

# ELECTRON COLLISIONS – PAST, PRESENT AND FUTURE.

J.W.McCONKEY.

*Department of Physics, University of Windsor, Ontario N9B 3P4, Canada.*

## **Abstract**

After broadly surveying the field of electron collisions over the past century and giving some of the highlights which have driven the field, the topic of electron spectroscopy is considered and its development outlined. As an example of current research, measurements of Cs cross sections in a magneto-optical trap are discussed in detail. Suggestions are given regarding possible future directions in the field.

## **Introduction.**

Electron-driven processes abound in practically every area of our experience. Electrons deposited from the solar wind, or released by solar photoionization, interact with upper atmosphere atoms and molecules to produce familiar auroral and airglow effects. At lower altitudes, lightning storms provide vivid illustrations of how electrons create powerful, natural releases of electrostatic energy. Missions such as Voyager and Galileo have revealed that electron collisions are important also in the atmospheres of other planets in our solar system, while the plasmas which abound in the deep space environment send a wealth of spectroscopic and other information to planet earth, much of which is electron driven. It is of interest to recall that it was in an attempt to explain the plasma, which resulted when an electric current was passed through a low pressure gas, that the electron was actually discovered (by J J Thomson in 1897).

Everywhere an electrical discharge is initiated, whether it is in a fluorescent light fixture or a flat panel display system, a tokamak high current thermonuclear device or a high powered, laser-inertial-confinement device, we find examples of where high technology industry is putting electrons to work for our benefit. Electron driven discharges are essential components of Plasma-Enhanced Chemical Vapour Deposition (PECVD) and Plasma-etching technologies that are vital for the manufacture of micro-electronic components and devices. Plasmas are also used for safe destruction and disposal of toxic wastes (Becker *et al*, 2000).

Another area where electron-driven processes are of importance is in the field of radiation damage. When high-energy radiation, such as X-rays or  $\gamma$ -rays, enters the body, low energy secondary electrons are produced, which interact strongly, and often destructively, with biological material. Boudaiffa *et al* (2000) and Martin *et al*

(2004) have shown that dissociative attachment of low energy electrons can lead to both single and double strand-breaking processes in DNA.

Recently, studies of the interaction of ultra-short, high-intensity laser pulses with atoms and molecules have produced startling effects in which the interaction of the electron with the radiation field of the laser plays a dominant role (see e.g. Niikura *et al* (2003), Weckenbrock *et al* (2003)).

Comprehensive discussions on electron-atom (molecule) collision physics can be found in the books of Massey and Burhop (1969), Massey *et al* (1969), McDaniel (1989) and in the volumes of *Advances in Atomic and Molecular (since 1990 Atomic, Molecular and Optical) Physics*. Recent reviews on various aspects of the topic are those of Brunger and Buckman (2002), [electron-molecule cross sections], Surko *et al* (2005), [positron interactions], Hotop *et al* (2003), [low energy electron molecule collisions], Christophorou and Olthoff (2001), [interactions with excited targets], Andersen and Bartschat (2001) [alignment and orientation effects], and Zecca *et al* (1996, 2001), [integral cross sections]. We note the special data publications of relevance to the plasma science community, Christophorou and Olthoff (2001a), Kimura and Itikawa (2001) and Inokuti (2000). The latest developments are usually published in *Physical Review A*, *Journal of Physics B*, *Journal of Chemical Physics* and *Journal of Physical and Chemical Reference Data*. The main forum for presenting results at the cutting edge of the field is the biannual International Conference on Photonic, Electronic and Atomic Collisions (ICPEAC). About one third of the papers presented at this conference are related to lepton collision research. This fraction has stayed approximately constant over the past 45 years. It is noteworthy that four of the five satellite meetings to this conference are partially or totally devoted to lepton collisions.

### **Surveying the Past - Historical Highlights.**

Over the past century of electron collisions, it is possible to highlight many major advances and discoveries. Some of the more significant are listed below. Detailed references may be obtained from the books listed in the previous paragraphs.

