Interazione delle particelle pesanti cariche con la materia

Particelle pesanti cariche -> m $\geq$ m(protone)

Perdita di energia specifica
(calcolo quanto-relativistico di Bethe-Bloch)

$$\frac{dE}{dx} = 4\pi NZ \frac{z^2 e^4}{m_e c^2 \beta^2} \left[\ln \frac{2 m_e c^2 \gamma^2 \beta^2}{I} - \beta^2 \right]$$

con $I = 12\ Z \quad eV$ energia media di ionizzazione

N la densità numerica degli atomi del materiale

Z il numero di elettroni per atomo

ze la carica dello ione proiettile

Interazione delle particelle pesanti cariche con la materia

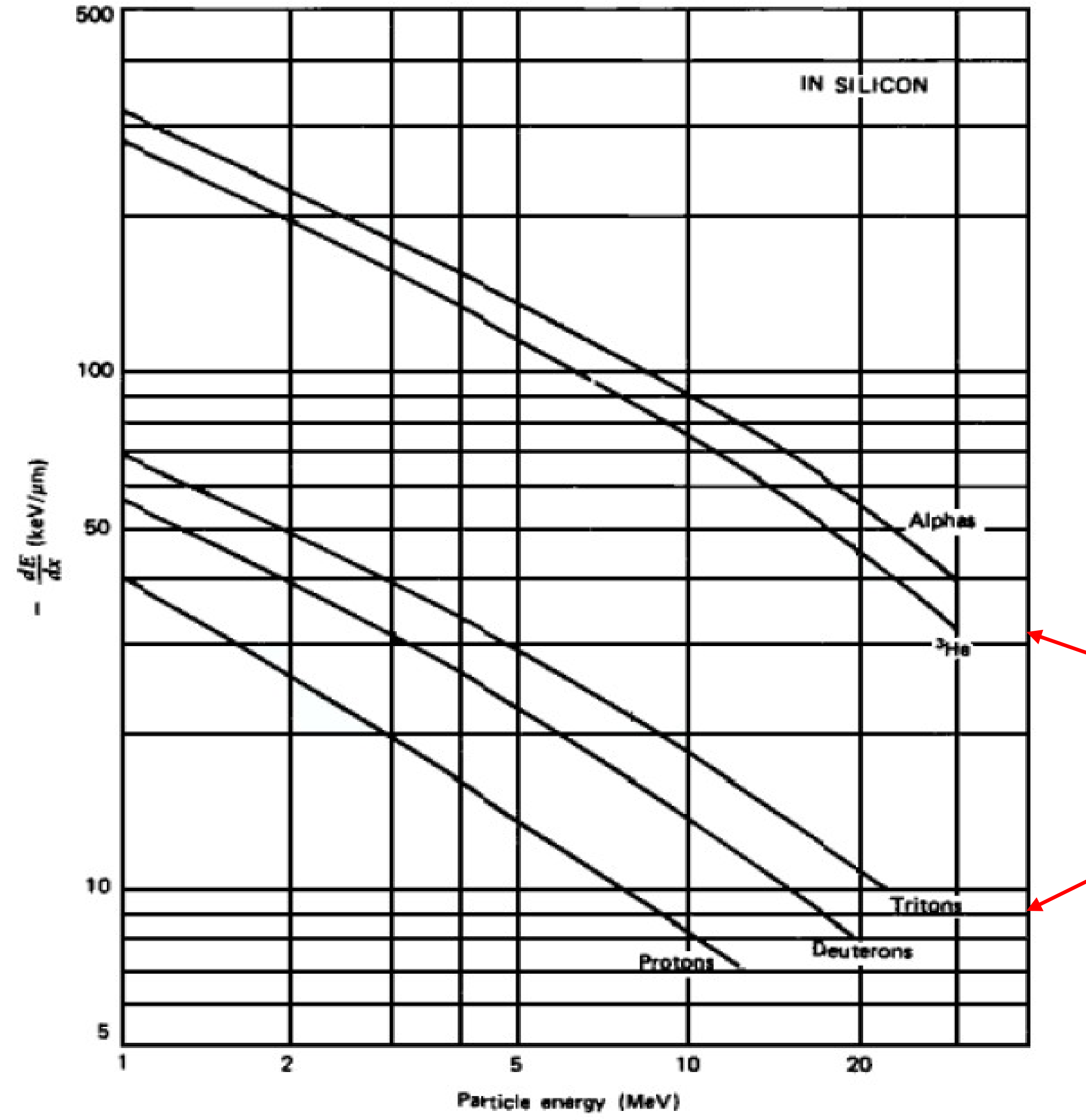


Figure 2-9 The specific energy loss calculated for different charged particles in silicon. (From Skyrme.[3])

$$\frac{dE}{dx} = 4\pi N Z \frac{z^2 e^4}{m_e c^2 \beta^2}\left[\ln\frac{2 m_e c^2 \gamma^2 \beta^2}{I} - \beta^2\right]$$

Dipendenza da caratteristiche del proiettile

A parità di energia:

- dipendenza da m
- dipendenza da z^2

Interazione delle particelle pesanti cariche con la materia

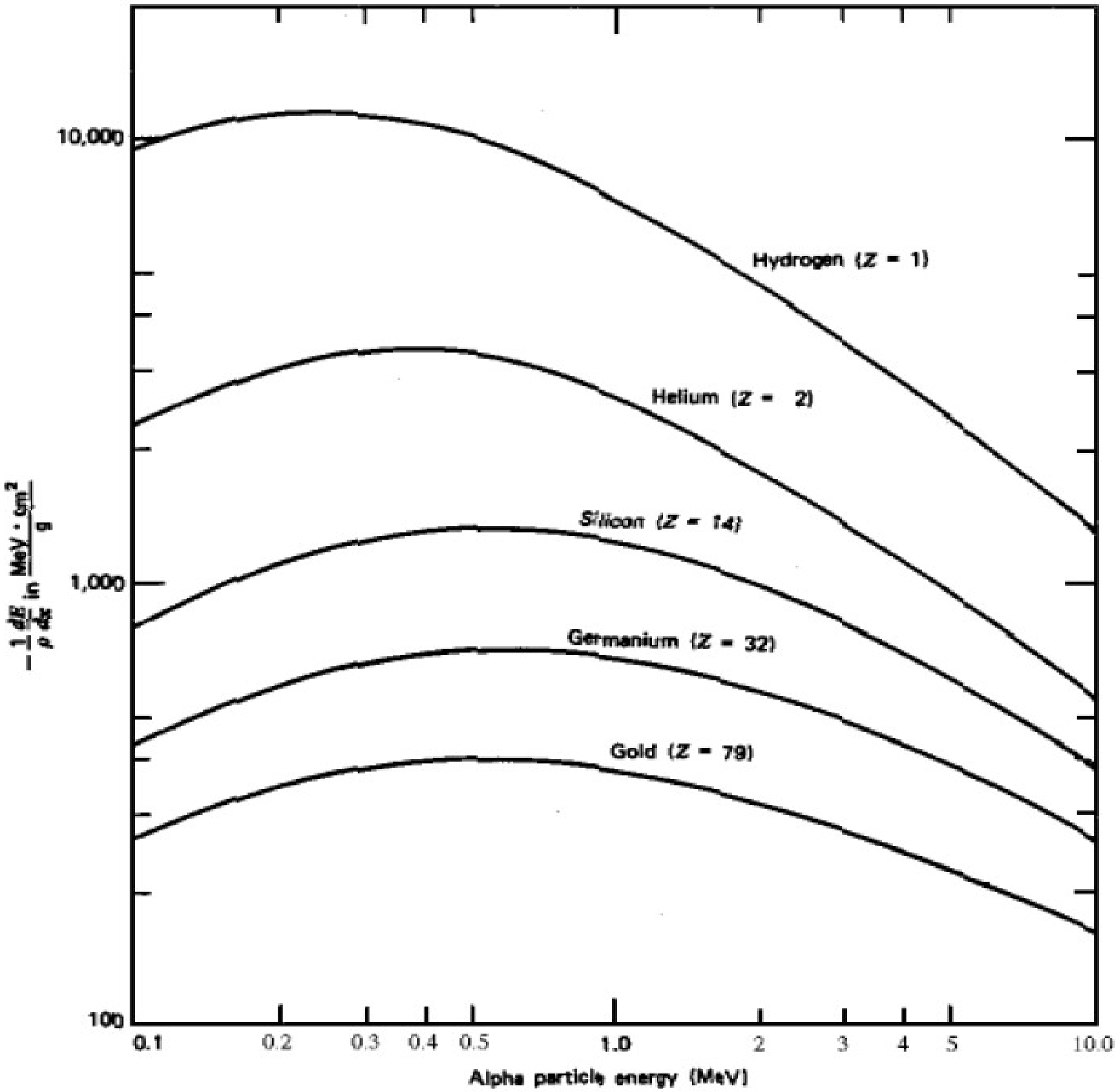


Figure 2-10 The specific energy loss calculated for alpha particles in different materials. *Values are normalized by the density of the absorber material.* (Data from Williamson et al.[4])

$$\frac{dE}{dx} = 4\pi N Z \frac{z^2 e^4}{m_e c^2 \beta^2}\left[\ln \frac{2 m_e c^2 \gamma^2 \beta^2}{I} - \beta^2\right]$$

