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SCALING OF CROSS SECTIONS IN ION-ATOM COLLISIONS

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Abstract:

Differential electron emission at 15° is investigated for 50-500 keV/amu hydrogen particles (H, H^+, H_2^+, H_3^+) impacting on He and H_2 targets. From ratios of cross sections relative to proton impact data, it is shown how bound projectile electrons influence the differential electron emission and where different ionization mechanisms are important. It is demonstrated that the H_2^+ and H_3^+ molecular ions interact as though they are composed of independent nuclei with the appropriate number of bound electrons, the electronic structure of the components appearing to be unimportant.

Introduction:

Investigations of how total and differential ionization cross sections scale as a function projectile charge can help identify the mechanisms by which atomic particles interact. For example, for fully stripped ion impact when first-order, perturbative coulomb forces dominate, both the total and differential target ionization cross sections increase quadraticly with the projectile charge. On the other hand, when strong interactions dominate, the cross sections increase at a slower rate or may not increase at all. In both cases, however, it is the coulomb force between the projectile nuclear charge and the target electrons which is important.

For dressed ion impact, new ionization channels are opened and the cross sections demonstrate a different scaling behavior. This is because the bound projectile electrons can either partially screen the projectile nuclear charge or they can interact directly with the target electrons. Screening reduces the coulomb force, and hence the cross sections, with respect to that for the fully stripped projectile. If the screening is complete and perturbative conditions are met, the cross sections would therefore scale quadraticly with the net projectile charge, q, where $q = Z - Ne$, Z being the nuclear charge and N the number of electrons having charge e. However, these scaling dependencies are modified when direct projectile electron-target electron interactions become important. Direct projectile electron-target electron interactions increases the cross sections with respect to the (partially) screened values.

A still different situation exists for molecular ion impact. In this case, the coulomb force exerted by the projectile is a combination of forces from individual nuclei which are bound together and surrounded by bound electrons in molecular orbitals. The question is whether the nuclei and bound electrons act in a coherent, or in an incoherent, manner as they interact with the target electrons. If they act incoherently, the cross sections should obey "additivity rules" which is not the case if they act coherently. Thus, for molecular ion impact, cross section scaling can provide information about how complex structures of particles interact.

Therefore, it is possible to obtain information about the dominant atomic interaction mechanisms by investigating scaling of total and differential ionization cross sections. Since differential cross sections are far more sensitive probes than are total cross sections, they can sometimes provide information that is "masked" in total cross section data. It is important to remember that there is also a pragmatic reason for investigating cross section scaling, namely to predict behavior outside the range of existing data.

Method:

Absolute doubly differential electron emission cross sections were measured for hydrogen particle, (H, H^+, H_2^+, and H_3^+), impact on helium and molecular hydrogen targets. The measurements were performed at an emission angle of 15° with respect to the beam direction in order to separate regions where projectile electron-target electron interactions, screening effects, projectile ionization, and binary collision effects are expected to be important. Impact energies ranged from 50 to 500 keV/amu. Electron emission energies ranged from 1 eV to energies above the binary encounter peak where the cross sections became immeasurably small. Experimental details are available in Ref. 1.

Results and Discussion:

An example of the data are shown in Fig. 1. The proton data exhibit the typical behavior for bare ion impact, namely a monotonic decrease in the cross section as a function of emitted electron kinetic energy with a pronounced binary encounter, BE, peak located at a position dictated by two-body kinematics. Above the BE peak the cross section rapidly decreases. For dressed ion impact, the major observable difference is that a broad peak is superimposed on a background similar to that for proton impact. This peak is due to electron emission from the projectile, e.g., the well-known electron-loss peak. Another difference, that of suppression of the dressed ion impact cross section with respect to a bare projectile, is observed for electron emission below the electron-loss peak, as shown by the atomic hydrogen impact data.

These features are more noticeable if we investigate ratios of cross sections rather than the cross sections themselves. Thus, in Fig. 2 the absolute cross sections for H, H_2^+, and H_3^+ impact were divided by those for proton impact. Comparing ratios of cross sections also tends to cancel experimental uncertainties associated with absolute target densities, solid angles, and electron detection efficiencies.