- 1903. First electron scattering experiment (Lenard).
- 1914. Franck-Hertz experiment. Birth of electron energy-loss spectroscopy.
- 1921. Discovery of Ramsauer-Townsend effect.
- 1925. Electron spin proposed (Uhlenbeck and Goudsmit)
- 1927. Dirac Equation. - Electron spin, magnetic moment, anti-particle.
- 1927. Electron wave effects. Interference and Diffraction phenomena.  
(Davisson & Germer, G P Thomson).

- 1922-30. Early attempts at cross-beam measurements.  
 1927-36. Total ionization X-section measurements with static gas targets.  
 1930-2005. Continuous development of theoretical methods and models.  
 1932. Positron Discovered. (Anderson).  
 1954-63. Development of electrostatic energy analysers, 127° & 180°.  
 1957-2005. H-atom used as test bed. (Fite, Williams, ....)  
 1957-62. Introduction of modern cross-beam methods.  
 1963. First resonance (He, 19.37eV) in electron scattering discovered (Schulz)  
 1969. Complete scattering experiments proposed (Bederson)  
 1969. First e-2e experiments. (Ehrhardt, Amaldi).  
 1970. First experiments involving excited targets.  
 1971-3. First e-hv coincidence work yielding atomic alignment and orientation.  
 1980. Development of high intensity spin-polarized electron beams.  
 1987. Development of EBIT machine for electron-ion interactions, (Levine, Marrs)  
 1987. Development of COLTRIMS technique for complete momentum imaging of collision fragments, (Schmidt-Bocking, Cocke, Ullrich).  
 1987. Development of ELECTRON COOLERS in ion storage rings for high-resolution recombination studies, (Danared et al).  
 1988. Introduction of "natural" parameters to define excited states (Andersen et al)  
 1992. Sub-meV resolution achieved for first time in gas phase (Hotop).  
 1995. MOTs used for e-collisions for first time (Lin).

In many cases the field was driven by technological advances which stimulated a need for quantitative electron collision data or the development of electron optical devices. This has been ongoing since Lee de Forest invented the first vacuum tube amplifier in 1906. Since about 1930 the development of Fluorescent Lamps and other forms of lighting, has provided a continual stimulus for electron collision measurements. World War II stimulated the development of microwave technology, semi-conductors, and digital computers, while a short time later in 1947 the transistor was invented. The 1950s saw the development of the Maser and the declassification (in 1958) of high-current (thermonuclear) plasma research. The 1960s and 70s saw the invention of various types of gas lasers which fuelled a need for understanding the processes involved, many of which involved electron impact in a plasma environment. The 1970s and 80s saw many successful missions to study the environments of other planets in our solar system. Huge bodies of data were accumulated which demanded accurate electron cross section data to aid interpretation of the processes involved. 1984 saw the development of the Plasma-Enhanced Chemical Vapour Deposition (PECVD) process and this was followed in 1992 by the development of Plasma Etching technology. Both of these are important in the manufacture of microelectronics components and devices. Again a wide body of electron collision data are required for device optimization. Research into thermo-nuclear plasmas has continued steadily over the past 50 years with a steady demand for collision related data. This demand will continue for the next

few decades as the building and commissioning of the International ITER machine gets under way in 2005. The last decade has seen enormous strides in photonics development so that it rivals or exceeds electronics in technological importance.

### ***Electron Spectroscopy – Birth and Development.***

The field of electron collisions has depended on the development of suitable measurement technology or, in the case of theory, of computational power. One of the key developments on the experimental side was in the area of electron energy loss spectroscopy. It is interesting to consider the earliest experiment in this field [Franck and Hertz, (1914)], because it was not until many decades later that the results were fully understood. The experiment was very simple in principle. Electrons were accelerated through a low pressure mercury gas towards a grid. On the other side of the grid was a collector biased slightly negatively relative to the grid. The current to the collector was monitored as a function of the accelerating potential between the electron source and the grid. If an electron lost energy, for example in an inelastic collision with a mercury atom, it could not overcome the negative bias, reach the collector and be measured. The result of the experiment was a series of peaks on the current-voltage graph. The peaks were separated by approximately 4.9 V. The experiment was interpreted (correctly) as demonstrating the existence of energy levels in the mercury atom with an excitation energy of approximately 5 eV. The experiment was a key to development of early ideas about atomic structure.