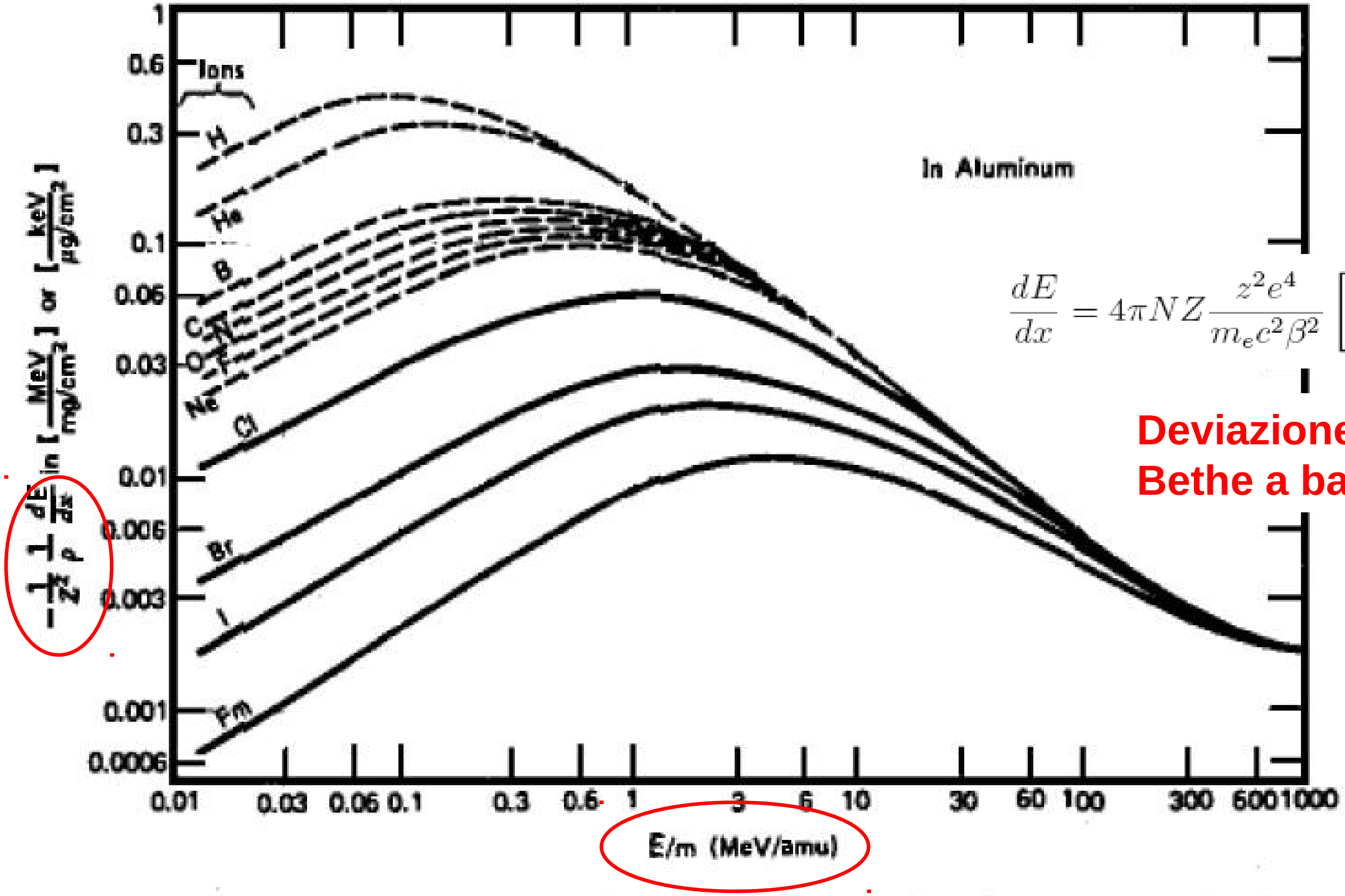
Dipendenza da caratteristiche del bersaglio

$dE/dx \propto NZ = N_{Av}\, \rho\, Z / A$ e quindi

$(1/\rho)(dE/dx) \propto Z / A$

Residua dipendenza di $(1/\rho)(dE/dx)$ da Z da cui dipende anche I

Interazione delle particelle pesanti cariche con la materia



$$\frac{dE}{dx} = 4\pi N Z \frac{z^2 e^4}{m_e c^2 \beta^2}\left[\ln\frac{2 m_e c^2 \gamma^2 \beta^2}{I} - \beta^2\right]$$

Deviazione da formula di Bethe a bassa energia

Figure 2-11 *Plots showing the specific energy loss of various heavy ions in aluminum.* The abscissa is the ion energy divided by its mass, and the ordinate is $-dE/dx$ divided by the density of aluminum and the square of the ion atomic number. Typical fission fragments (e.g., iodine) show a continuously decreasing $-dE/dx$ while slowing from their initial energy (~ 1 MeV/amu). (From Northcliffe and Schilling.[7])

Interazione delle particelle pesanti cariche con la materia

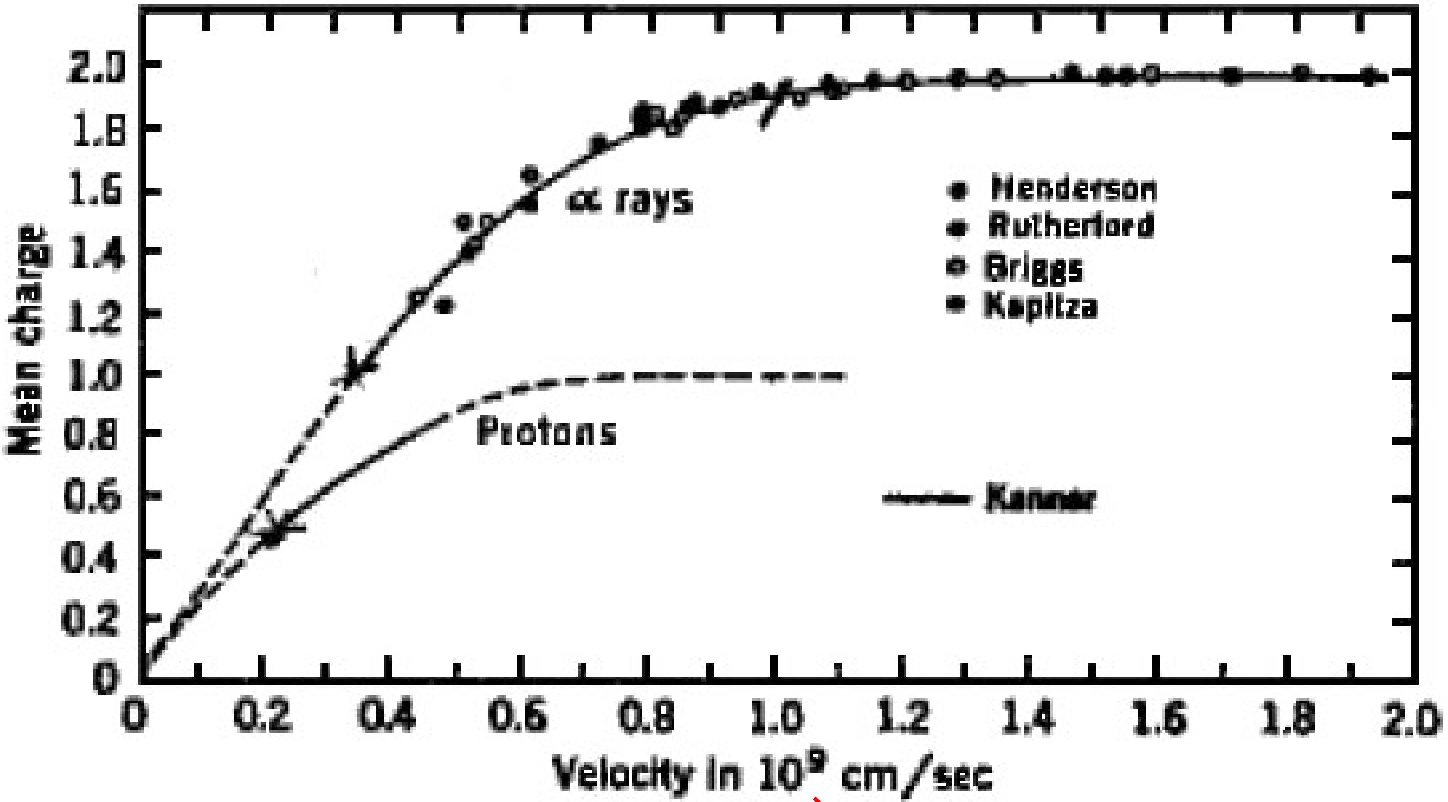
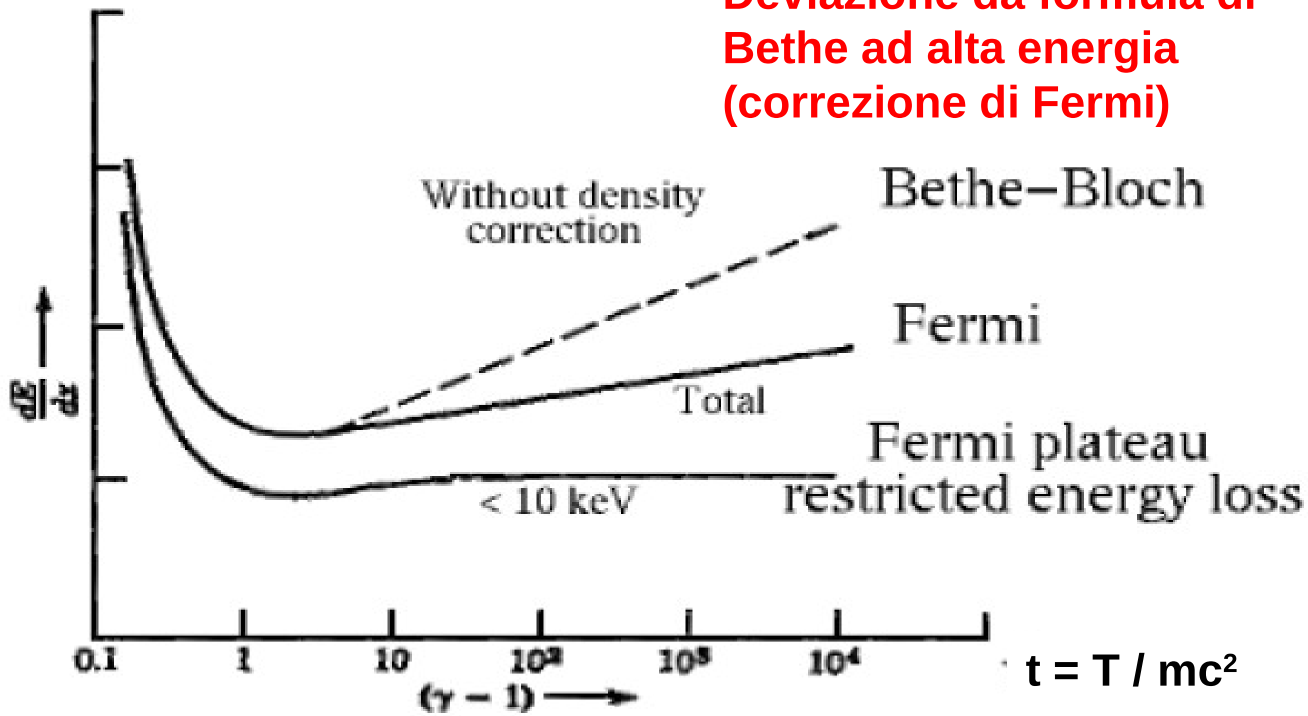


Fig. 1.1 Mean charge ez_{av} for α rays and protons, due to capture and loss of electrons.

