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Stopping Power of Multiply Charged Ions

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Fast ions, such as protons and alphas, interact with, and deposit energy in, target ions and molecules by converting kinetic energy of the projectile to target electronic energy. Such energy deposition occurs in situations as different as deep space and plasmas and can involve targets as different as atomic ions and rather complicated organic molecules [1]. In most cases, the deposition of electronic energy by a fast ion with velocity v in a target of scatterer particle density n is described by the equation:

$$-\frac{dE}{dx} = nS(v) \quad (1)$$

Where $S(v)$ is the stopping cross section of the target and, in the Bethe approximation [2] which assumes the projectile velocity is much larger than the target electron velocities, is given by:

$$S(v) = \frac{4\pi e^4 Z_1^2 Z_2}{mv^2} \ln \frac{2mv^2}{I_0} \quad (2)$$

Here Z_1 and Z_2 are the projectile charge and target electron number, respectively, and I_0 is the target mean excitation energy, The mean excitation energy is defined [3] as the first energy weighted moment of the dipole oscillator strength distribution:

$$\ln I_0 = \frac{\int \frac{df}{dE} \ln E dE}{\int \frac{df}{dE} dE} \quad (3)$$

The determining factor for the amount of electronic energy deposited in a target by a fast ion. Thus, for electronic energy deposition by a fast ion at a given velocity in a target, the larger the mean excitation energy of target, the less electronic energy will be deposited. It should also be noted that the target may fragment or some projectile energy may be transferred to the target nuclear kinetic energy, but those possibilities are not considered here.

As an example, consider the simple case of protons colliding with an aluminum ion [3]. Although Aluminum ions are not frequently found in either plasmas or free space, Alq+ is chosen as an illustration as it has enough electrons, and thus enough differently charged ions, that changes in stopping properties with ionic charge can be illustrated. The table presents the calculated mean excitation energy [4] and stopping cross section for a proton with an (arbitrary) velocity of 20 a.u. (10 MeV) colliding with various aluminum ions. This is an arbitrary projectile velocity chosen for illustration only. Any other Bethe acceptable projectile velocity would give qualitatively similar results. No values for the stopping cross section are given for Al^{11+} and Al^{12+} as the velocity of the 1s electrons in Al is larger than the projectile velocity, and thus the Bethe approximation does not apply. Otherwise, the results are as expected with theincreasing mean excitation energy of more highly charged ions leading to a decrease in stopping cross section.

It is also interesting to note that the largest changes in the mean excitation energy with ion charge, and thus in the stopping cross section as well, come when the outermost electrons, which give the largest contribution to the stopping cross section, come from differing electronic subshells, such as $Al^{2+} \rightarrow Al^{3+}$, $Al^{8+} \rightarrow Al^{9+}$, and $Al^{10+} \rightarrow Al^{11+}$ (Table 1).

	I_0 (au)	S (v=20) (au)
Al	4.851	1.145
Al^{1+}	6.366	0.956
Al^{2+}	8.283	0.784
Al^{3+}	11.407	0.612
Al^{4+}	12.881	0.516
Al^{5+}	14.630	0.427
Al^{6+}	16.746	0.343
Al^{7+}	19.709	0.264
Al^{8+}	24.063	0.189
Al^{9+}	31.865	0.116
Al^{10+}	45.507	0.053
Al^{11+}	88.452	*
Al^{12+}	92.726	*

Table 1: Mean Excitation Energies and Stopping Cross Sections for $v = 20\,a.u.$ Protons colliding with Aluminum Ions.

Similar results are found for many other of the light ions [4]. Although similar studies have not yet been carried out for heavier atomic ions, similar results are to be expected.

If the target is a molecule or molecular ion, things are much more complicated. In principle the same collision of an ion with a polyatomic target leads to the same conversion of projectile kinetic energy to electronic energy and deposition of electronic energy in the target. Although each target atomic ion has a well-defined mean excitation energy, the same is not true for polyatomic targets. For molecules, the mean excitation energy depends on the molecular conformer [5] and orientation of the target with respect to the projectile [6]. In addition, while an atomic ion can be excited or ionized, a polyatomic target can be excited, ionized, fractionated, reoriented, or some combination of the foregoing.

Due to the complications mentioned here, very little has been done on polyatomic targets. Little has been done here, but much more work needs to be done, both theoretically and experimentally.

Another, as yet to be theoretically studied system is energy deposition by a polyatomic projectile!

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