As the spectroscopy of the mercury atom unfolded in subsequent years, it was established that there were indeed some energy levels with an excitation energy of around 5 eV. However these levels were designated  $6^3P_{0,1,2}$  whereas the ground state was  $6^1S_0$ . Excitation of a triplet level from the ground state necessitated an exchange process in which a projectile electron took the place of a target electron of opposite spin. It was some 60 years after the original experiment that Kessler, Hanne and colleagues at Munster did an experiment with spin polarized electrons to demonstrate that such an exchange process did indeed take place. Also, using a combination of sophisticated experimental and theoretical tools, they established the magnitude and near threshold variation of the excitation cross sections of the individual  $6^3P_{0,1,2}$  states with incident electron energy. A number of important facts became evident. First, the  $^3P_0$  cross section was very small. This explained why the peaks in the Franck-Hertz experiment were not separated by 4.7 eV (the  $^3P_0$  excitation energy). Second, the  $^3P_1$  excitation cross section was dominated by a strong resonance enhancement right at its 4.9 eV threshold. Thus the reason why the Franck-Hertz experiment worked so dramatically was because of a phenomenon which was not discovered until some 60 years later!

Little progress in improving the resolution of energy loss spectroscopy occurred until mid-20<sup>th</sup> century when a surge of development work occurred leading to the so-called 127<sup>o</sup> cylindrical, the 180<sup>o</sup> hemispherical and various other analysers [see e.g. McDaniel (1989) for details]. Energy resolutions of 50 meV were readily obtained and this figure was rapidly reduced to below 10 meV as the century progressed. The current state of the art in gas-phase electron spectroscopy is probably represented by Allan (2004) with resolutions as low as 7 meV. Allan's instrument incorporates a Wien filter to allow discrimination between electrons and negative ions and also a magnetic angle changing device [Read and Channing, (1996)] that allows the backscattering region to be accessed and thus differential cross sections to be measured over the entire angular range. Incident energies in the tens of meV are routinely possible. Use of laser photoionization techniques have enabled electron sources of very narrow energy spreads to be achieved and electron attachment studies to be carried out at sub meV resolutions, [see Hotop *et al*, (2003) for details and references].

In parallel with all the experimental advances in instrumentation and techniques, there have been equally impressive developments in theoretical methods. These are highlighted in the cited reviews and in many of the invited presentations at this Conference. The interplay between experiment and theory is demonstrated in the many publications which deal with both the experimental and theoretical aspects of the particular scattering problem under consideration. These close collaborations bode well for the future health and development of the field.

### **Case Study from the Present – Measuring Electron Cross Sections in MOTs.**

Use of MOTs for collision cross section determinations is based on very similar ideas to those present in the atomic beam experiments carried out at NYU in the 1960s. Rubin *et al* (1960) pioneered the use of the so-called “atomic beam recoil” technique for measuring electron scattering cross sections and Visconti *et al* (1970) applied it in a systematic study of the total cross sections for electron scattering from the alkalis. Lin and co-workers at the University of Wisconsin recognised that the sensitivity of the atom recoil technique could be greatly enhanced if optically trapped atoms rather than an atomic beam were used as the target. In a series of elegant, pioneering papers [Schappe *et al*, 1995, 1996, Keeler *et al*, 2000], they presented measurements of both total and ionization cross sections from ground state rubidium and also ionization cross sections out of the 5<sup>2</sup>P excited state of this atom.