$v\ (10^{9}\ \mathrm{cm/s}) = 1.39 * \mathrm{sqrt}\ (E(\mathrm{MeV})\ /\ A)$

Interazione delle particelle pesanti cariche con la materia

Deviazione da formula di Bethe ad alta energia (correzione di Fermi)



t = T / mc^2

Fig. 13.5 Energy loss, including the density effect. The dotted curve is the total energy loss without density correction. The solid curves have the density effect incorporated, the upper one being the total energy loss and the lower one the energy loss due to individual energy transfers of less than 10 keV.

Interazione delle particelle pesanti cariche con la materia

RANGE

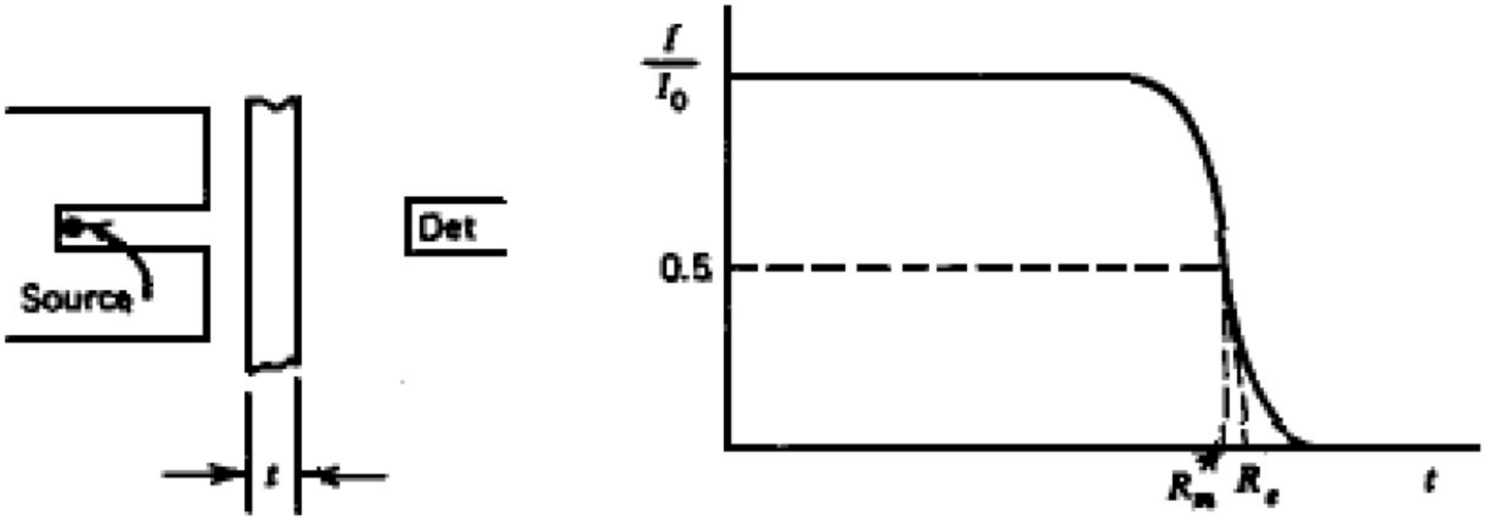


Figure 2-5 An alpha particle *transmission experiment*. I is the detected number of alpha particles through an absorber thickness, t, whereas I_0 is the number detected without the absorber. The mean range R_m and extrapolated range R_e are indicated.

Interazione delle particelle pesanti cariche con la materia

RANGE

Indicando con u la velocità del proiettile la formula di Bethe può essere riscritta come

$$dx = \frac{m_1}{z_1^2} \frac{m_e}{4\pi e^4} \frac{1}{NZ} \frac{u^3 \, du}{\ln\left(2 m_e u^2 / I\right)}$$

$$R = \frac{m_1}{z_1^2} \int_{u_i}^{0} f(u) \, du$$

$R \approx k\, m_1\, u^4 / z_1^2 = k'\, E^2 / m_1\, z_1^2$

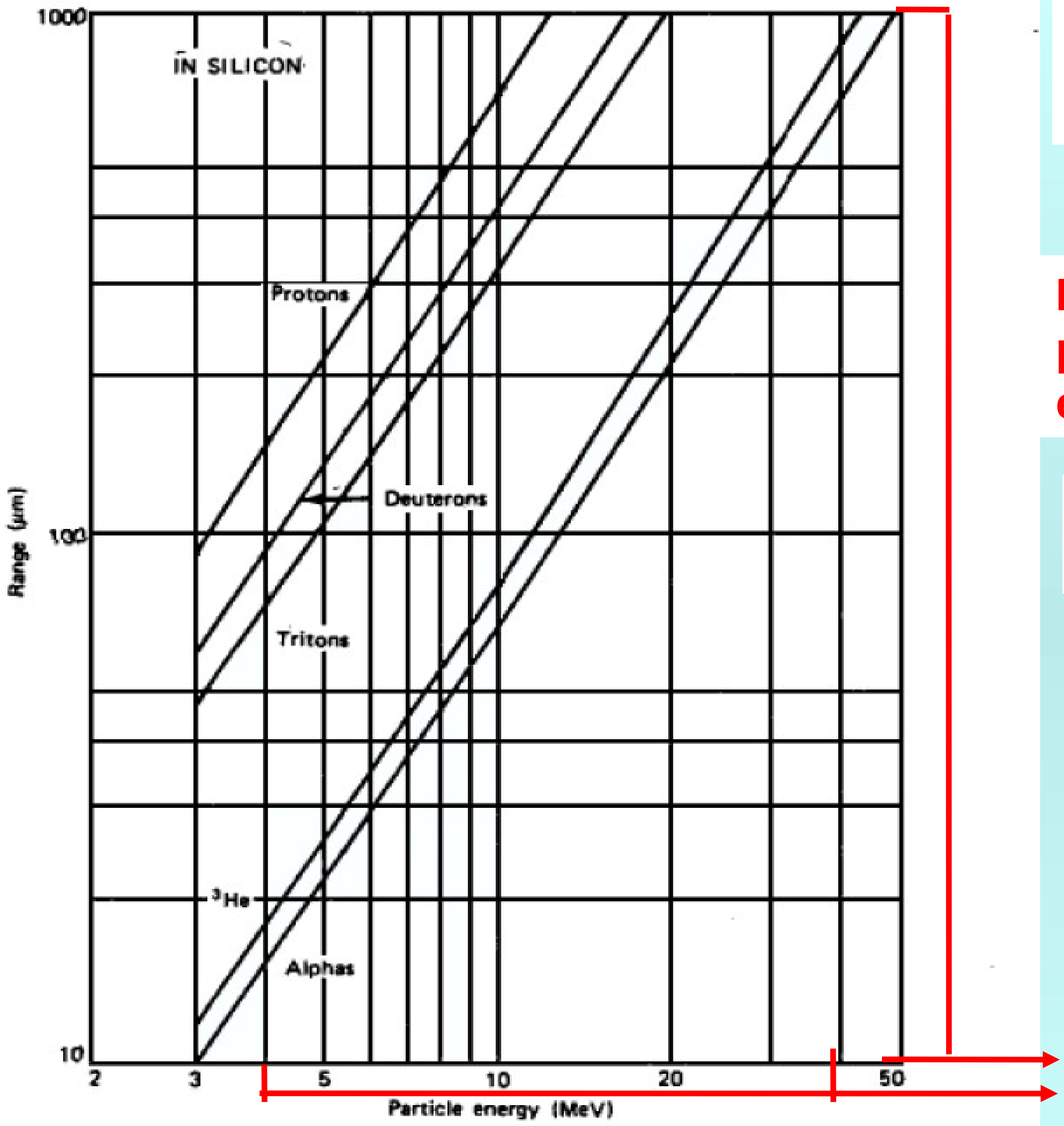


Figure 2-7 Range–energy curves calculated for different charged particles in silicon. The near-linear behavior of the log–log plot over the energy range shown suggests an empirical relation of the form $R = aE^b$, where the slope-related parameter b is not greatly different for the various particles. (From Skyrme.[3])

