A.4.2. One- and Two-Electron Processes in Ion-Hydrogen Molecule Collisions--*E. Wells, K.D. Carnes, Vidhya Krishnamurthi, D. Studanski* and I. Ben-Itzhak*

In collaboration with H. Knudsen, Institute of Physics and Astronomy, University of Århus, DK-8000 Århus C, Denmark.

We continued our studies of one- and two-electron processes initiated in hydrogen molecules by ion impact. These studies complement similar studies conducted on helium atoms. Of particular interest is the dependence of the ratios of the two-electron process to the single-electron process on projectile velocity and charge. The double to single ionization (DI to SI) ratio for helium has been the subject of many theoretical and experimental studies (see, for example [1-4]). Similar studies on molecular hydrogen can be performed either by measuring the same ratio (DI to SI) or by measuring the ratio of ionization-excitation (IE) to single ionization (SI). In the latter one takes advantage of the fact that all the electronically excited states of H_2^+ are dissociative within the Franck-Condon region (see, for example, [5-7]). We have studied in the past the velocity dependence of the IE to SI ratio using fast proton impact ionization and have tried to determine its behavior at high velocities [5].

In recent years we have studied the velocity dependence of the DI to SI ratio and the charge dependence at a fixed velocity of both the DI to SI and IE to SI ratios using similar experimental techniques. The measurement of the double ionization of the hydrogen molecule is more complicated than that of the atomic helium target due to the large kinetic energy release upon dissociation. We used the coincidence time-of-flight technique and identified the double ionization events by a $H^+ + D^+$ coincidence. To improve the accuracy of the measurements we used the HD isotope, thus increasing the time difference between the H^+ and D^+ fragments [8]. Some of the measurements were conducted and reported in the previous grant period, additional data have been collected and analyzed since, and some models were invoked to interpret the data.

The velocity dependence of the DI to SI ratio for fast proton impact ionization of HD is shown in Fig. 1, where it is also compared to measurements of fast proton and electron impact ionization by Edwards *et al.* [6], and electron impact ionization by Kossmann *et al*. [9]. The data were also fitted to the velocity dependence

$$R = a_0 + a_1 \frac{q}{v} + a_2 \left(\frac{q}{v} \right)^2 , \qquad (1)$$

suggested by McGuire [2] to explain the difference between positive and negative charge at the same velocity. The *q/v* term causes electron impact ionization to be more effective because a_1 is negative, as can be seen from the fit.

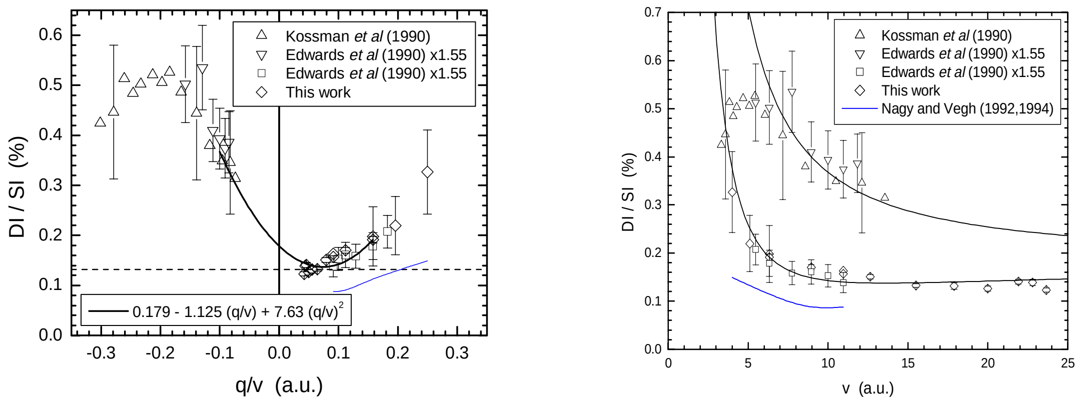

Figure 1. The measured ratio of double to single ionization of hydrogen molecules bombarded by fast protons (squares and diamonds) and electrons (triangles) as a function of *q/v* (**left**) and *v* (**right**). The thick solid line through the points is the fit of Eq. (1), while the thin line is from the calculated ionization cross sections by Nagy and Vegh [10,11].

We also show in the figure the ratio evaluated from the theoretical single and double ionization cross sections computed by Nagy and Vegh [10,11]. This theoretical prediction underestimates the ratio by almost a factor of two.

The high velocity limit of this ratio was extrapolated to be about 0.18±0.02%, which is about 2/3 of the same ratio in He [12]. We have also shown that the difference between the two targets is mainly due to a large difference in the single ionization cross sections while double ionization by fast protons is roughly equal for both targets [Publication #14]. We have suggested that this difference in single ionization stems from the lower binding energy in the molecular target.