The electron-loss peak is again quite evident in these data. In addition, other mechanisms become apparent when we investigate the cross section scaling. Let us first consider dressed atomic ion impact, e.g., H impact. For this discussion, it is easier to visual the mechanisms if we speak about collision impact parameters rather emitted electron kinetic energies. The reader is reminded that low- and high-energy electron emission from the target implies distant and close collisions respectively and that projectile electrons are predominantly restricted between 100 and 700 eV (see Fig. 1) by kinematic reasons. With this in mind, the H data demonstrates that the bound projectile electron is ineffective in screening the projectile nuclear charge for close collisions, i.e., in the region of the BE peak, but is rather effective for intermediate distances, i.e., between 10 and 50 eV. Thus the cross sections for H and H^+ are the same in the BE region but the H cross section is smaller for low to intermediate electron energies. However, for very distant collisions, i.e., for very low-energy electron emission, the cross section does not decrease to zero as would be expected for complete screening by the bound electron because the direct projectile electron-target electron interaction mechanism becomes important in distant collisions. The importance of this mechanism is evidenced by the increasing ratio below 10 eV.

Similar features are seen for the molecular ion data. In addition, directing our attention to the BE region we note that the cross sections for H_2^+ are twice those for proton impact and for H_3^+ they are three times as large. This means that in close collisions the molecular ions interact as though their components are independent entities. Two decades ago Wilson and Toburen[2] observed this property in their study of H_2^+ - H_2 collisions. They also commented on the effects of screening as evidenced by the cross section ratios falling below these limiting values. The present data provide additional information, namely that direct projectile electron-target electron interactions are also important for molecular ion impact. From the data in Fig. 2 it appears that this mechanism increases the cross section from the asymptotic value of q^2, the net ionic charge squared, and that the increase is linearly proportion to the number of bound electrons, which means that the bound electrons also interact with the target in an incoherent manner. This explains the ratios of 2 and 3 for low energy electron emission induced by H_2^+ and H_3^+. That a limiting value of 1 is not observed for H impact could be explained if neutral particles require closer collisions in order to induce target ionization; hence the screening may not reach it limiting value of q. This, however, is merely supposition; additional investigations are required to investigate this feature.

As shown, in the BE region the molecular ions appear to interact as though they consist of independent nuclei. This implies that cross section "additivity" may be applied, i.e., that the cross section for H_2^+ may be approximated by the sum of the cross sections for H^+ and H. Likewise the cross section for H_3^+ may be approximated by the sum of the cross sections ($H^+ + H_2^+$) or ($H + H + H^+$). These comparisons are shown in Fig. 3. Remarkably good agreement is demonstrated throughout the entire spectrum. Similar agreement was found at lower impact energies and for a molecular hydrogen target.

Conclusions:

Cross section scaling was investigated for hydrogen particle impact on helium and molecular hydrogen. From ratios of cross sections for dressed hydrogen particles, relative to proton impact data, it was shown how bound projectile electrons influence the differential electron emission and where different ionization mechanisms are important. For H_2^+ and H_3^+ impact, it was demonstrated that molecular ions interact as though they are composed of independent nuclei with the appropriate number of bound electrons. The electronic structure of the components appears to be unimportant. This implies that cross section "additivity" can be used to simulate interactions between energetic molecular particles.

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References:

1. R.D. DuBois, Phys Rev. A 48, 1123 (1993).
2. W.E. Wilson and L.H. Toburen, Phys Rev A 7, 1535 (1973).

Figure Captions:

Fig. 1. Absolute doubly differential cross sections for hydrogen particles impacting on helium. The electron emission angle is 15° and the impact energy is 500 keV/amu.

Fig. 2. Doubly differential cross section ratios for hydrogen particle impact on helium.

Fig. 3. A comparison of cross sections measured for H_2^+ and H_3^+ impact with those obtained by incoherently adding the cross sections of the components of the molecular ions. See text for details. Note that the H_2^+ data have been shifted by an order of magnitude for display purposes.