Fattore 100
Fattore 10

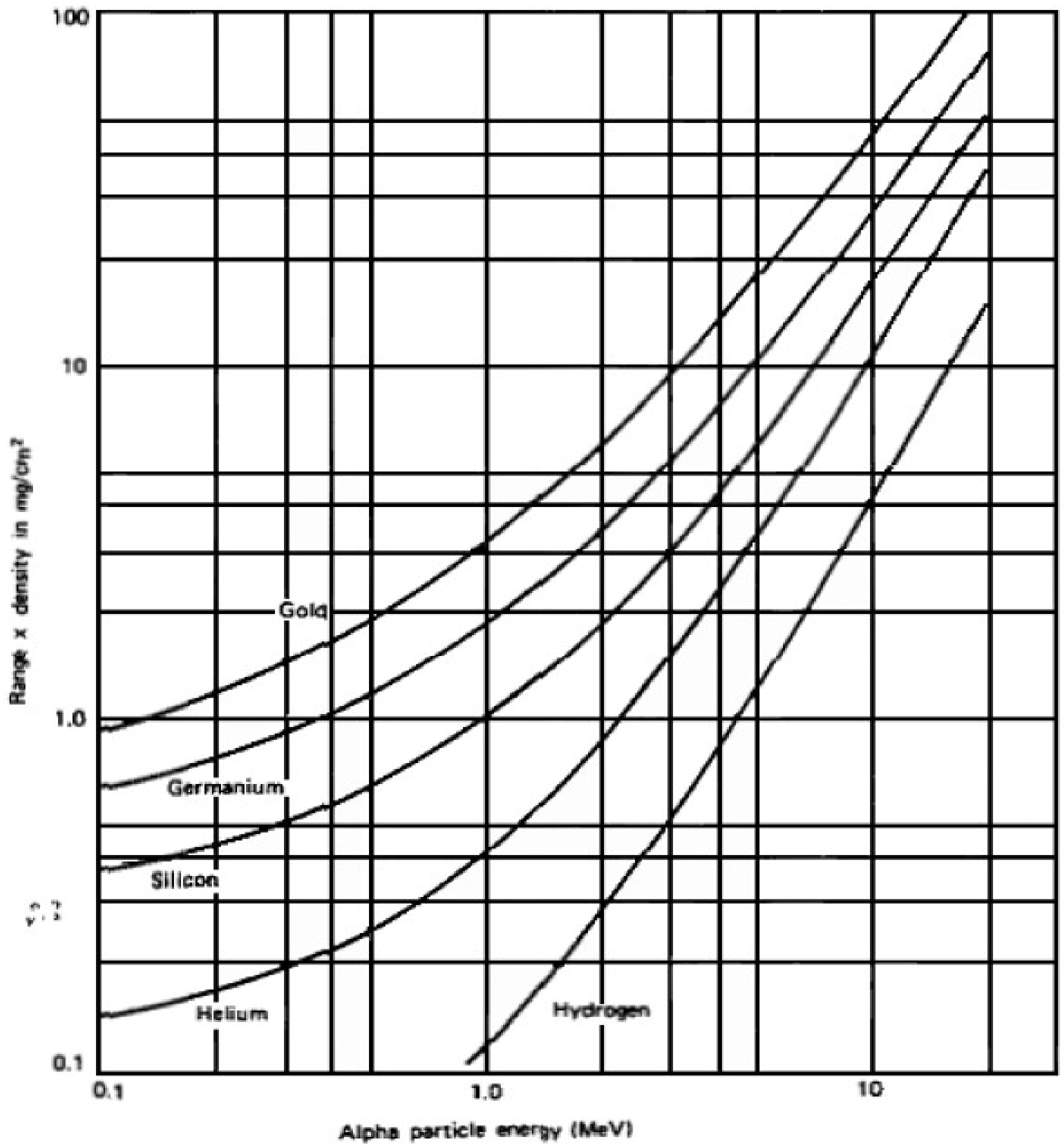


Figure 2-8 Range–energy curves calculated for alpha particles in different materials. Units of the range are given in mass thickness (see Section III.B.2) to minimize the differences in these curves. (Data from Williamson et al.[4])

Interazione delle particelle pesanti cariche con la materia

RANGE

$$dx = \frac{m_1}{z_1^2}\,\frac{m_e}{4\pi e^4}\,\frac{1}{NZ}\,\frac{u^3\,du}{\ln\left(2m_e u^2/I\right)}$$

$R \approx k'\, m_1\, u^4 / N\, Z\, z_1^2$

Per particelle alfa incidenti:

dipendenza da Z di $R^*\rho = R^*NM_m / N_A$ con M_m massa molare

Interazione degli elettroni con la materia

Perdita di energia specifica collisionale

Particelle cariche pesanti

$$\frac{dE}{dx} = 4\pi N Z \frac{z^2 e^4}{m_e c^2 \beta^2}\left[\ln \frac{2 m_e c^2 \gamma^2 \beta^2}{I} - \beta^2\right]$$

Elettroni

$$\left(\frac{dE}{dx}\right)_{coll} = 4\pi \frac{N Z e^4}{m_e \beta^2 c^2} \cdot \left\{ \ln \frac{(\gamma - 1)(\gamma + 1)^{1/2}}{2^{1/2}} \frac{m_e c^2}{I} - \beta^2 \right.$$
$$\left. \boxed{+\left[1 - \ln 2 \left(2(1-\beta^2)^{1/2} - 1 + \beta^2\right) + \frac{1}{8}\left(1 - (1-\beta^2)^{1/2}\right)^2\right]} \right\}$$

Termine correttivo del 10-20%

Interazione degli elettroni con la materia

Perdita di energia specifica radiativa

$$\left(\frac{dE}{dx}\right)_{rad} = -(4/137)Z^2e^4N_0\frac{T_e+m_ec^2}{(m_ec^2)^2}\left[\ln\frac{2(T_e+m_ec^2)}{m_ec^2}-\frac{1}{3}\right]$$

$$\frac{(dE/dx)_r}{dE/dx)_c} \sim \frac{(t+1)\ Z}{1600}$$

$t = T_e / m_ec^2$

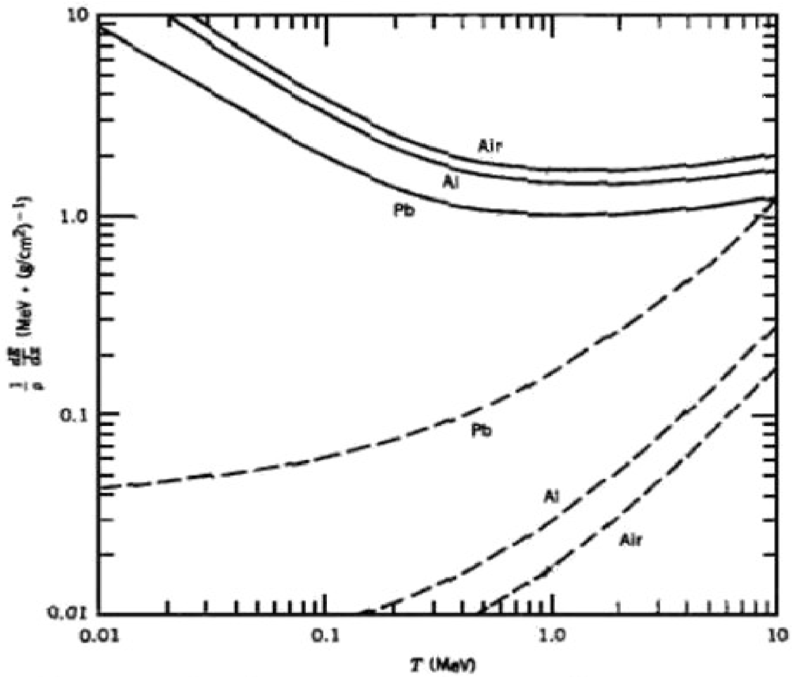


Figure 7.3 Energy loss by electrons in air, Al, and Pb. To suppress the large variation in *dE/dx* arising from the number of electrons of the material, the quantity $\rho^{-1}(dE/dx)$ is plotted. Solid lines are for collisions; dashed lines are for radiation. For additional tabulated data on energy losses, see L. Pages et al., *Atomic Data* **4**, 1 (1972).

Interazione degli elettroni con la materia

Back-scattering

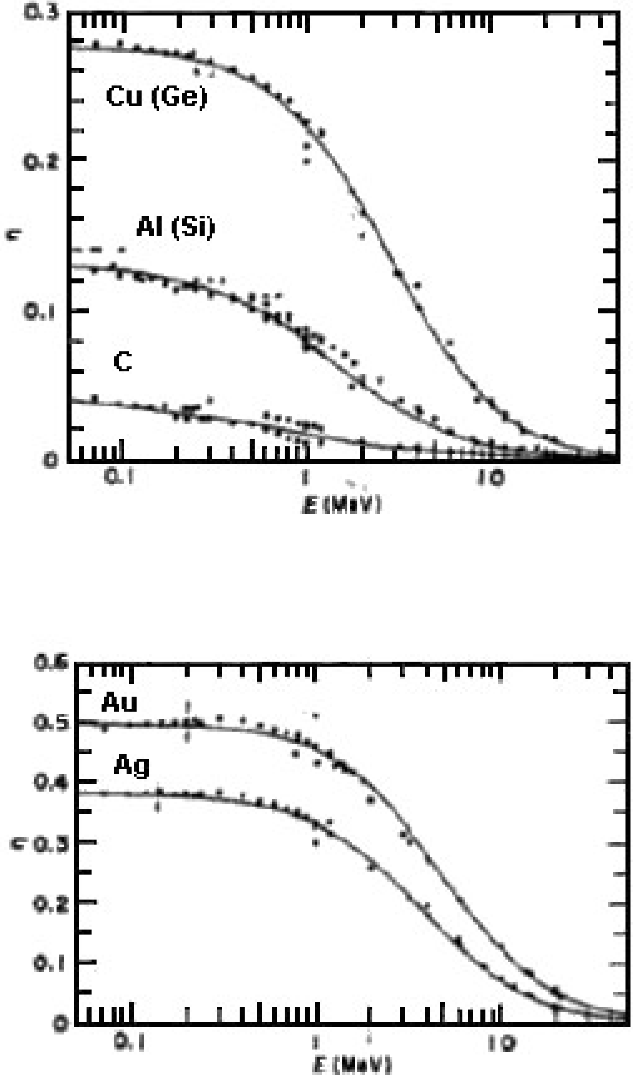


Figure 2-17 Fraction η of normally incident electrons that are backscattered from thick slabs of various materials, as a function of incident energy E. (From Tabata et al.[18])

Interazione degli elettroni con la materia

RANGE

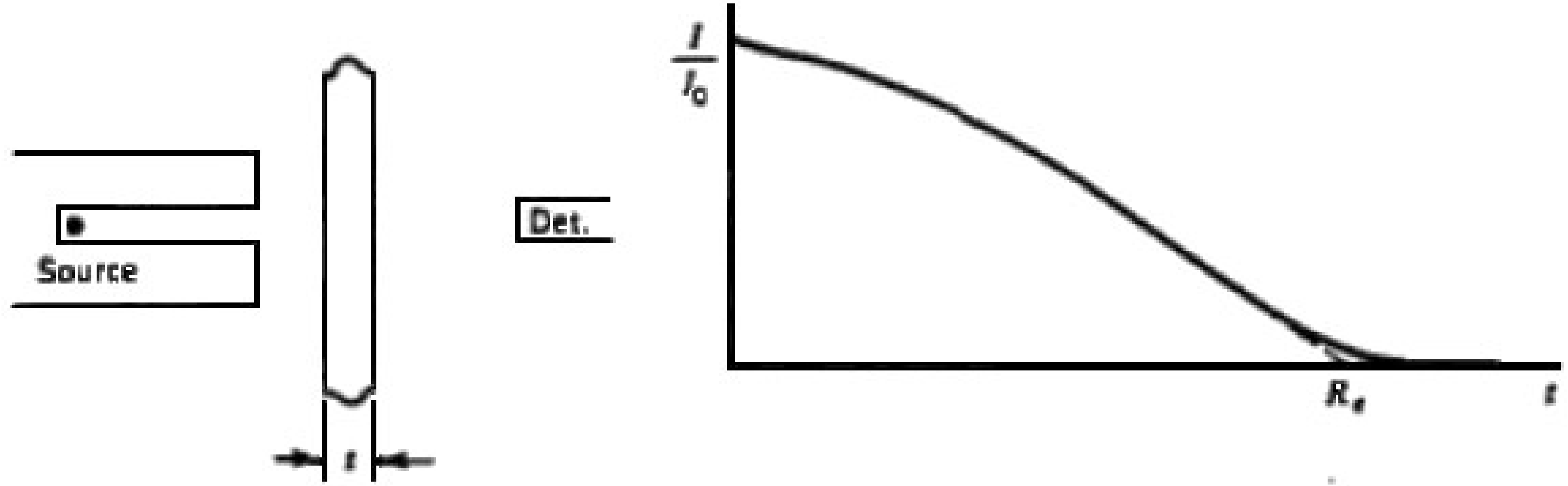


Figure 2-13 Transmission curve for monoenergetic electrons. R_e is the extrapolated range.