In addition to the studies of the DI to SI ratio as a function of the proton velocity we measured the dependence of this ratio and the IE to SI ratio on the projectile charge at a fixed high velocity of 6.3 a.u. (1 MeV/amu) [Publications #3, 4, 83]. These ratios are shown in Fig. 2 as a function of projectile charge.

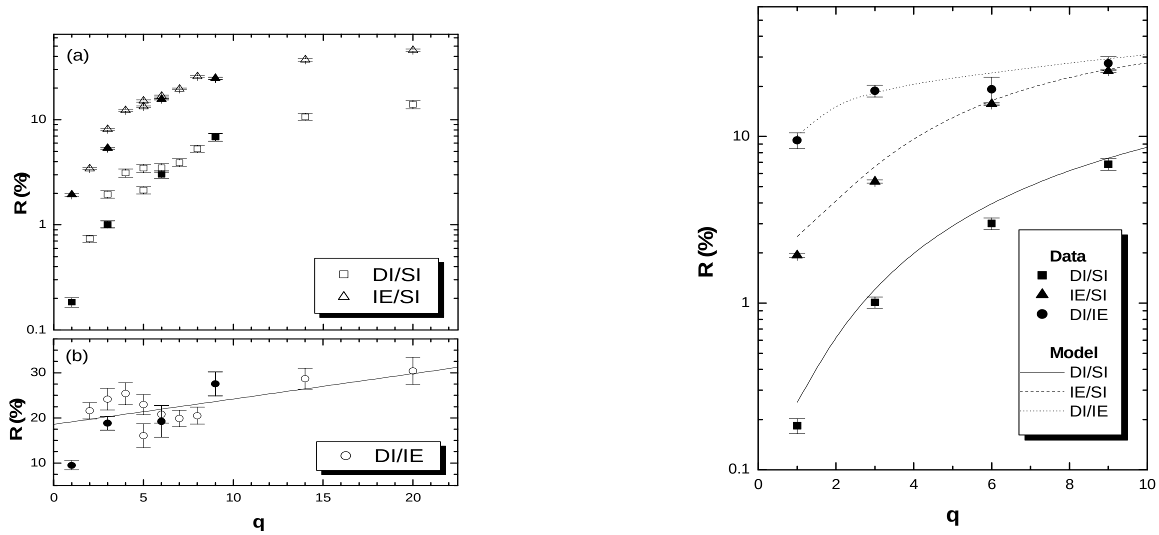

Figure 2. Left: The measured ratio of (a) DI to SI, IE to SI, and (b) DI to IE as a function of projectile charge. **Right:** The same ratios for bare projectile impact in comparison to our model calculations [Publication #83].

A model based on the independent electron approximation was derived [Publication #83] to interpret the data for bare projectiles, shown in Fig. 2. The active electron ionization and excitation probabilities are assumed to fall exponentially with increasing impact parameter, and their constants are found from the proton impact data. This model is similar to the model used to interpret the measurements of multiple ionization of CO in similar collisions [Publication #13]. In this case, however, it was crucial to include the e-e mechanism for double ionization. This mechanism was important only for the low-charge ions at the collision velocity under study.

References

*REU student.

1. H. Knudsen and J.F. Reading, Phys. Rep. 212, 107 (1992).
2. J.H. McGuire, Phys. Rev. Lett. 49, 1153 (1982).
3. J.H. McGuire, N. Berrah, R.J. Bertlett, J.A.R. Samson, J.A. Tanis, C.L. Cocke, and A.S. Schlachter, J. Phys. B 8, 913 (1995).
4. J. Ullrich, R. Moshammer, H. Berg, R. Mann, H. Tawara, R. Dörner, J. Euler, H. Schmidt-Böcking, S. Hagmann, C.L. Cocke, M. Unverzagt, S. Lencinas, and V. Mergel, Phys. Rev. Lett. 71, 1697 (1993).
5. I. Ben-Itzhak, Vidhya Krishnamurthi, K.D. Carnes, H. Aliabadi, H. Knudsen, U. Mikkelsen, and B.D. Esry, J. Phys. B 29, L21 (1996).

6. A.K. Edwards, R.M. Wood, A.S. Beard, and R.L. Ezell, Phys. Rev. A 42, 1367 (1990), *ibid*., 44, 797 (1991).
7. E. Krishnakumar and S.K. Srivastava, J. Phys. B 27, L251 (1994).
8. I. Ben-Itzhak I, Vidhya Krishnamurthi, K.D. Carnes, H. Aliabadi, H. Knudsen, and U. Mikkelsen, Nucl. Instrum. And Meth. 99, 104 (1995).
9. H. Kossmann, O. Schwarzkopf, and V. Schmidt, J. Phys. B 23, 301 (1990).
10. L. Nagy and L. Vegh, Phys. Rev. A 46, 284 (1992).
11. L. Nagy and L. Vegh, Phys. Rev. A 50, 3984 (1994).
12. I. Ben-Itzhak, E. Wells, D. Studanski, Vidhya Krishnamurthi, K.D. Carnes, and H. Knudsen, to be submitted to J. Phys. B.