A New Scaling Law For Ionization

R.D. DuBois[1], E.C. Montenegro[2] and G.M. Sigaud[3]

[1]*Department of Physics, Missouri University of Science and Technology, Rolla, MO, 65409, USA*
[2]*Instituto de Física, Universidade Federal do Rio de Janeiro, PO 68528, 21941-972 Rio de Janeiro,RJ, Brazil*
[3]*Departamento de Física, Pontifícia Universidade Católica do Rio de Janeiro,*
Caixa Postal 38071, Rio de Janeiro, RJ 22452-970, Brazil

Abstract. A new scaling law for ionization is presented. Our new model scales the cross sections by $Z^{4/3}$ and the impact energies by $Z^{2/3}$, rather than by Z in both cases as suggested by Olson et al. Using available CDW-EIS calculations and experimental data for ionization of helium by fully stripped ions, it is shown that this "modified Z" scaling yields a universal curve throughout the entire energy regime, not just for the region above the cross section maximum. Similar results are obtained for ionization of molecular hydrogen.

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INTRODUCTION

Information about the absolute probabilities, what reaction products are produced, and how much energy and momentum are transferred in inelastic interactions between atomic particles is required in a wide variety of fields. But the specialized needs for each field means that such information is required for a virtually endless number of systems and energies. For example, in astrophysics, the primary interest is in interactions between fully-stripped, low Z ions and low Z atoms or simple molecules whereas for atmospheric physics, the interest is in interactions between protons and dressed low Z ions and simple molecules. For plasmas, industrial uses primarily involve low- to medium-charged keV ions, in contrast, high-energy-density research studies use high energy highly-charged ions ranging from alpha particles to very heavy ions. For dosimetry and medical uses, knowledge about keV to MeV low Z ions interacting with bulk materials or biosystems is important. Information about inelastic interactions is also essential in the design and operation of high energy accelerators and storage rings. This means that the systems of interest range from Z = 1 to 92 for atoms, plus simple to complex molecules; the ion charge states range from -1 to Z, including 0; the energies range from a few keV to hundreds of MeV/u.

Since it is impractical, or impossible, to perform measurements or calculations for every system of interest, ever since the advent of atomic physics many scaling rules have been proposed with the overall goal to use one set of experimental data or theory and scale it to obtain information for any arbitrary system and energy. Scaling rules also enhance our understanding of the underlying interaction mechanisms. Probably the most notable scaling is the first Born approximation which, for single target ionization by energetic bare ions predicts that the cross sections scale as $(Z/v)^2$, where Z and v are the projectile charge and velocity, respectively. In practice, this familiar "Z^2 scaling" means that the cross section divided by Z^2 plotted versus v^2 should be the same for any bare ion impact. However, as illustrated in Fig. 1 using the CDW-EIS calculations of Fainstein et al. [1], Born scaling fails as Z/v increases, either due to an increase in Z or a decrease in v. For example, for single ionization of helium Z^2 scaling only works at energies above ~ 4 MeV/u for fully stripped oxygen, below ~300 keV/u it doesn't even work for He^{2+} impact. Based on data for electron loss by heavy, highly stripped ions Olson et al. [2] showed that a broader range of agreement can be obtained if both the cross sections and the impact velocities are divided by Z. This is shown in Figure 2. However, below a scaled energy of 100 keV/u/Z, significant differences still occur.

For scaling more complicated systems, namely collisions involving dressed projectiles, both the target and the projectile can be ionized. Using the Born

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approximation, Bates and Griffing [3] showed that for ionization of one of the collision partners, the bound electrons of the other act both passively (by partially screening their own nuclear charge) and actively (where they directly interact with electrons of the other). These passive and active roles are often referred to as the screening and antiscreening contributions. Bates and Griffing showed that the respective target/projectile cross sections scale as $[Z_{eff}^2 + N_{eff}]/v^2$, where for ionization of one of the collision partners Z_{eff} and N_{eff} are the partially screened nuclear charge and the number of active electrons of the other partner. However, the major difficulty in applying this scaling is in determining Z_{eff} and N_{eff}, as they depend on the collision velocity and the impact parameter plus, for target ionization, on the projectile charge state. Therefore, the typical technique used is to compare cross sections for dressed ion impact with those for bare ion impact. Doing so yields values for $Z_{effective}$, which is equal to the square root of the bracketed term above. The other difficulty is that again these scalings are based on perturbative theory. Therefore, this scaling also breaks down when Z/v becomes large. For projectile ionization, we recently showed [4] that adding a "saturation" term to the screening contribution was necessary for extremely large Z/v.