Interazione degli elettroni con la materia

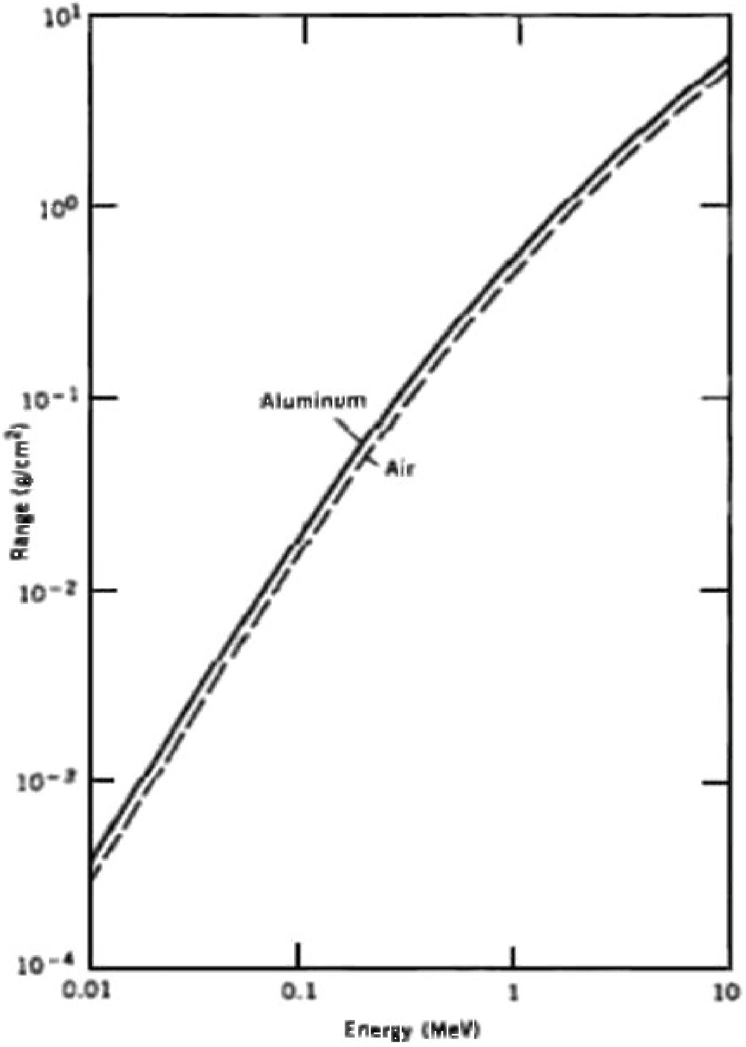


Figure 7.4 Range-energy relationship for electrons in air and in aluminum.

RANGE

Interazione della radiazione e.m. con la materia

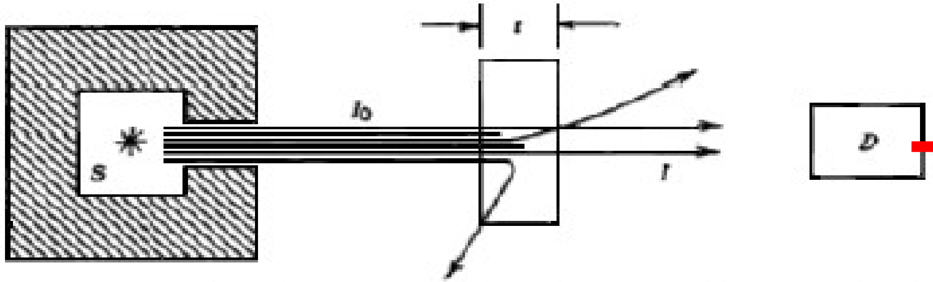


Figure 7.9 An experiment to measure absorption of radiation in a slab of material of thickness *t*. A beam of radiation from the source S is collimated and then is scattered or absorbed by the material. The remaining intensity *I* reaches the detector D.

$$dn_c = (NZ\ dx)\sigma_c\ n$$

coefficiente di attenuazione lineare

$$\sigma = N\ Z\ \sigma_c\ \ cm^{-1}$$

$$n = n_0\ e^{-\sigma x} = n_0\ e^{-\frac{\sigma}{\rho}(\rho x)}$$

$$\frac{\sigma}{\rho} = N_A\ \frac{Z}{M_m}\ \sigma_c\ g^{-1}cm^2$$

coefficiente di attenuazione lineare di massa

Interazione della radiazione e.m. con la materia

Principali interazioni

E_γ

- Effetto fotoelettrico

per $E_\gamma > BE_K$

$$\sigma_{ph}(per\ 1\ elettrone\ 1s) = \frac{128\pi}{3}\frac{e^2h}{m_ec}\frac{1}{E_\gamma}\left(\frac{BE_K}{E_\gamma}\right)^3 \frac{e^{-4\varepsilon\arctan(1/\varepsilon)}}{1-e^{-2\pi\varepsilon}}\ cm^2$$

$$\varepsilon = [BE_K/(E_\gamma - BE_K)]^{1/2}$$

per $E_\gamma \approx BE_K$

$$\sigma_{ph}(per\ 1\ elettrone\ 1s) \simeq \frac{6.31\cdot 10^{-18}}{Z^2}\left(\frac{BE_K}{E_\gamma}\right)^{8/3}\ cm^2$$

- Scattering Compton

$$\sigma_c = 2\pi r_e^2\left\{\frac{1+\alpha}{\alpha^2}\left[\frac{2(1+\alpha)}{1+2\alpha} - \frac{1}{\alpha}\ln(1+2\alpha)\right] + \frac{1}{2\alpha}\ln(1+2\alpha) - \frac{(1+3\alpha)}{(1+2\alpha)^2}\right\}\ \frac{cm^2}{elettrone}$$

$$\alpha = h\nu/m_ec^2$$

- Creazione di coppie

Per $h\nu \gg m_e\ c^2$

$$\sigma_{pair} = \frac{Z^2}{137}\ r_e^2\ \left(\frac{28}{9}\ \ln 183\ Z^{-1/3} - \frac{2}{27}\right)\ cm^2$$

Interazione della radiazione e.m. con la materia

- Effetto fotoelettrico

$$\sigma_{ph}(per\ 1\ elettrone\ 1s) \simeq \frac{6.31 \cdot 10^{-18}}{Z^2} \left(\frac{BE_K}{E_\gamma}\right)^{8/3} \ cm^2$$

$$BE_K \sim 13.5(Z-1)^2\ eV$$

$$BE_L \sim 13.5(Z-5)^2/4\ eV$$

$$BE_M \sim 13.5(Z-13)^2/9\ eV$$

coefficiente di attenuazione lineare per effetto fotoelettrico

$$\tau = \{(5 \div 6)/4\}\ \sigma_{ph} N\ cm^{-1}$$

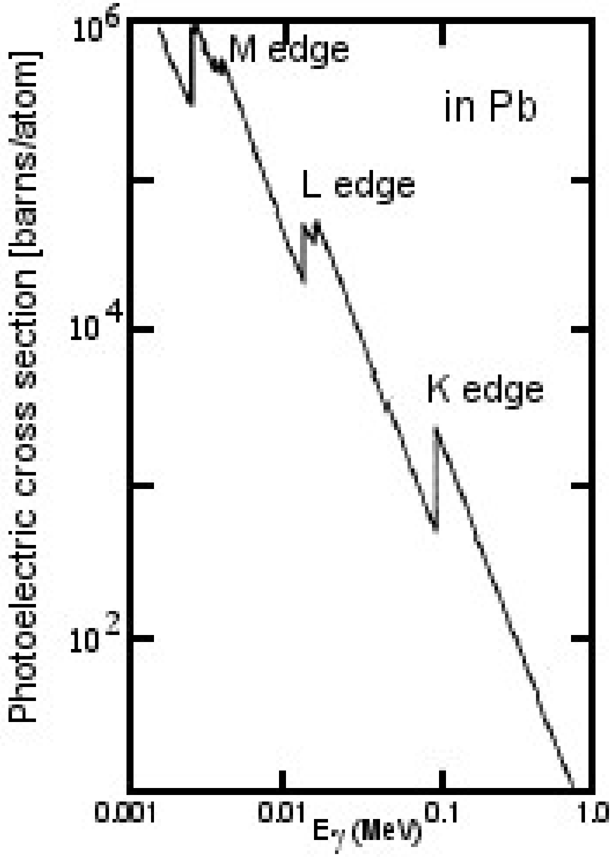
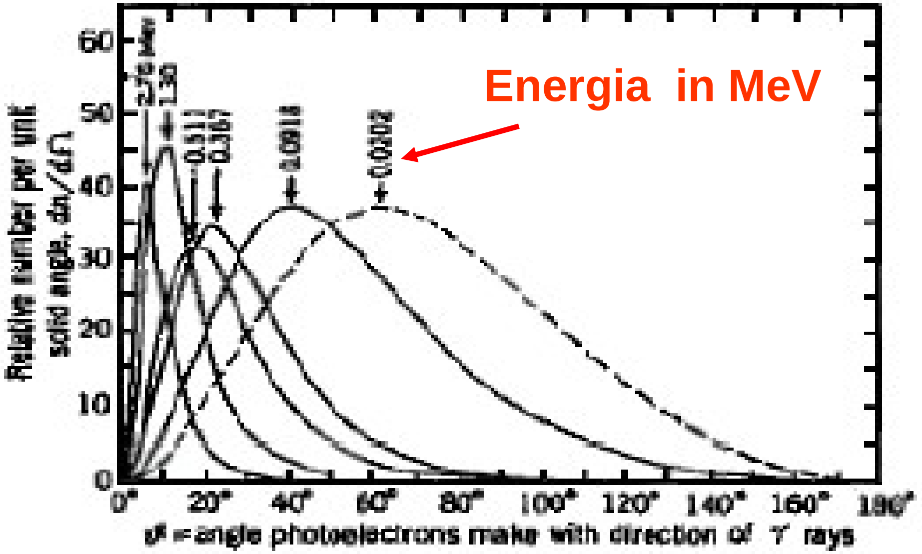


Figure 7.5 Photoelectric cross section in Pb. The discrete jumps correspond to the binding energies of various electron shells; the K-electron binding energy, for example, is 88 keV. To convert the cross section to the linear absorption coefficient τ in cm^{-1}, multiply by 0.033.

