

Projectile Spin and Stopping Power

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Understanding of the interaction and energy exchange of fast ionic projectiles with targets of various sorts is of interest in fields as widely disparate as astrophysics and radiation therapy. The basis of the interaction is energy transfer, typically from the projectile to the target. However, energy flow can be from the target to the projectile if the target is in an electronically excited state. The disposition of the post-collision transferred energy is of greatest interest, as it can lead to target electronic excitation, ionization and fragmentation, among other things. The question then arises as to what properties of the projectile and of the target determine the outcome of the collision.

In typical cases, where one has an ion beam focused on a macroscopic target, projectile kinetic energy is initially converted primarily to target electronic energy on collision. The quantity describing such energy transfer is the energy deposited by the projectile per unit length of the trajectory, known as the electronic stopping power, $-dE(v)/dx$, of the target, which depends on the projectile velocity, given in units of the Bohr velocity v_0 , and the scatterer electronic properties and target density n . To facilitate comparison among different target systems, the stopping power is frequently normalized with respect to scatterer density, to produce what is referred to as the stopping cross-section of the target $S(v)$:

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

The stopping cross section with appropriate constants removed, is referred to in the usual Bethe-like theories [1], as the stopping number, $L(v)$:

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

Here Z_1 and Z_2 are the projectile charge and target electronic charge, respectively. The stopping number is further expanded in powers of the projectile charge,

$$L(v) = \sum_{i=0} Z_1^i L_i \approx L_0 + Z_1 L_1 + Z_1^2 L_2 + \dots \quad (3)$$

yielding

$$S(v) = \frac{4\pi e^4 Z_1^2 Z_2^2}{mv^2} \sum_{i=0} Z_1^i L_i(v) \quad (4)$$

The stopping number $L(v)$, is normally written in terms of derived quantities which, using the Bethe [2], Lindhard [3,4], and Bloch[5] forms for L_0 , L_1 , and L_2 , respectively, yields

$$L(v) = \ln \frac{2mv^2}{I_0} - C_1 v e^{-C_2 v} + Z_1 \cdot \frac{3\pi e^2 I_0}{2\hbar m v^3} \ln \frac{2mv^2}{I_0} - Z_1^2 \frac{1.202}{v^2} \quad (5)$$

for the stopping number. The dominant term here is L_0 , or the Bethe, term $\left(\ln \frac{2mv^2}{I_0} - C_1 v e^{-C_2 v}\right)$, and calculations of the stopping power of a system are often approximations using only this term. If higher accuracy is needed, this is not reasonable, as although the higher terms are small, they are not negligible.

Of the quantities in Equation 5, the critical quantity is the mean

excitation energy of the target I_0 , which is defined [1] as the first energy weighted moment of the target dipole oscillator strength distribution (DODS), defined by Bethe [2] as:

$$\ln I_0 = \frac{\int \frac{df}{dE} \ln E dE}{\int \frac{df}{dE} dE} \quad (6)$$

The stopping power of various targets is frequently measured, and the mean excitation energy extracted using a model such as the one articulated above. Similarly, the relevant quantities can be calculated quantum mechanically, frequently at the level of the random phase approximation (RPA). Note that there are no properties of the projectile that affect the mean excitation energy of the target in a collision, and only the projectile charge and velocity affect the electronic stopping power.

If the projectile contains nuclei, in addition to the electronic stopping power, there may be projectile collisions with target nuclei, leading to some transfer of projectile kinetic energy to target nuclei. Although such nuclear stopping is a consideration, it usually is considerably less than electronic stopping.

However, the projectiles may have other properties that may be important in this situation.

Consider an ionic projectile stripped of all the electrons, moving towards a target with some velocity. The fundamental quantities defining the ion are not just its charge and mass, but also its spin. The question then arises as to whether spin can play a role in stopping power of targets for ions. The first thing to note is that such a question must apply only to fermions, such as electrons and protons, as bosons have integral spin. Any such effect must be tied to spin symmetry. Thus one might ask if a target could have different stopping powers, for example, for spin up protons vs. for spin down protons. Again, an effect would not be expected unless there were some symmetry characteristic in the target that could couple with the spin symmetry of the projectile.

Recently there has been reported a small effect of the chirality of some molecules for measuring molecular dissociative electron attachment (DEA) as a function of low energy electron beam helicity [6]. In particular, beams of spin pure electrons gave different breakup patterns for chirally different targets, for example the enantiomers

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of simple optically active molecules. One possible explanation was expressed that the spin polarized electrons themselves, “might preferentially destroy one enantiomer.”

The question then arises as to whether a similar effect might be found for the properties of the interaction of spin polarized ion projectiles with target molecules. A similar example might be, in the stopping power of the enantiomers of simple optically active molecules for spin polarized protons. As polarized proton beams are available [7], an experiment could be done, for example on the enantiomers of the simple amino acids, such as alanine. There would be four possibilities for each of the two proton polarizations on each of the enantiomers. Are there differences?

If there are differences, to explain or predict them, one must turn to theory.

Initially, one would not expect any difference in the DOSD of two enantiomers of an optically active target, as the connectivity and atomic positioning are the same in both cases, and thus the mean excitation energies would be expected to be the same. Although there may be small variations in the DOSDs due to changing non-bonded interactions as parts of the molecule rotate and vibrate, one would not expect any enantiomeric differences. Even if the parity-violation operator were included as an extra perturbation, one would expect only very small differences. Then, when the mean excitation energy is formed (Equation 6), such small differences would be expected to be washed out by the natural logarithm. Even were there to be a measurable difference in I_0 , there would be no effect of proton helicity.

Similarly, proton projectiles would experience the same nuclear distribution in enantiomeric targets, so nuclear stopping would not be considered to contribute to any effect.

If there is an effect, it must thus be that the polarized proton projectiles have some further interaction with the chiral target molecules, with preferential interaction with one enantiomer, rather than be based in electronic stopping.

However, there is also another possibility: If, for example, the target molecule has a net non-zero spin state, it could interact differently with

differently spin states of the projectile proton. As, in general, ortho and para states of molecules behave as independent species, unconnected to one another by electromagnetically-allowed transitions, and would interact differently with differently polarized projectile protons. To calculate such an effect would be difficult, as such a calculation would require a stopping theory that includes interaction between target and projectile and thus goes beyond semi-classical Bethe theory. Both the target and the projectile would have to be treated quantum mechanically in order to describe the effect.

An obvious possible experiment would be polarized protons on ortho and para molecular hydrogen. One can imagine an effect depending on the polarization of the projectile compared to that of the components of ortho hydrogen, but no effect for para. Such a situation would be consistent with the speculation from the electron case mentioned above that there must be some interaction other than purely electronic.

Both the experiment and theory for polarized proton beams are awaited!

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