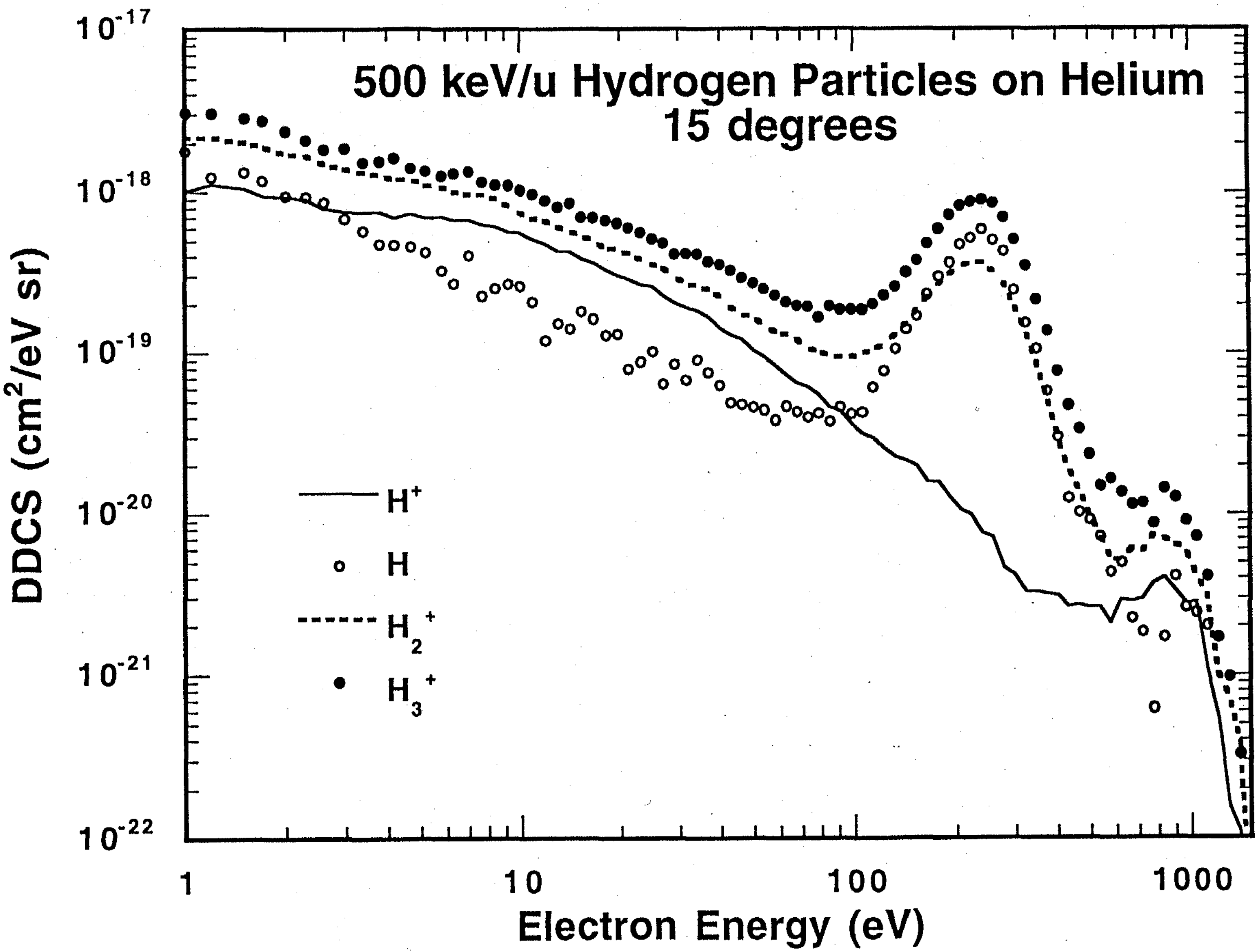

500 keV/u Hydrogen Particles on Helium
15 degrees
DDCS (cm²/eV sr)
Electron Energy (eV)
H⁺
H
H₂⁺
H₃⁺
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
10⁻²⁰
10⁻²¹
10⁻²²
1
10
100
1000