Interazione della radiazione e.m. con la materia

Effetto fotoelettrico

Distribuzione angolare dei fotoelettroni



Energia in MeV

dσ/dΩ

Fig. 1.2 Directional distribution of photoelectrons per unit solid angle, for energies as marked. The curves are not normalised with respect to each other. Solid curves are calculated from Sauter's (S0) relativistic formula; dashed curve from Fischer's (F50) nonrelativistic formula. [*From Davisson and Evans* (D12).]

Interazione della radiazione e.m. con la materia

Scattering Compton

$$\frac{d\sigma_c}{d\Omega} = \frac{r_e^2}{2}\left(\frac{\nu^*}{\nu}\right)^2\left(\frac{\nu}{\nu^*}+\frac{\nu^*}{\nu}-\sin^2\theta\right)$$

con

$$\frac{h\nu^*}{h\nu}=\frac{\nu^*}{\nu}=\frac{1}{1+\alpha(1-\cos\theta)}$$

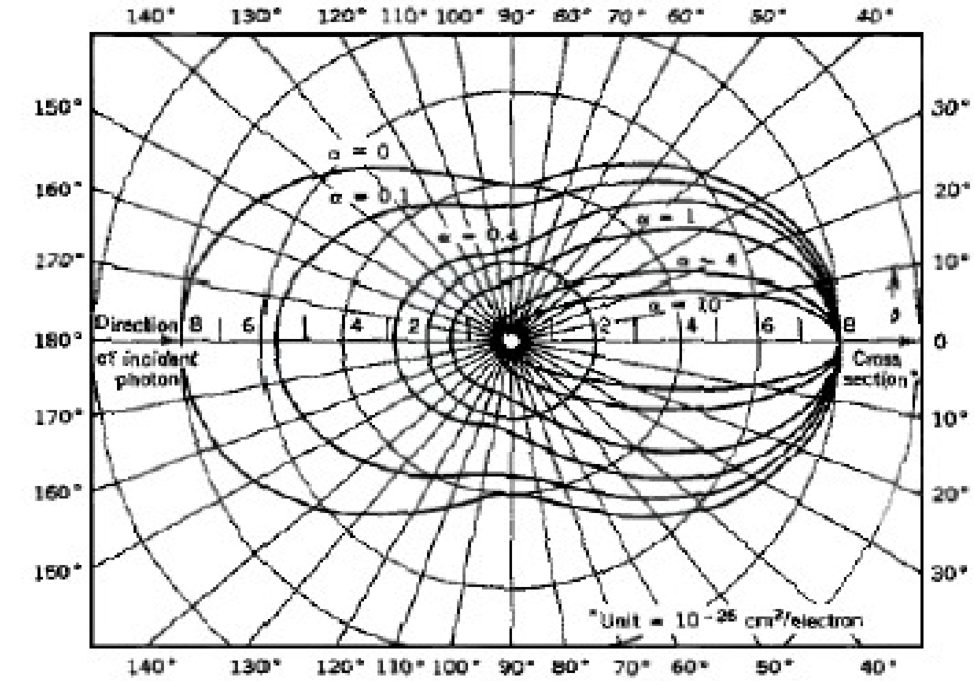
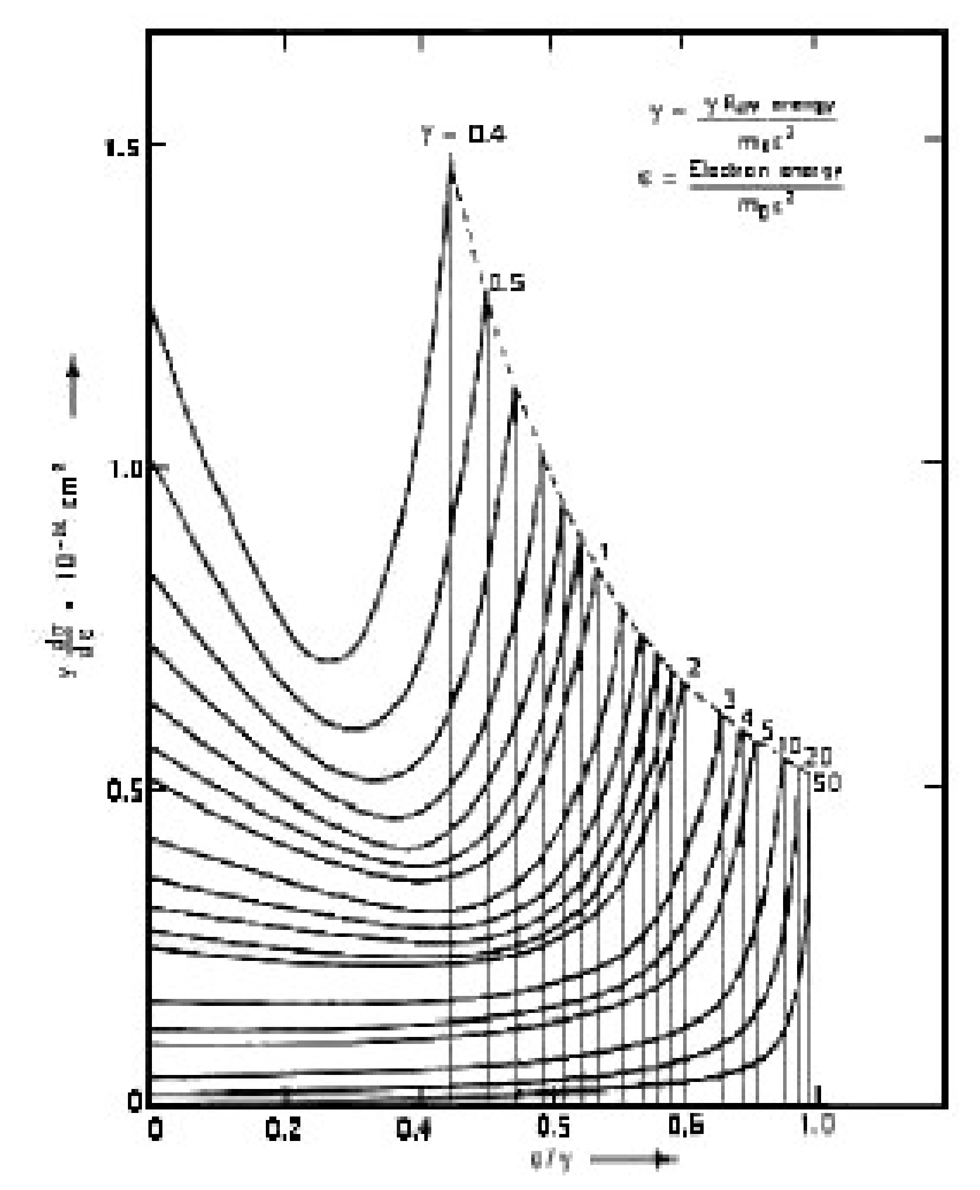


Figure 7.7 The Compton-scattering cross section for various incident energies. The polar plot shows the intensity of the scattered radiation as a function of the scattering angle θ. From R. D. Evans, *The Atomic Nucleus* (New York: McGraw-Hill, 1955).

Interazione della radiazione e.m. con la materia



Scattering Compton

Energia dell'elettrone di rinculo

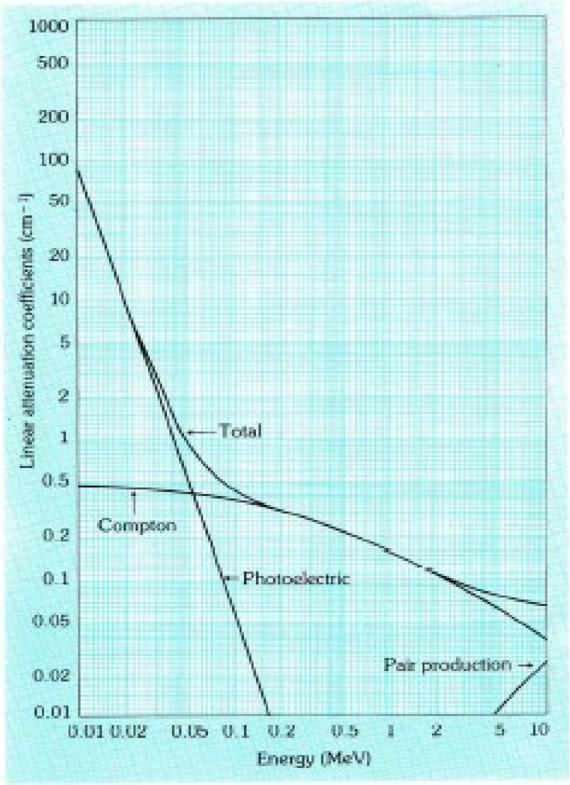
$$t_e = \frac{\alpha^2(1-\cos\theta)}{1+\alpha(1-\cos\theta)}$$

Distribuzione in energia dei fotoelettroni

$$\left(\frac{d\sigma}{dt_e}\right)\frac{1}{\pi r_e^2} = \frac{2\alpha^4 - 2\alpha^2(2\alpha+1)t_e + (3\alpha^2+2\alpha+1)t_e^2 - \alpha t_e^3}{\alpha^4(\alpha-t_e)^2}$$