The alkalis are particularly suitable for measurements using a MOT because of the availability of suitable diode lasers matching the wavelengths of the resonance transitions of these species. Further, because the act of trapping results in the preparation of a target with a large fraction of excited species, it is possible (as

demonstrated by Keeler *et al*, 2000) to obtain absolute cross section data involving these excited species. Interest in such data is intense, particularly from the plasma physics and industrial communities. Cesium is perhaps the most interesting alkali target because of its use in atomic clocks and in studies of thermo-ionic conversion in plasmas [Kuehn *et al*, 1978]. Further, being the heaviest of the alkalis, Cesium is also of great interest from a theoretical point of view because relativistic and atomic structure effects should be strong. In addition, significant disagreements existed between experimental measurements and between experiment and available theory, (see Zecca *et al*, (1996)).

### ***Principle of Method.***

When a collection of trapped atoms is irradiated by a beam of electrons and collisions occur, momentum is transferred to the atoms causing them to be ejected from the trap. Atoms are ejected from the trap due to the electron-atom collisions at a rate:

$$\Gamma_e = \sigma J / e \quad (1)$$

where  $\sigma$  is the cross section for ejecting atoms from the trap,  $J$  is the electron current density and  $e$  the electronic charge. Measurements of  $\Gamma_e$  and  $J$  yield  $\sigma$  directly. For very small scattering angles where the transfer of momentum in the collision is below some limiting value, the collision will not be violent enough to remove the atom from the trap. Calculations show that for our system (laser beam diameter, timing sequence etc) with elastically scattered electrons of 5 eV energy, electrons scattered at angles smaller than about  $5^\circ$  will not impart enough momentum to eject atoms from the trap. This is a negligible portion of the total solid angle. At higher impact energies the ranges of low angle scattering, which result in no contribution to the loss of atoms from the trap, become even smaller.

### ***Experimental Considerations.***

These have been outlined in detail in publications from our group, MacAskill *et al* (2002), Lukomski *et al* (2005) and so will only be briefly summarized here. We note also that a comprehensive review of the various techniques needed for measuring different types of cross sections using MOTs is available [Schappe *et al*, 2002]. The MOT is of a standard design except the anti-Helmholtz pair of coils, providing the magnetic trapping field, is positioned inside the ultra high vacuum vessel. They provide an axial field gradient of approximately 10 G/cm for an operating current of 2A. A specially designed pulsing circuit is used with these coils to allow the current to be switched rapidly by a TTL signal. This circuit also provides a means of rapidly dissipating the coil current to minimize the decay time of the magnetic field during switching.

The optical set-up for laser cooling of the atoms is standard so the reader is referred to our earlier publications for details. The atom cloud was monitored using two infra-red sensitive cameras positioned in the same, horizontal, plane. This allowed accurate monitoring of the position of the atom cloud which was vital in insuring proper overlap of the electron beam with the trapped atoms.

The multi-element electron gun was designed to produce a broad near-parallel beam in the 5-400eV electron energy range. An oxide coated cathode was used and two pairs of electrostatic deflectors allowed accurate control and steering of the electron beam. Since accurate knowledge of the current density in the region of the MOT was necessary, two movable, 0.010" diameter, wire probes were arranged so that the electron beam profile could be monitored in two dimensions in a plane perpendicular to the e-beam direction. After scanning the e-beam diameter the wire probes could be retracted so that they did not interfere with the trapping laser beams. At each electron energy the gun controls were optimized so that the two measured diameters were as similar as possible. The measured profiles were then compared with a theoretical model where uniform density over the cross-sectional area of the beam was assumed. Good agreement between the measured and theoretical profiles was always obtained.

A Faraday Cup system was used to monitor the total beam current. From the measurements of e-beam profile (discussed in the previous paragraph) and total beam current, the current density,  $J$ , (Equation 1), in the region of the atom cloud, was obtained. The MOT trapped atom fluorescence is collected and monitored continuously using a cooled EMI 9558 photomultiplier (PM) tube. The analogue output of the PM is digitized and monitored using a multichannel scaling plug-in card in the control computer. Thus the time variation of the trap fluorescence was recorded and displayed.