To shed some light on this problem, a recent collaborative effort between the Missouri University of Science and Technology and the Federal and Catholic Universities in Rio de Janeiro modelled projectile ionization in fast, heavy ion collisions with atoms [4]. The model that was developed yielded relatively good agreement with observed target Z and impact velocity dependences. We have now turned our attention to target ionization with the emphasis on both bare and dressed ion impact on a wide range of atomic and molecular targets and energies. In particular, we are interested in a simple model that will be applicable from approximately 10 keV/u to several MeV/u and for projectile charge states ranging from neutral to fully stripped. Here we present results from a portion of that work. The next section describes a new scaling law that is shown to work extremely well over the entire energy range for ionization of simple targets by fully-stripped and very high-charge-state ions. Future work will address dressed ion impact. Work is in progress to improve the scaling below the maximum.

NEW MODEL AND RESULTS

As seen in Figures 1 and 2, the ionization cross sections have similar shapes. However, identical horizontal and vertical shifts, as is done using the Olson et al. scaling procedure, do not yield a universal curve. Via trial and error, it was found that a modification of this scaling to Φ/Z^{2-n} and $(E/M)/Z^n$, with $n \sim 2/3$, removed the low-energy breakdown that is seen in Fig. 2. Note that our model preserves the overall scaling of $(Z/v)^2$, as must be the case at high energies. Fig. 3 compares our "modified Z" scaling applied to the CDW-EIS calculations of Fainstein et al. [1] and available experimental data [5-10]. For this comparison, cross sections for single ionization of helium are used. In almost all cases, the scaled data are compressed to a "universal curve" over the entire energy range.

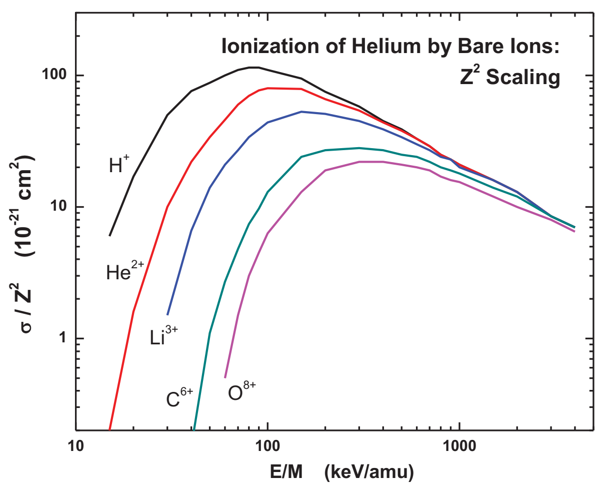

FIGURE 1. (color online) Z^2 scaling for single ionization of helium by fully stripped ions. The single ionization cross sections are divided by the square of the projectile charge. The cross sections are the CDW-EIS calculations of Fainstein et al. [1].

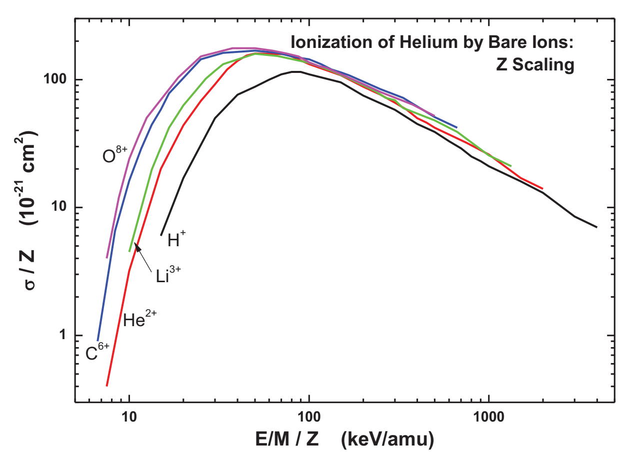

FIGURE 2. (color online) Z scaling for single ionization of helium by fully stripped ions. The single ionization cross sections and the impact energies are divided by the projectile charge. The cross sections are the same as in Fig. 1.