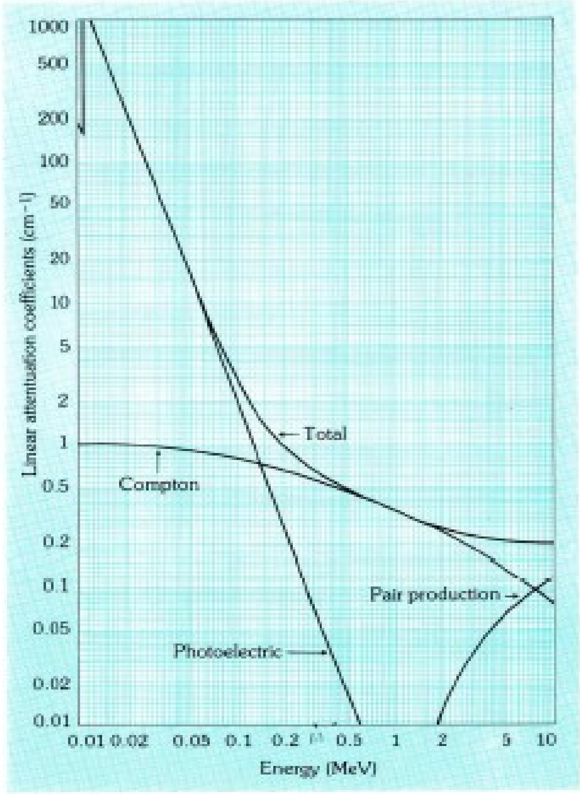
Interazione della radiazione e.m. con la materia

Si



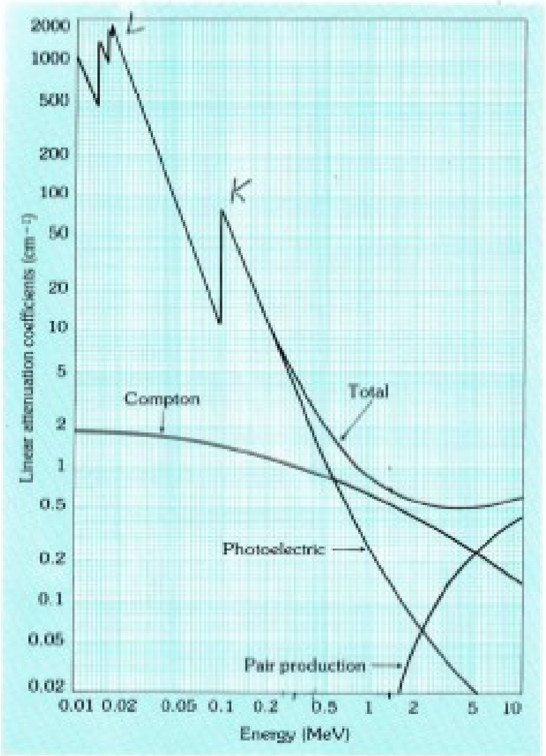
Specific mass = 2420 kg/m^3
Atomic number: Z = 14
Electron Binding Energy:
K-edge = 1.84 keV
Average K X-Ray Energy: 1.75 keV

Ge



Specific mass = 5350 kg/m^3
Atomic number: Z = 32
Electron Binding Energy:
K-edge = 11.1 keV
Average K X-Ray Energy = 10 keV

Pb

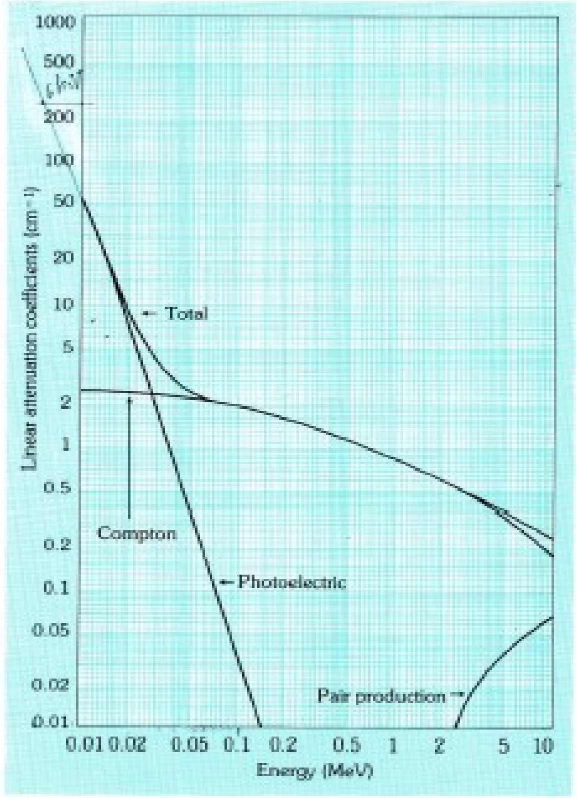


Specific mass = 11350 kg/m^3
Atomic number: Z = 82
Electron Binding Energies:
K-edge = 88.02 keV
L_I-edge = 15.87 keV
L_{II}-edge = 15.21 keV
L_{III}-edge = 13.05 keV
Average K X-Ray Energy = 76.74 keV

Interazione della radiazione e.m. con la materia

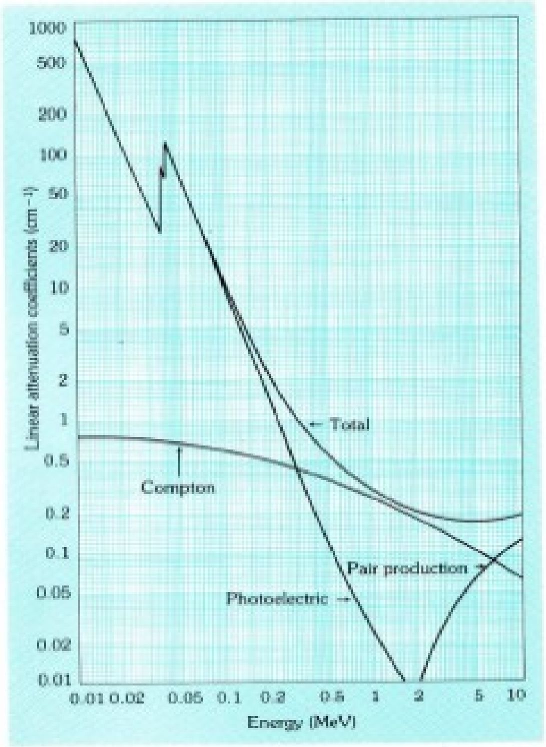
[illegible] 5 cm $e^{-5 \times 2.6 \times 10^{-2}} \sim 0.88$

Air
× 10⁻⁴



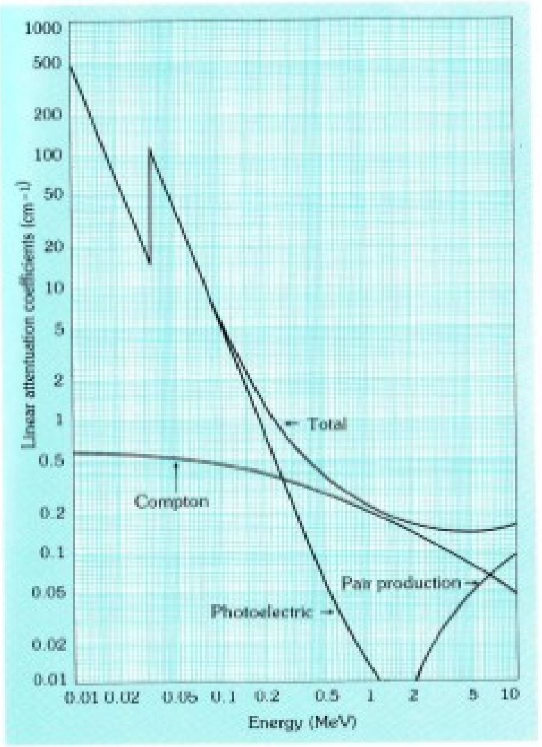
Specific mass = 1.293 kg/m³
Composition of "air"
78.04 volume percent nitrogen
21.02 volume percent oxygen
0.94 volume percent argon

CsI



Specific mass = 4510 kg/m³
Atomic number: Z (I) = 53
Z (Cs) = 55
Electron Binding Energies:
K-edge (I) = 33.17 keV
K-edge (Cs) = 35.98 keV
L_I-edge (Cs) = 5.72 keV
L_{II}-edge (Cs) = 5.36 keV
L_{III}-edge (Cs) = 5.01 keV
Average K X-Ray Energy (Cs) = 31.6

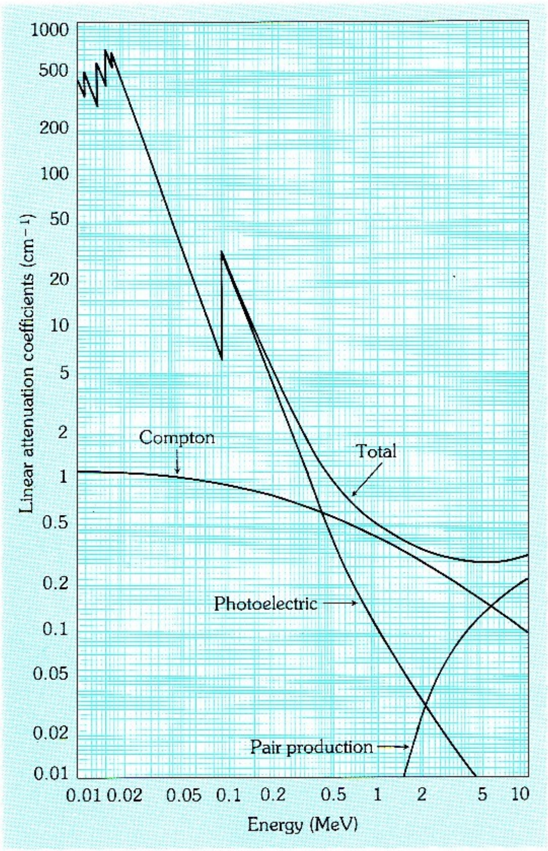
NaI



Specific mass = 3670 kg/m³
Atomic Number: Z(I) = 53
Z(Na) = 11
Electron Binding Energies:
K-edge (I) = 33.17 keV
L_I-edge (I) = 5.19 keV
L_{II}-edge (I) = 4.85 keV
L_{III}-edge (I) = 4.56 keV
Average K X-Ray Energy (I) = 29.2 keV