Since it is not possible to introduce the electron beam while the trapping magnetic field is on, the experiment proceeds in a pulsed mode. The timing sequence for this is as follows. First the trap is turned off for a time,  $T_B$ , (typically 20 msec) by switching off the magnetic field and the re-pumping laser. During alternate trap-off times an electron beam pulse is introduced for a time,  $T_e$  (typically 8 msec) after a delay  $\tau_e$  (1 msec). Trap fluorescence is monitored continuously with alternate cycles being stored in separate memories. The time evolution of the trap fluorescence, both with and without the presence of the electron beam pulse, is obtained and processed as discussed later.

All of the measurements presented here are determined by recording two fluorescence signals. The first is measured in the absence of the electron beam pulse, and is necessary to establish a net background loss rate. This background loss rate is a combination of factors including thermal expansion, inelastic collisions

within the trap, gravitational acceleration, time-varying magnetic fields that occur during switching, and collisions with vacuum residuals. The second signal is measured in the presence of the electron beam pulse, and displays a larger loss rate that includes the net background losses, mentioned earlier, and also losses due to electron collisions. These fluorescence signals are measured sequentially. This ensures consistency in trapping parameters during data collection and minimizes longer term variations in background fluorescence, electron beam current, laser intensity and frequency detuning. Since, in this work, we are interested in cross sections involving ground state Cs atoms, the re-pumping laser is switched off prior to the introduction of the electron beam. Rapid optical pumping to a dark hyperfine level of the ground state occurs immediately, thus ensuring a total ground state target.

### *Data Analysis*

During continuous operation of the trap, in the absence of an electron beam, the steady state trap population is given by:

$$\frac{dN}{dt} = L - \Gamma_0 N \quad (2)$$

for a loading rate  $L$  from the atomic vapor, and a loss rate  $\Gamma_0$  which takes into account various trap loss mechanisms including inelastic collisions within the trap and collisions with vacuum residuals. Eliminating the trapping magnetic field or the output from either laser, effectively removes any loading and so the term is dropped from the differential equation leaving:

$$\frac{dN}{dt} = -\Gamma_0 N \quad (3)$$

In the presence of an electron beam, the loss rate is altered to  $\Gamma = \Gamma_0 + \Gamma_e$ , where  $\Gamma_e$  is the loss rate due to electronic collisions, presented in Eqn.(1). From this, we obtain the following equations describing trap populations:

$$N(t) = N_0 e^{-\Gamma_0 t} \quad (4a)$$

$$\tilde{N}(t) = \tilde{N}_0 e^{-(\Gamma_0 + \Gamma_e)t} \quad (4b)$$

where  $N(t)$  describes the trap population as a function of time in the absence of an electron beam, and  $\tilde{N}(t)$  describes populations in the presence of an electron beam.

To isolate the electron induced trap loss rate one takes the ratio of these two equations obtaining:

$$\frac{N(t)}{\tilde{N}(t)} = \frac{N_0}{\tilde{N}_0} e^{\Gamma_e t} \quad (5)$$

Due to the long 500ms time period of our pulsing scheme, the steady state populations with and without the electron beam are the same and, consequently,  $N_0 / \tilde{N}_0 \cong 1$ . As the electron beam is present for a time  $T_e$ , the loss rate is obtained directly from:

