Pt	78	195.084(9)	0.39983	112.2	195.7	6.54	1.128	21.450	042.	4098.	
Au	79	196.966569(5)	0.40108	112.5	196.3	6.46	1.134	19.320	337.	3129.	
Pb	82	207.2(1)	0.39575	114.1	199.6	6.37	1.122	11.350	00.6	2022.	
U	92	[238.02891(3)]	0.38651	118.6	209.0	6.00	1.081	18.950	408.	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

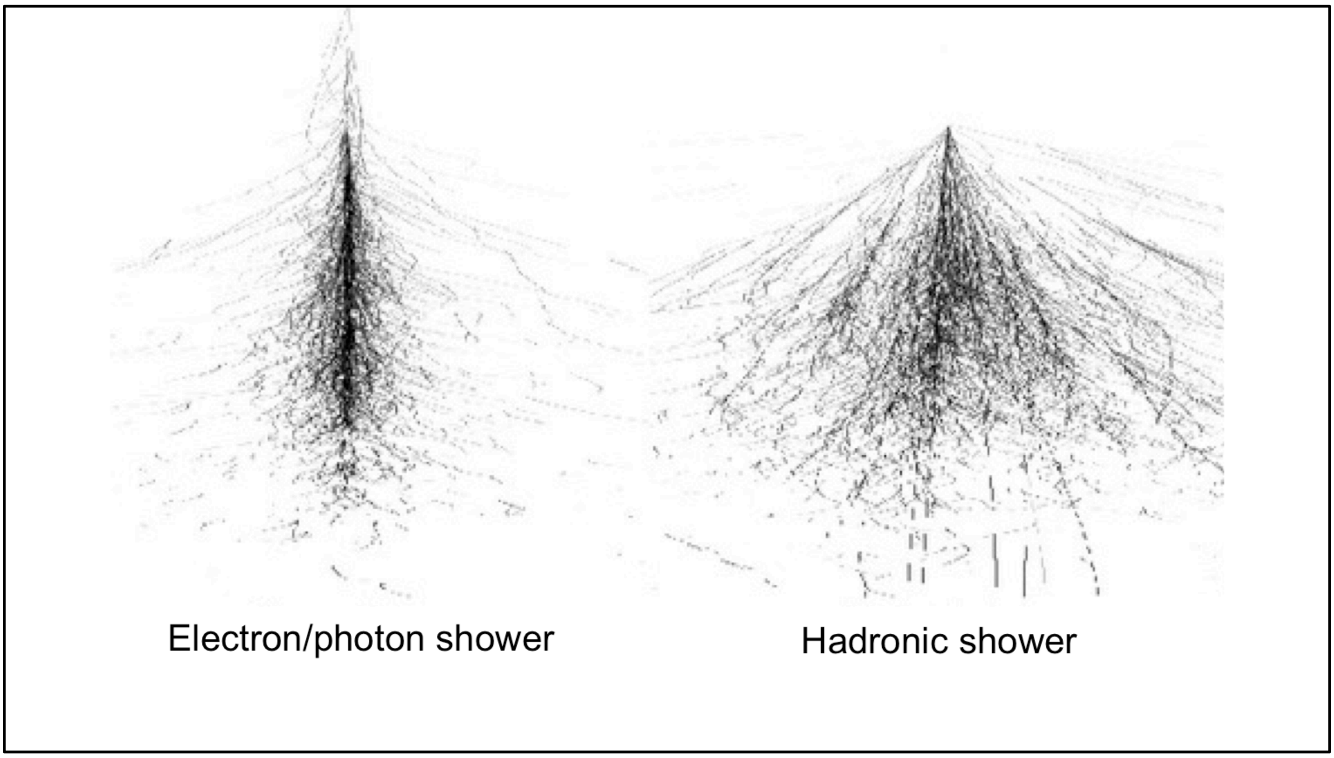
Many material properties are tabulated by the Particle Data Group, particularly the **volume density** and the **radiation length**. You will find them on the Web at the indicated address.



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

A property specific to positrons is that they can annihilate with atomic electrons of the material. This process is important at low energy, i.e. at the **end of the path** just before the positron stops. From annihilation at rest, two photons are emitted back-to-back, each with an energy of $E = m_e = 511$ keV.

At energies above about 10 MeV, **electrons and positrons** lose energy mainly by bremsstrahlung, which dominates over ionization and excitation. This means that many photons are produced when a high energy electrons goes through matter. Those are mostly converted into electron-positron pairs, as discussed in the next video. These pairs will emit photons in turn.



In this way, high energy electrons generate **electron/photon showers** in matter, which are populated by a large number of particles.

The strong interaction of hadrons with the nuclei of the material can also cause showers, called **hadronic showers**. These are typically less populated at comparable energy, because the lightest hadron, the pion, has a mass of about hundred MeV. For the same reason, they are wider and less regular than electromagnetic showers.

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}}	$dE/dx\|_{min}$ { 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

- Again, a table provided by the **Particle Data Group** summarizes the properties of materials often used in particle detectors.
- The characteristic lengths for nuclear interactions are typically **comparable to the radiation length for lighter** materials, **but much larger for heavy materials.**

In the next video, we will discuss in more detail how photons interact with matter.