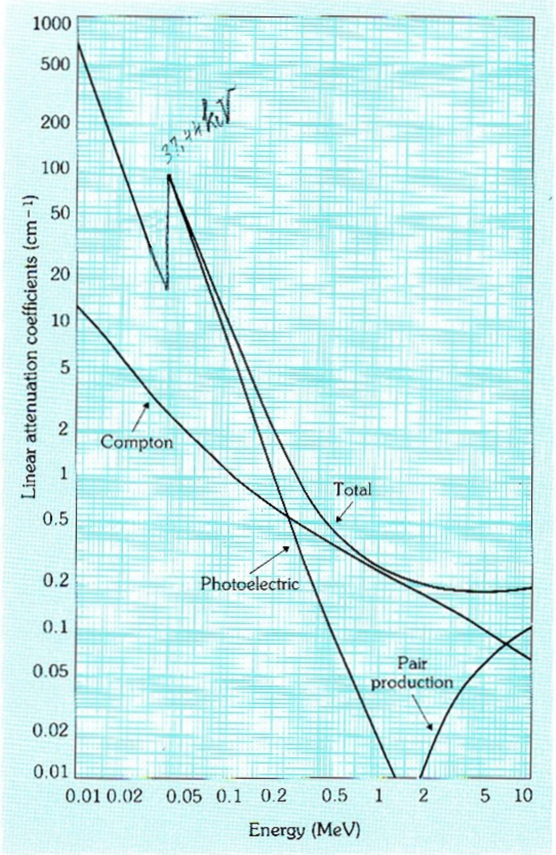
Interazione della radiazione e.m. con la materia

BGO



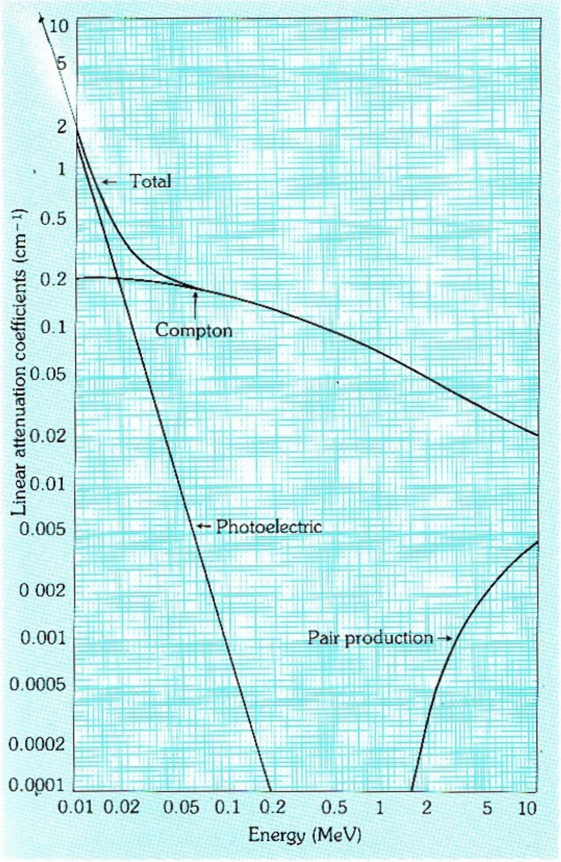
Specific mass = 7130 kg/m^3
Atomic number: Z (Bi) = 83
Z (Ge) = 32
Electron Binding Energies:
K-edge (Bi) = 90.53 keV
L_I-edge (Bi) = 16.39 keV
L_{II}-edge (Bi) = 15.71 keV
L_{III}-edge (Bi) = 13.42 keV
K-edge (Ge) = 11.10 keV
Average K X-Ray Energy (Bi) = 78.9 keV

BaF$_2$



Specific mass = 4880 kg/m^3
Atomic number: Z(Ba) = 56
Z(F) = 9
Electron Binding Energies:
K-edge (Ba) = 37.44 keV
L_I-edge (Ba) = 5.99 keV
L_{II}-edge (Ba) = 5.62 keV
L_{III}-edge (Ba) = 5.25 keV
K-edge (F) = 0.69keV

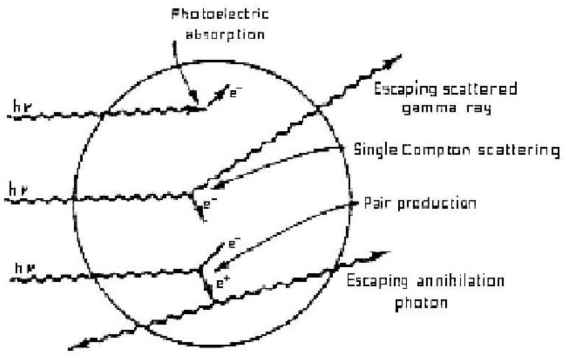
Plastic Scintillator

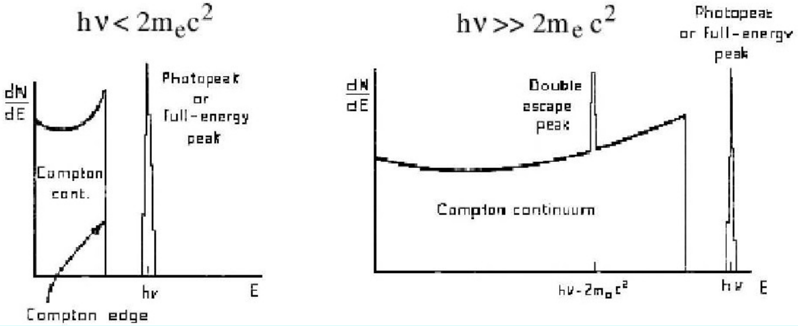


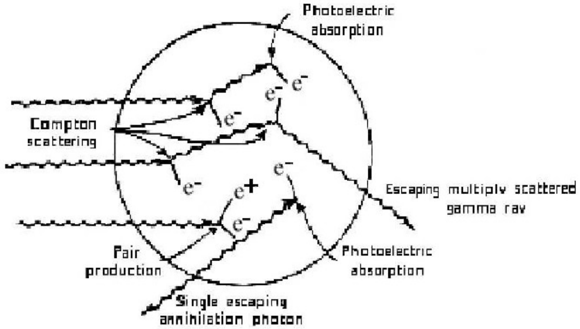
Specific mass = 1050 kg/m^3
No atoms per cm^3
H: 5.25×10^{22}; C: 4.75×10^{22}
N: 1.8×10^{18}; O: 1.8×10^{18}
Atomic number: Z (C) = 6
K-edge (C) = 0.28 keV

Interazione della radiazione e.m. con la materia

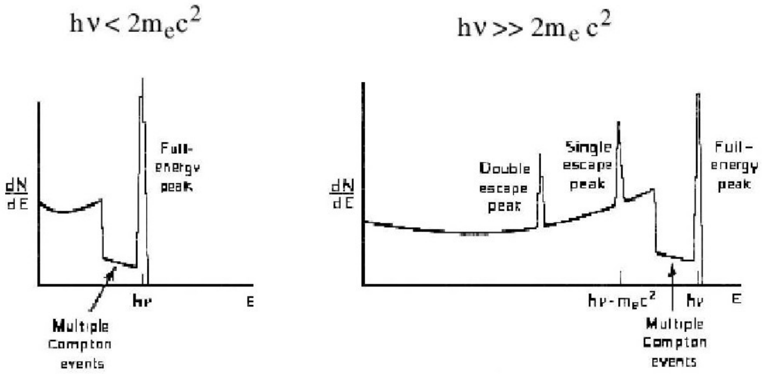
“rivelatore piccolo”







“rivelatore medio”



Interazione di particelle cariche e radiazione e.m. con la materia

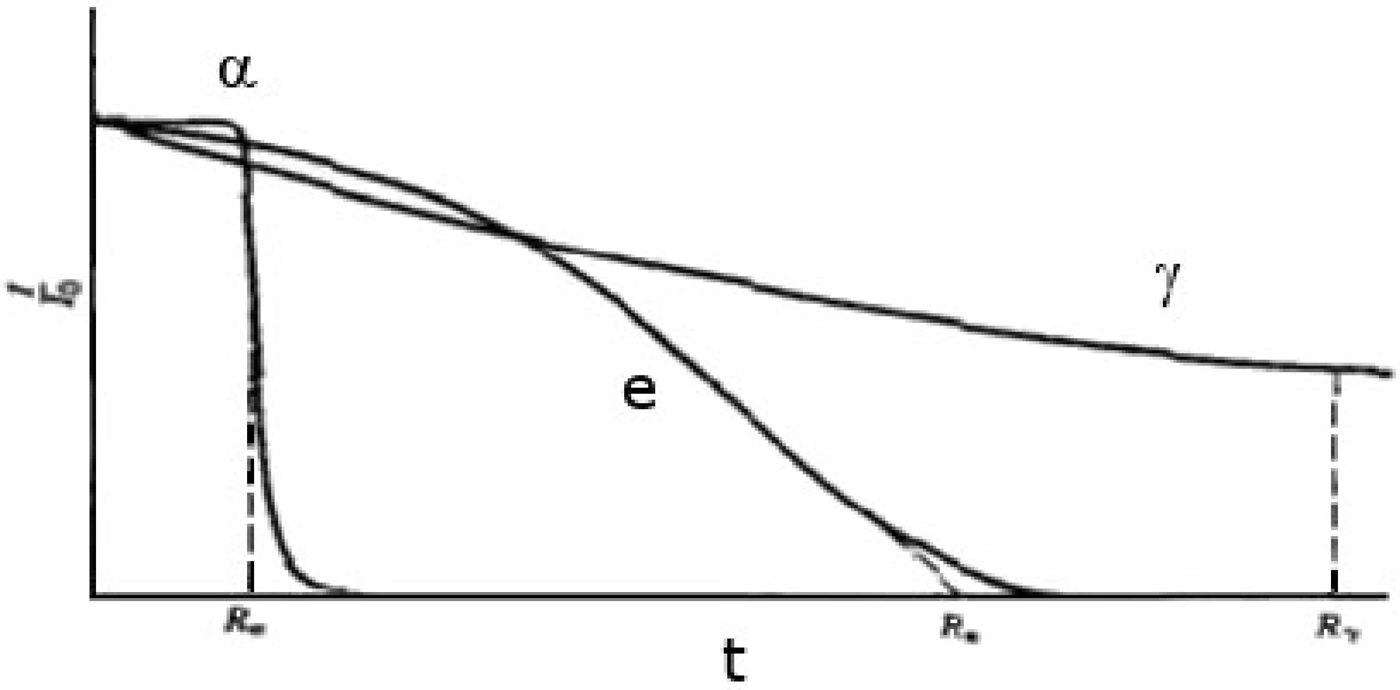


Figure 7.11 The transmitted intensity measured in a geometry such as that shown in Figure 7.9. For α's, the value of t such that $I/I_0 = 0.5$ is the mean range; for photons, with their simple exponential dependence, we can define the mean range similarly. For electrons, it is customary to define the *extrapolated* range by extending the linear portion of the absorption curve as shown. The horizontal scale is not at all linear; the range for γ's may be 10^4 that for α's.