$$\ln\left(\frac{N(T_e)}{\tilde{N}(T_e)}\right) = \Gamma_e T_e \quad (6)$$

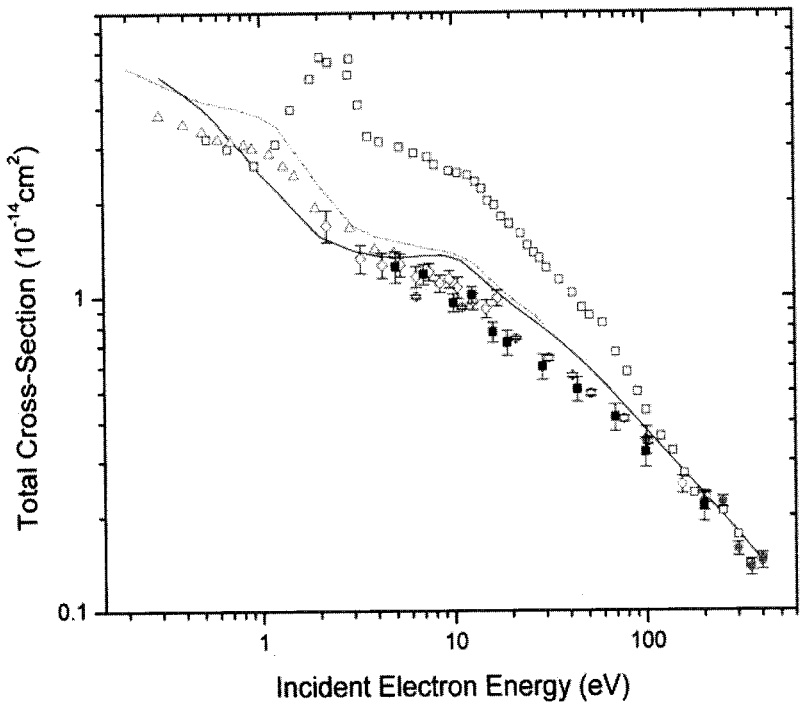
In this work the cross section for ground state ( $6^2S_{1/2}$ ) Cs is measured using the fluorescence during the *reloading* phase. As the re-pumping laser must be off while the electron beam is pulsed on to ensure only the  $6^2S_{1/2}$  state is populated, the trap is “dark” during the expansion phase. Following the removal of the re-pumping laser, the trap ceases to fluoresce in approximately 0.5 ms. While the actual response of the trap is not directly observable during the electron interaction time, the effect is reflected in the net difference of the trap populations during the initial reloading. The difference in the fluorescence, observed at the beginning of the reloading phases for the electron beam off and on, is due solely to the electron collisions that occurred during the expansion phase. We note that for each measurement, evaluation of any background fluorescence (from untrapped atoms or scattered laser light) had to be carried out. This was obtained by repeating the measurements using the same timing sequence as before but with the trapping magnetic field permanently off. By subtracting the resultant background signal we obtain the fluorescence yield due only to the population of trapped atoms.

### **Results and Discussion.**

The figure gives our experimental data for the total cross section out of the Cs  $6^2S_{1/2}$  ground state. Also included are data sets from earlier work. A number of points are immediately evident. Very good agreement exists between all the high-energy experimental results, (even those of Brode, 1929) above 100 eV. Below 100 eV Brode’s data are clearly spurious. Our data agree very well with those of Surdutovich *et al* (2004) over the entire energy range covered by both data sets. Agreement with the early data of Jaduszliwer and Chan (1992) in the region below 20 eV is also very good.

With the convergence of the experimental results obtained using three very different techniques, it is possible to assess the accuracy of the calculations. The figure suggests that although the CCC calculations yield accurate data at the higher energies, this is not the case as the energy is reduced below 75 eV. Divergence from

experiment continues down to at least 5 eV. The Breit-Pauli R-Matrix calculations of Bartschat (1993, 2000) and, particularly the CCC results, MacAskill *et al.*, (2002), indicate a “shoulder” in the cross section at around 10 eV. This feature is largely absent from the experimental data. Below 9 eV the two theoretical curves diverge from one another. Some of this divergence is possibly due to structure differences or inner shell effects. It is an unavoidable fact that with increasing complexity of the target, the structure approximations become of increasing importance relative to the scattering approximations.



**Figure 1.** Measured and calculated Cs total cross sections as a function of electron energy. Open squares, Brode (1929); open triangles, Visconti *et al.*, (1970); open diamonds, Jaduszliwer and Chan, (1992); open circles, Surdutovich *et al.*, (2004); solid circles, MacAskill *et al.*, (2002); solid squares, Present Work; solid line, CCC theory, MacAskill *et al.*, (2002); dashed line, RMPS theory, Bartschat (1993, 2000).

