# Energy Loss of Charged Relativistic Particles and the Element Periods*

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The stopping power per electron for charged relativistic particles is known to be a function of the electron density of the matter traversed. As the latter is a periodic property of the elements, the stopping power should also be periodic. A calculation shows the energy loss to have maxima at the alkali metals and minima between them. It is suggested that this effect partly caused the periodicity found long ago by Crowther in in the absorption of $Pa^{234}$ beta rays. Differences in stopping power for chemical isomers and element modifications are also discussed.

THE energy loss due to ionization and excitation during the passage of charged particles through matter is subject to a reduction at relativistic velocities because of the importance of distant encounters and the polarization of the intervening material. When this "density effect" has reached its full efficiency, the mean excitation potential in the Bethe-Bloch formula disappears. Then the energy loss formula takes the following form,[1]

$$-\frac{1}{n}\frac{dE}{dx}=\frac{2\pi e^4 Z^2}{mc^2}\left\{\log\left[\frac{mc^2}{e^2}\left(\frac{mc}{\hbar}\right)^2\frac{1}{\pi n(1-\beta^2)}\right]-1\right\}, \quad (1)$$

after rearrangement to give the energy loss per electron/cm². The formula applies to "heavy" particles, e.g., protons and mesons, and should be somewhat modified for electrons.

As the electronic density $n$ in (1) is a *periodic* function of the atomic number of the elements, the energy loss should also show periodicity at fixed velocity if (1) holds, (although this periodicity would be less pronounced than the atomic volume, for instance). Figure 1 shows the result of a calculation for the case of $(1-\beta^2)^{-\frac{1}{2}}=196.5$, which corresponds to 184 Gev for protons,[2] 29 Gev for $\pi$ mesons, 21 Gev for $\mu$ mesons, and 100 Mev for electrons. The densities have been taken for ordinary temperature except for those elements existing as gases at this temperature, where the liquid density was taken.

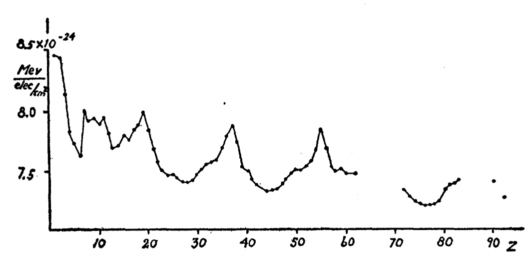


FIG. 1. Energy loss according to formula (1) as a function of atomic number. Note the peaks at $_{19}$K, $_{37}$Rb, and $_{55}$Cs and the intervening minima.

It is seen that the elements form a series of concave sections, each section containing one period and the maximum points corresponding to the alkali metals. The two first periods are less pronounced than the fourth and fifth because of individual deviations. There seem to be no published measurements suitable for comparison, but it is interesting to note that the picture is very similar to the results of Crowther,[3] who measured the mass absorption coefficient for $Pa^{234}$ beta rays (2.3-Mev maximum energy). This property is very difficult to interpret theoretically, but it should contain the trends of the energy loss of the electrons.[4] Discussing the periodic behavior, Bothe suggested[4] that it might be due to a periodicity in the characteristic frequencies in the Bohr stopping theory, but no closer analysis was given. Calculations, approximating the excitation potentials of the various shells with the ionization potentials, have shown such an effect to be very small, the periodicity due to the outer electrons being masked by the inner ones. Even if the approximation used is somewhat in error, the density effect seems to be much larger even in this low-energy region. The observed deviations from a simple function of $Z$ is, however, three or more times larger than the theoretical; therefore, it cannot yet be concluded that the periodic behavior observed by Crowther is due to the density effect only (despite the similarity in shape). The best procedure would be to measure the energy loss directly. Such studies are in progress here using 5-Mev electrons, where the energy loss due to radiation is not too large.

In addition to carbon, studied by Paul and Reich,[5] other element modifications should afford good opportunities of studying the density effect, e.g., arsenic whose yellow modification is expected to be 4 percent more effective in stopping than the gray one. Chemical isomers, e.g., organic compounds like diethylether and buthanol, should also differ. Melting processes should also be studied.

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[1] H. Bethe and J. Ashkin, in *Experimental Nuclear Physics* edited by E. Segrè (John Wiley and Sons, Inc., New York, 1953), Vol. I, p. 225.

[2] 1 Gev (giga electron volt) = $10^9$ ev.

[3] J. A. Crowther, Phil. Mag. 12, 379 (1906).

[4] W. Bothe, *Handbuch der Physik* (Springer Verlag, Berlin, 1933), Vol. 22, Part 2.

[5] W. Paul and H. Reich, Z. Physik 127, 429 (1950).