Fig. 1

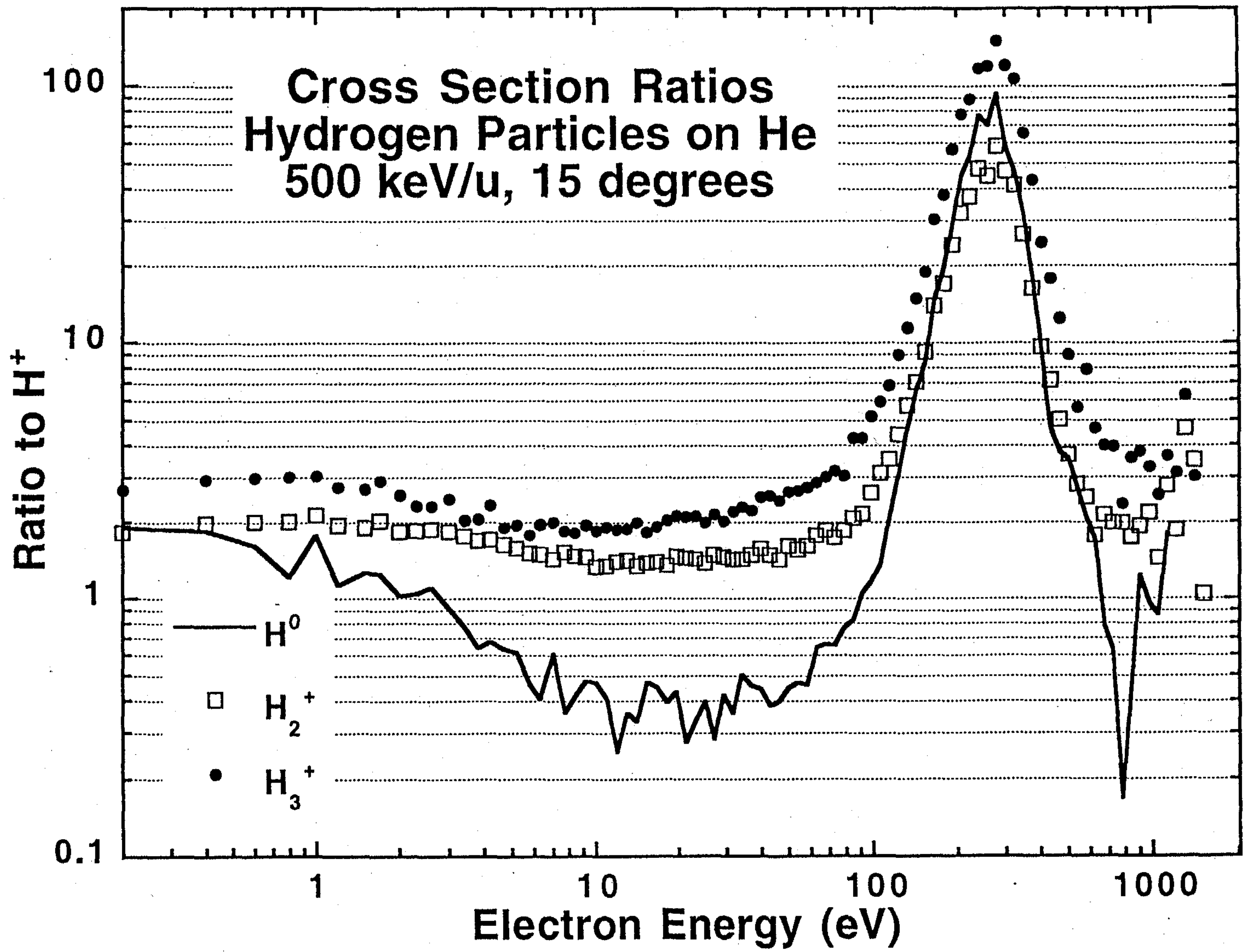
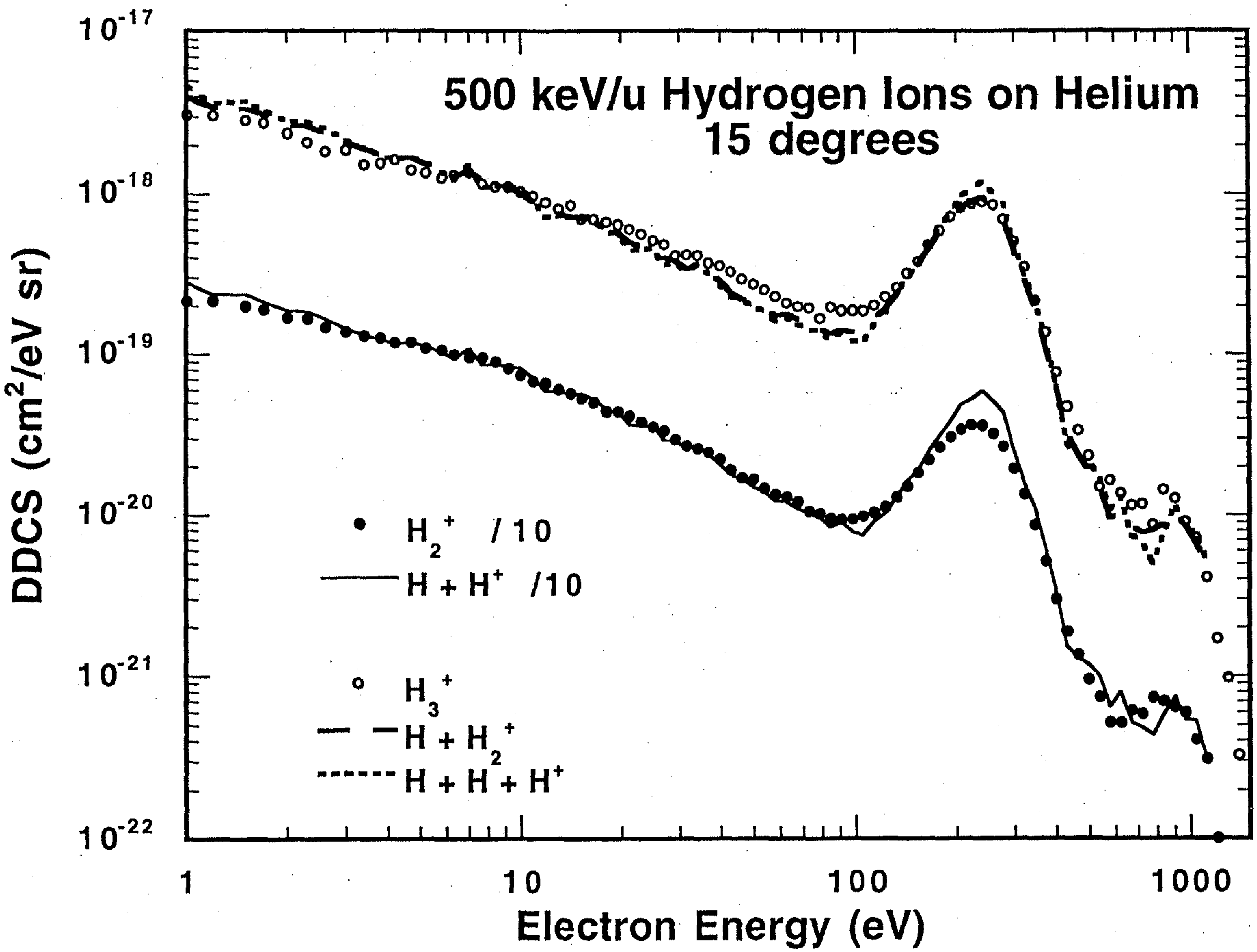

Cross Section Ratios
Hydrogen Particles on He
500 keV/u, 15 degrees
Ratio to H+
Electron Energy (eV)
100
10
1
0.1
1
10
100
1000
H0
H2+
H3+

Fig. 2



500 keV/u Hydrogen Ions on Helium
15 degrees
DDCS (cm²/eV sr)
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
10⁻²⁰
10⁻²¹
10⁻²²
1
10
100
1000
Electron Energy (eV)
H₂⁺ /10
H + H⁺ /10
H₃⁺
H + H₂⁺
H + H + H⁺

Fig. 3