Bartschat (private communication, 2005) has calculated values for the main contributions to the total cross section as a function of energy. From these data the following facts are evident. Below approximately 7 eV, elastic scattering provides the largest contribution to the total cross section. Above that energy, excitation of the 6p levels quickly dominate with smaller contributions from excitation of 5d and other discrete levels and from ionization. The presence of the “shoulder” in the theoretical data in the region of 10 eV is due largely to a broad maximum in the 6p cross section near that energy with an additional, smaller, contribution from elastic scattering. Bartschat’s calculations of the 6p cross section are in quite good agreement with the measurements of Chan and Gallagher (1978) in the 10-30 eV region. Thus the observed differences between theory and experiment for the total cross section near 10 eV are most likely due to an over estimation of the calculated elastic scattering contribution.

### *Excited state data.*

Using a laser configuration in which both trapping and re-pumping lasers are on continuously it is possible to obtain an optical molasses in which a substantial fraction (~30%) of the atoms are in the excited  $6^2P$  state. Further, by choosing a timing sequence for the magnetic field and the electron beam pulses such that atoms which have suffered collisions are normally re-trapped, it is possible to isolate ionizing collisions where no re-trapping is possible. We have made preliminary measurements of ionization out of the  $6^2P$  state over the energy range from 5 to 400eV and find that the excited state cross section is 2-5 times larger than the ground state ionization cross section for energies greater than 30 eV. Below that energy the ratio increases rapidly due to the lower threshold energy for ionization out of the excited state. Full details of these measurements will be presented in a separate publication.

### **The Future ?**

Because electron collision science is an enabling discipline, cross section and other data will continue to be required to optimize plasma-related technology, to explain planetary and space-related observations, and to develop and test new theoretical techniques, particularly in connection with collisions with larger, more exotic molecules. In this latter connection it is important that experimentalists and theorists continue to work closely together on carefully chosen “benchmark” targets and processes, where reliable quantitative experiments are possible and where theoretical advances can be checked. Measurements from more than one laboratory would provide important accuracy checks. As the size and complexity of molecules, (encountered in technological or environmental situations), increase it is clear that measurement of all the relevant cross sections will not be possible. Thus, development of dependable theoretical tools will become more and more of a necessity. At the other end of the size scale challenges still exist in the development of our understanding of the simplest atomic systems such as atomic hydrogen and

helium. It is noteworthy that a considerable number of the submitted papers to this conference deal with some of these problems.

Since it has been established that low-energy electrons play an important role in radiation damage in biological systems (see introduction), there will continue to be an increasing interest in this aspect of the overlap between physics and biology. Production of reliable quantitative information in this field presents major challenges to both experimentalists and theorists. A further area of relatively recent interest where electron collisions have been shown to be important is in the interaction with matter of high intensity, ultra-short laser pulses. Significant new physics has already emerged from these studies and it is clear that this will continue to be a very fertile frontier where basic quantum considerations will be probed.

#### **Acknowledgements:**

I wish to acknowledge the many contributions made to this work by my students and Post-Doctoral fellows, my colleagues and collaborators. Generous financial support from NSERC, CIPI and CFI, Canada is gratefully noted.

#### **References:**

- Allan M, Phys Scripta, **T110**, 161, (2004)  
 Andersen N and Bartschat K, "*Polarization, Alignment and Orientation in Atomic Collisions*", Springer, Berlin, (2001).  
 Bartschat K, J Phys B, **26**, 3595, (1993).  
 Bartschat K and Fang Y, Phys. Rev. A, **62**, 052719, (2000)  
 Becker K H, McCurdy C W, Orlando T M and Resigno T N, "*Electron-driven Processes: Scientific Challenges and Technological Opportunities*", US DOE Report, (2000).  
 Boudaiffa B, Cloutier P, Hunting D, Huels M A and Sanche L, Science **287**, 1658, (2000)  
 Brode R B, Phys Rev, **34**, 673, (1929).  
 Brunger M J and Buckman S J, Phys Rep, **357**, 215, (2002).  
 Chan S T and Gallagher A C, Phys Rev A, **17**, 551, (1978).  
 Christophorou L G and Olthoff J K, Adv At Mol Opt Phys, **44**, 155, (2001).  
 Christophorou L G and Olthoff J K, Adv At Mol Opt Phys, **44**, 59, (2001a).  
 Franck J and Hertz G, Verhand Deut Physik Ges, **16**, 457, (1914).  
 Hanne G F and Kessler J, J Phys B, **9**, 791, (1976)  
 Hotop H, Ruf M-W, Allan M and Fabrikant I I, Adv At Mol Opt Phys, **49**, 85, (2003).  
 Inokuti M, Adv At Mol Opt Phys, **43**, (2000)

