Journal of Physical Chemistry & Biophysics

Sabin, J Phys Chem Biophys 2013, 3:5
DOI: 10.4172/2161-0398.1000e115

Editorial
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Energy Deposition by Swift Hadrons in Mixed Gas Targets: The Mean Excitation Energy of Planetary Atmospheres

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In many widely varying types of systems, energy is deposited by the collision of swift hadrons (typically H^+ or He^{2+}), with target molecules, resulting in the conversion of projectile kinetic energy to various types of energy in the target, through various processes. The ability to absorb energy from a hadronic projectile is referred to as the *stopping power* or linear energy transfer (LET), $-{dE}/{dx}$, of the target species.

For a single component system, the stopping power for fast projectiles can be described in SI units by Bethe's formulation [1].

$$-\frac{dE}{dx}=n\frac{4\pi e^4 Z_1^2 Z_2}{mv^2}\ln\frac{2mv^2}{I_0} \tag{1}$$

Here, n is the scatterer density, Z_1 is the projectile charge, Z_2 is the target electron number, v is the projectile velocity and m and e are the electron mass and charge, respectively. The quantity I_0 is the *mean excitation* energy of the target, and is the single materials quantity that describes the ability of the target to absorb energy from a projectile [1]. It is obtained as the first energy weighted moment of the dipole oscillator strength distribution of the target [1,2].

$$\ln I_0=\frac{\int\frac{df}{dE}\ln E\,dE}{\int\frac{df}{dE}dE} \tag{2}$$

It should be noted that the complete dipole oscillator strength distribution of the target, including all discrete and continuous transitions, is required.

In many situations, however, such as planetary atmospheres, [1] plasmas and warm, dense matter, the target can be composed of various components with various scatterer densities. In order to treat the stopping power of such a mixture, providing the components are non-interacting, each component would be treated separately and the results summed, as

$$\frac{dE}{dx}=\sum_{i=components}\left(\frac{dE}{dx}\right)_i \tag{3}$$

However, it would be more convenient to treat the mixture as a single substance as in eq.1, with its own mean excitation energy, I_0^{mix}. The stopping power for the mixture as a whole for a projectile of charge Z_1 would then be

$$\left(-\frac{dE}{dx}\right)_{mix}=n_{mix}\frac{4\pi e^4 Z_1^2 Z_{mix}}{mv^2}\ln\frac{2mv^2}{I_0^{mix}} \tag{4}$$

Here, n_{mix} is a density of scattering centers, where $n_{mix}=\sum_i n_i$. Z_{mix} is the weighted average of the number of electrons per scatterer, $Z_{mix}=\sum_i n_i Z_i \Big/ n_{mix}$, and I_0^{mix} is the mean excitation energy appropriate to the mixture. Such treatment would derive from a sum of stopping powers of the components, weighted by their relative density of scattering centers, as in eq. 3.

$$\begin{aligned}\left(-\frac{dE}{dx}\right)_{mix}&=\sum_i n_i\frac{4\pi e^4 Z_1^2 Z_i}{mv^2}\ln\frac{2mv^2}{I_0^i}\\&=\frac{4\pi e^4 Z_1^2}{mv^2}\sum_i n_i Z_i\ln\frac{2mv^2}{I_0^i}\end{aligned} \tag{5}$$

Equating equations 4 and 5, one obtains

$$\ln I_0^{mix}=\frac{\sum_i n_i Z_i\ln I_0^i}{\sum_i n_i Z_i} \tag{6}$$

Thus, the mean excitation energy of the mixture of non-interacting components is simply the appropriate weighted average of the mean excitation energies of those components.

Applying the foregoing to the constituents of the atmospheres of solar planets [5] and using the standard molecular mean excitation energies of Janni [6], a single mean excitation energy for each of the solar planetary atmospheres can be calculated. The molecular mean excitation energies used were: $I_0^{He}=39.10eV$, $I_0^{H_2}=20.40eV$, $I_0^{O_2}=115.7eV$, $I_0^{O_2}=115.7eV$ and $I_0^{CO_2}=102.35eV$.

The results for the mean excitation energies of the atmospheres for the solar planets are given in the Table 1.

It should be noted that trace atmospheric components (<1%) were not included, as inclusions make very small differences in the mean excitation energies of the atmosphere, and even smaller differences in the values of 1n I_0, which is the quantity that governs energy deposition by swift, massive particles in the atmospheres. For example, the mean excitation energy for Earth's atmosphere, without including the 1% Ar is 101.89 eV, leading to a difference of 0.59 in I_0 and 0.006 in 1n I_0.

Thus, energy deposition by auroral hadrons in planetary atmospheres, such as, for the many newly discovered Goldilocks planets, may be accurately estimated from the projectile flux and planetary composition.

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Received November 12, 2013; **Accepted** November 15, 2013; **Published** November 19, 2013

Citation: Sabin JR (2013) Energy Deposition by Swift Hadrons in Mixed Gas Targets: The Mean Excitation Energy of Planetary Atmospheres. J Phys Chem Biophys 3: e115. doi:10.4172/2161-0398.1000e115

Planet	Atmospheric composition	I_0 (eV)
Mercury	98% He 2% H^2	38.59
Venus	96.5% CO^2 3.5% N^2	102.24
Earth	78.1% N^2 20.9% O^2 1% Ar	102.48
Mars	95.3% CO^2 2.7% N^2 2% Ar	103.25
Jupiter, Saturn Uranus, Neptune	89% H^2 11% He	24.43

Table 1: Mean excitation energies of the atmospheres of the solar planets

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