Deep Interference Minima in Differential Cross Sections for Electron-impact Ionization

James Colgan, T-1

A recent paper published by James Colgan and coauthors as a "Fast-Track Communication" [1] has provided some insight into a long-standing puzzle in atomic collision physics.

The paper investigates an unusual deep minimum found in the triple differential cross sections (TDCS) resulting from the electron-impact ionization of helium for noncoplanar electron geometries. Such TDCS minima, which are effectively zeros in the cross section, are usually the result of selection rules (most often found in photoionization studies) or resulting from strong electron-electron correlation effects, where the two outgoing electrons repel each other at a given geometry. The minimum explored here, and as shown in Fig. 1, was discovered experimentally more than 15 years ago [2,3], and its existence has been difficult to explain, as no obvious selection rules or correlation effects seemed to play a role in the phenomena. The investigations by Colgan et al. [1] used an accurate nonperturbative time-dependent close-coupling (TDCC) approach to compute the triple differential cross sections for the ionization of helium at several incident energies, and for the various geometries of the experiment. The experimental data was reproduced extremely well by the TDCC calculations, as shown in Fig. 1. Figure 1 shows the TDCS for various incident electron energies, for given gun angles ψ as indicated (where the gun angle is the angle made between the incident electron beam and the plane of detection of the two outgoing electrons). The TDCS is presented as a function of the angle ξ, where 2ξ is the angle between the outgoing electrons.

Further analysis showed that the minima were due to strong destructive interference between the many partial waves (approximately 10 total angular momentum L terms are included for the calculations shown in Fig. 1) contributing to the TDCS. The strongly positive contributions from the direct terms in the partial wave sum are almost exactly cancelled by the negative contributions arising from the interference terms. Such destructive interference has also been found to contribute to other unusual TDCS phenomena, such as the rapidly changing TDCS when the bond length is varied in studies of double photoionization of molecular hydrogen [4].

Colgan et al. [1] also found that the deep minimum is present in the electron-impact ionization of molecular hydrogen, a system that has been much less explored, both theoretically and experimentally. However, to observe the minimum in this case, it is necessary to consider ionization from molecules at specific orientations. For example, in Fig. 2 the dashed line shows the TDCS for ionization of H_2 at molecular angles $\theta_N = 50°$; $\phi_N = 0°$, (where the angles are with respect to the z-axis, which is defined by the incident electron direction). A sharp minimum is clearly evident. The only experiments to date on this system studied unoriented molecules, and no deep minima were found. The TDCC calculations (solid line), when averaged over all orientations, were also found to be in excellent agreement with experiment, as shown in Fig. 2. It is hoped that this study will stimulate the measurement of electron-impact ionization cross sections from oriented molecules, which is a formidable technical challenge. Further investigations of this intriguing phenomenon are also currently underway, with attention being placed on whether vortices in the correlated electronic wave functions are also playing a role.

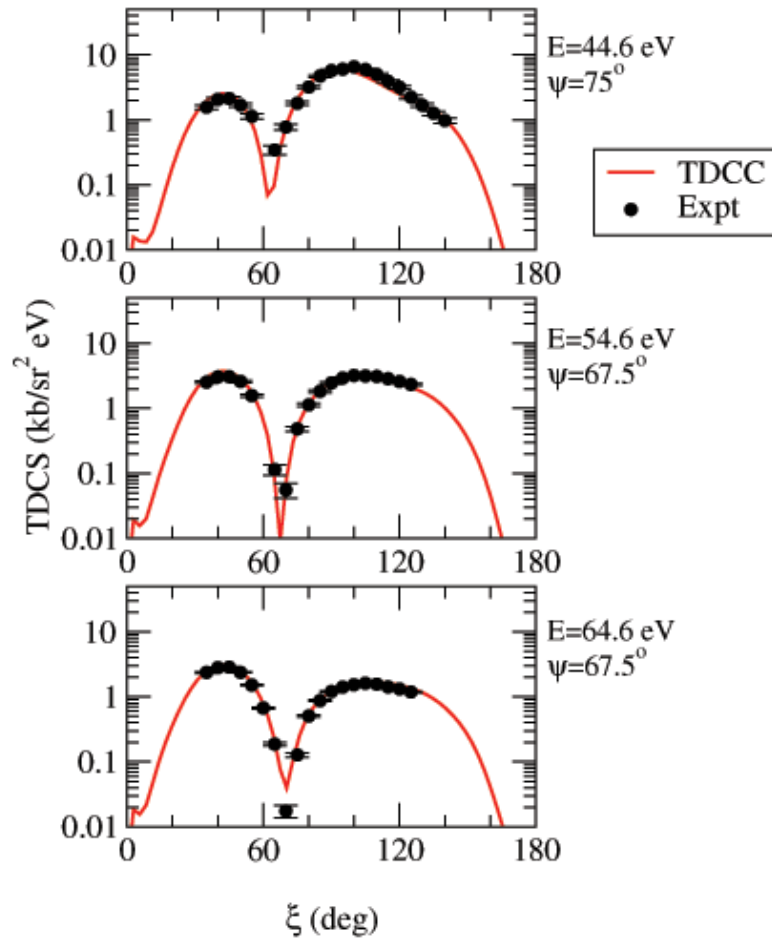**For more information contact James Colgan at jcolgan@lanl.gov.**