- Jaduszliwer B and Chan Y C, Phys Rev A, **45**, 197, (1992).
- Karwasz G P, Brusa R S and Zecca A, La Rivista del Nuovo Cimento, **24**, # 1 and 4, (2001)
- Keeler M L, Anderson L W and Lin C C, Phys Rev Lett, **85**, 3353, (2000).
- Kimura M and Itikawa Y, Adv At Mol Opt Phys, **44**, (2001)
- Kuehn D G, Sutliff D E and Chanin L M, Appl Phys Lett, **33**, 906, (1978)
- Lukomski M, MacAskill J A, Secombe D P, McGrath C, Sutton S, Teeuwen J, Kedzierski W, , Reddish T J, McConkey J W and van Wijngaarden W A, J Phys B, **38**, 3535, (2005).
- MacAskill J A, Kedzierski W, McConkey J W, Domyslawska J and Bray I, J Elect Spect Rel Phen , **123**, 173, (2002).
- Martin F, Burrow P D, Zhongli C, Cloutier P, Hunting D and Sanche L, Phys Rev Lett, **93**, 068101, (2004).
- Massey H S W and Burhop E H S, "*Electronic and ionic impact phenomena*", 2nd edition, Oxford Press, (1969).
- Massey H S N, Burhop E H S and Gilbody H B, "*Electronic and Ionic Impact Phenomena*", Vols 1 & 2, Clarendon Press, Oxford, (1969).
- McDaniel E W, "*Atomic Collisions, Electron and Photon Projectiles*", John Wiley & Sons, New York, (1989).
- Mott N F and Massey H S N, "*The Theory of Atomic Collisions*", Clarendon Press, Oxford, (1965).
- Niikura H, Legare F, Hasbani R, Ivanov M Y, Villeneuve D M and Corkum P B, Nature, **421**, 826, (2003).
- Read F H and Channing J M, Rev Sci Instrum, **67**, 2372, (1996).
- Rubin K, Perel J and Bederson B, Phys Rev, **117**, 151, (1960)
- Schappe R S, Feng P, Anderson L W, Lin C C and Walker T, Europhys Letts, **29**, 439, (1995).
- Schappe R S, Walker T, Anderson L W and Lin C C, Phys Rev Lett, **76**, 4328, (1996)
- Schappe R S, Keeler M L, Zimmerman T A, Larsen M, Feng P, Nesnidal R C, Boffard J B et al, Adv Atom Mol Opt Phys, **48**, 357, (2002)
- Surdutovich E, Kauppila W E, Kwan C K, Miller E G, Parikh S P, Price K A and Stein T S, Nucl Inst Meth **B**, **221**, 97, (2004).
- Surko C M, Gribakin G F and Buckman S J, J Phys B, **38**, R57, (2005).
- Thomson J J, Phil Mag, **44**, 293, (1897).
- Visconti P, Slevin J and Rubin K, Phys Rev A, **3**, 1310, (1970).
- Weckenbrock M, Becker A, Staute A, Kammer S, Villeneuve D M, Corkum P B and Dorner R, Phys Rev Lett, **91**, 123004, (2003).
- Zecca A, Karwasz G P and Brusa R S, La Rivista del Nuovo Cimento, **19**, # 3, (1996).