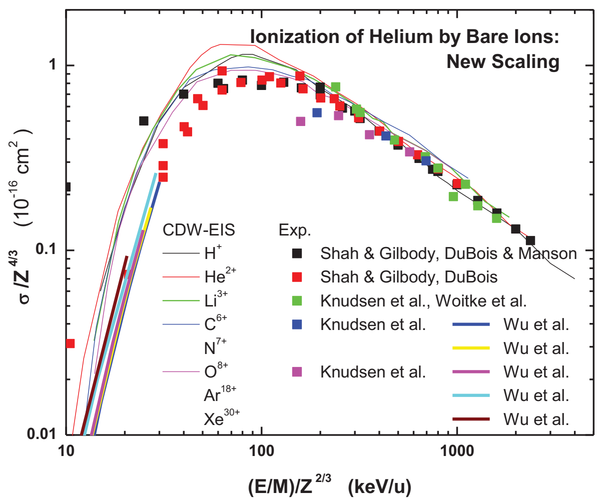

FIGURE 3. (color online) Our "modified Z" scaling for single ionization of helium by fully stripped ions. The single ionization cross sections are divided by $Z^{4/3}$ and the impact energies are divided $Z^{2/3}$. The thin solid lines are the CDW-EIS cross sections of Fainstein et al.[1]; the experimental data are from ref. 5-10.

As stated, initially this scaling and the value for n were found via trial and error. However, later it was noted that the scaling could be tested and the value for n be obtained by plotting $(E/M)_{max}$ and Φ_{max} versus Z, where $(E/M)_{max}$ and Φ_{max} are the energies and magnitudes at the cross section maximum. Doing so yielded fitted values of 0.88 for n and 1.09 for n-2. But, these values do not provide as good a compression of the data as that seen in Fig. 3. Additional tests showed that a slightly smaller value of n, namely 0.6, results in near perfect agreement for the various low-energy data of Wu et al. [10]. However, due to the similarity of our scaling and that proposed by Bohr [11], we have used n = 2/3.

Figure 4 shows the same scaling applied to ionization of molecular hydrogen by fully stripped ions [12]. Again the agreement is quite good except at the lowest energies. With regard to the very low energies, Wu et al. observed a similar behaviour. The reader is referred to their paper for details.

SUMMARY

A new "modified Z" scaling model for ionization has been presented. In was shown that by using an unequal division of the Z^2 scaling, namely where the cross section is scaled by $Z^{4/3}$ and the impact energy is scaled by $Z^{2/3}$, the breakdown of Z scaling at low impact energies is removed. This scaling is shown to work quite well for ionization of helium and H_2 by fully stripped and highly-charged ions which means it may be quite useful in plasma studies or for astrophysical purposes. The next step, currently in progress, is to apply this same scaling to dressed ion impact.

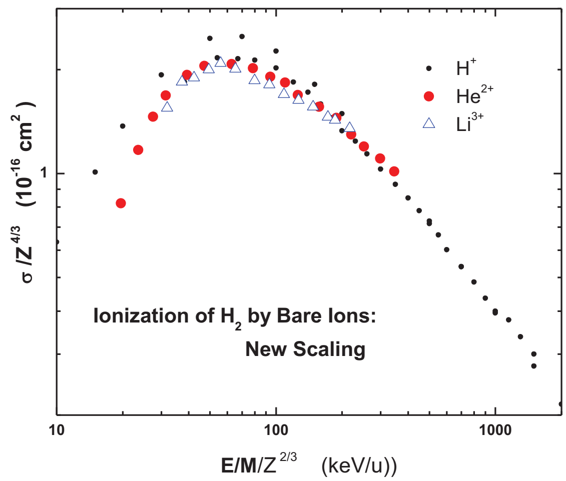

FIGURE 4. (color online) Our "modified Z" scaling for single ionization of molecular hydrogen by fully stripped ions. The single ionization cross sections are divided by $Z^{4/3}$ and the impact energies are divided $Z^{2/3}$. The experimental data are from ref. 12.

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