Fig. 1. Triple differential cross sections for the electron-impact ionization of helium for three incident electron energies and gun angles as indicated. In all cases the outgoing electrons have equal energy sharing. The experimental data are compared with TDCC calculations (solid red lines).
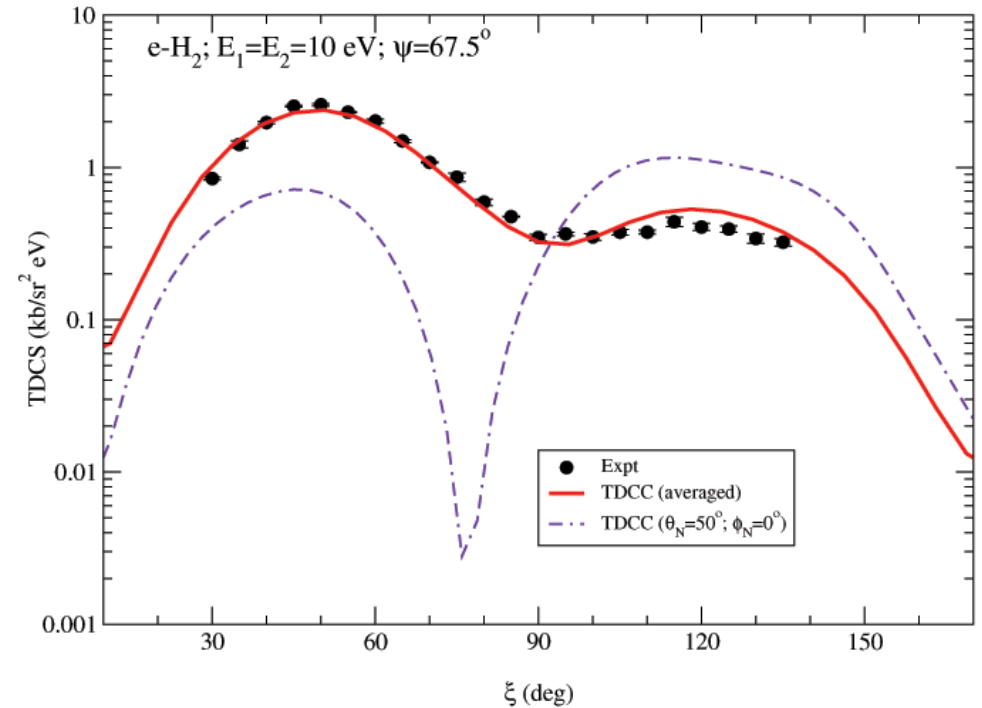

Fig. 2. Triple differential cross sections for the electron-impact ionization of molecular hydrogen at an incident electron energy of 35.4 eV. Experimental data are compared with TDCC calculations (solid red line), which are averaged over all molecular orientations. The double-dashed purple line indicates a TDCC calculation for a specific molecular orientation ($\theta_N = 50°$; $\phi_N = 0°$), where it can be seen that a deep minimum is predicted.

[1] J. Colgan et al., *J. Phys. B* **42,** 171001 (2009).
[2] A.J. Murray, F.H. Read, *J. Phys. B* **26,** L359 (1993)
[3] A.J. Murray, F.H. Read, *Phys. Rev. A* **47,** 3724 (1993).
[4] T.J. Reddish et al., *Phys. Rev. Letts.* **100,** 193001 (2008).