δx, there are fluctuations in the actual energy loss. The distribution is skewed toward high values (the Landau tail) [1,16]. Only for a thick layer $[(dE/dx)\delta x \gg T_{\rm max}]$ is the distribution nearly Gaussian.

A mixture or compound can be thought of as made up of thin layers of pure elements in the right proportion (Bragg additivity). In this case,

$$\frac{dE}{dx} = \sum w_j \left.\frac{dE}{dx}\right|_j , \tag{10.4}$$

where $dE/dx|_j$ is the mean rate of energy loss (in MeV g cm^{-2}) in the jth element. Eq. (10.1) can be inserted into Eq. (10.4) to find expressions for $\langle Z/A\rangle$, $\langle I\rangle$, and $\langle\delta\rangle$; for example, $\langle Z/A\rangle = \sum w_j Z_j/A_j = \sum n_j Z_j / \sum n_j A_j$. However, $\langle I\rangle$ as defined this way is an underestimate, because in a compound electrons are more tightly bound than in the free elements, and $\langle\delta\rangle$ as calculated this way has little relevance, because it is the electron density which matters. If possible, one uses the tables given in Refs. 13 and 12, or the recipes given in Refs. 8 or 10, which include effective excitation energies and interpolation coefficients for calculating the density effect correction.

Ionization losses by electrons and positrons [12] are not discussed here. Above the critical energy, which is a few tens of MeV in most materials, bremsstrahlung is the dominant source of energy loss.

10.3. Restricted energy loss rates for relativistic ionizing particles

Fluctuations in energy loss are due mainly to the production of a few high-energy knock-on electrons. Practical detectors often measure the energy *deposited*, not the energy *lost*. When energy is carried off by energetic knock-on electrons, it is more appropriate to consider the mean energy loss excluding energy transfers greater than some cutoff $T_{\rm cut}$. The restricted energy loss rate is

$$-\left.\frac{dE}{dx}\right|_{T<T_{\rm cut}} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\rm upper}}{I^2} - \frac{\beta^2}{2}\left(1+\frac{T_{\rm upper}}{T_{\rm max}}\right) - \frac{\delta}{2}\right] \tag{10.5}$$

where $T_{\rm upper} = {\rm MIN}(T_{\rm cut}, T_{\rm max})$. This form agrees with the equation given in previous editions of this *Review* [17] for $T_{\rm cut} \ll T_{\rm max}$ but smoothly joins the normal Bethe-Bloch function (Eq. (10.1)) for $T_{\rm cut} > T_{\rm max}$.

10.4. Energetic knock-on electrons (δ rays)

The distribution of secondary electrons with kinetic energies $T \gg I$ is given by [1]

$$\frac{d^2N}{dT\,dx} = \frac{1}{2}Kz^2\frac{Z}{A}\frac{1}{\beta^2}\frac{F(T)}{T^2} \tag{10.6}$$