Projectile Momentum Uncertainty Effects in Electron Vortex Beam Collisions

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Electron Vortex Beams have Unique Properties

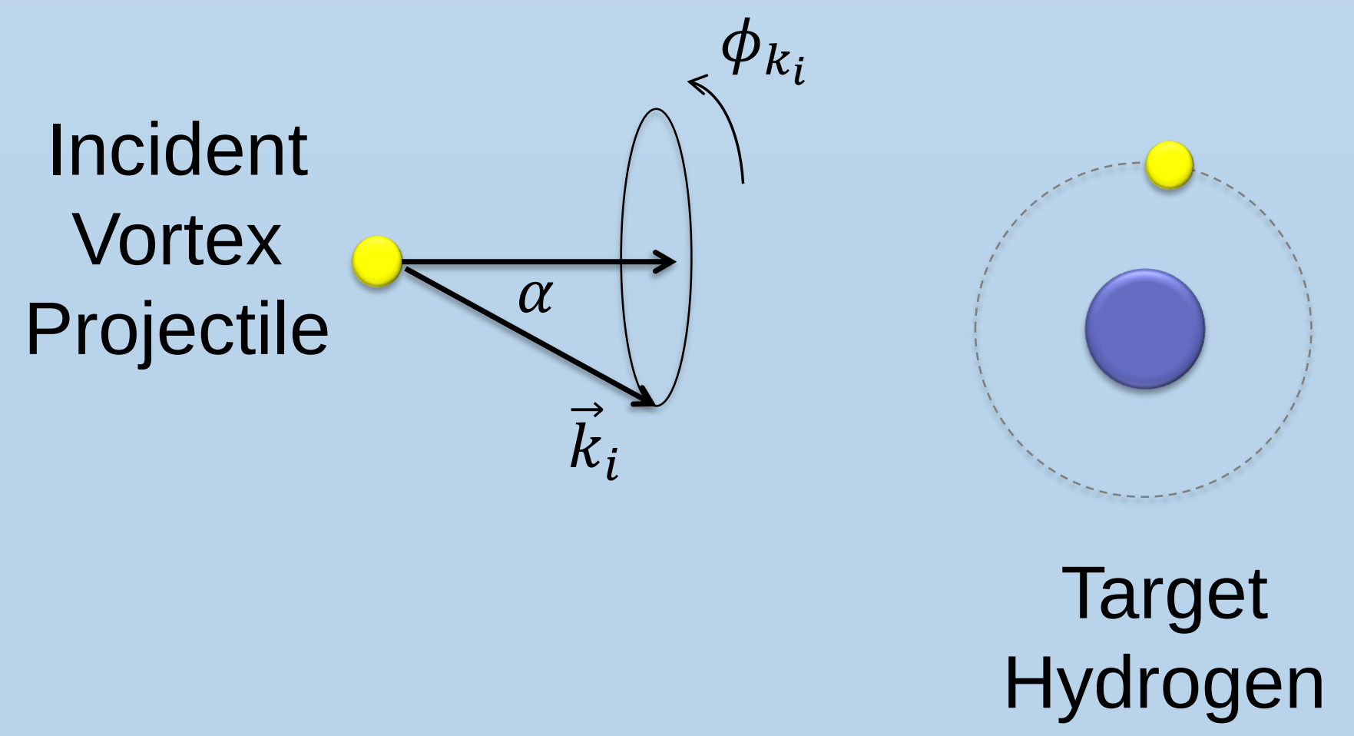
Electron vortex beams (EVBs) are freely propagating beams with non-zero orbital angular momentum (OAM) and non-zero transverse momentum. They have a phase singularity at their center and show a hollow, doughnut like, shape when projected onto a plane. Proposed uses include improved resolution of electron microscopy and identification of chiral structures. However, in order to access these applications a deeper understanding of EVBs interactions with matter is required and currently remains largely unexplored.

Double differential cross sections (DDCS) provide information about the mechanism that leads to ionization. Our previous studies [1,2] indicated vortex and non-vortex projectiles result in significantly different ionized electron distributions.

We calculate the DDCS for ionization of hydrogen by vortex and non-vortex projectiles to determine if ionization by vortex projectile uses the same mechanisms as non-vortex projectiles.

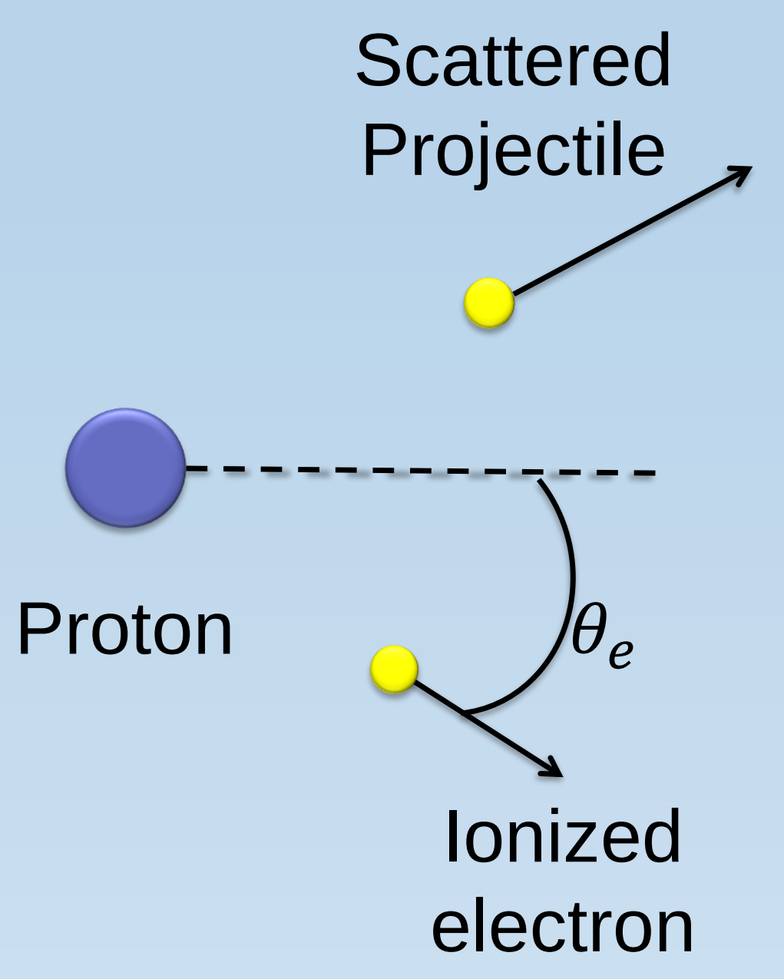
Ionization

An incident vortex projectile with opening angle α collides with a target hydrogen atom in the ground state. During the collision, the projectile scatters from the target, losing its vortex properties. The hydrogen atom's electron is ionized and both outgoing electrons leave the collision as non-vortex free particles.
The incident projectile's momentum vector is uncertain and lies on a cone of half angle α. The DDCS can be written as a sum of individual DDCS for each incident momentum azimuthal angle ϕ_{k_i}.


Incident Vortex Projectile

Target Hydrogen

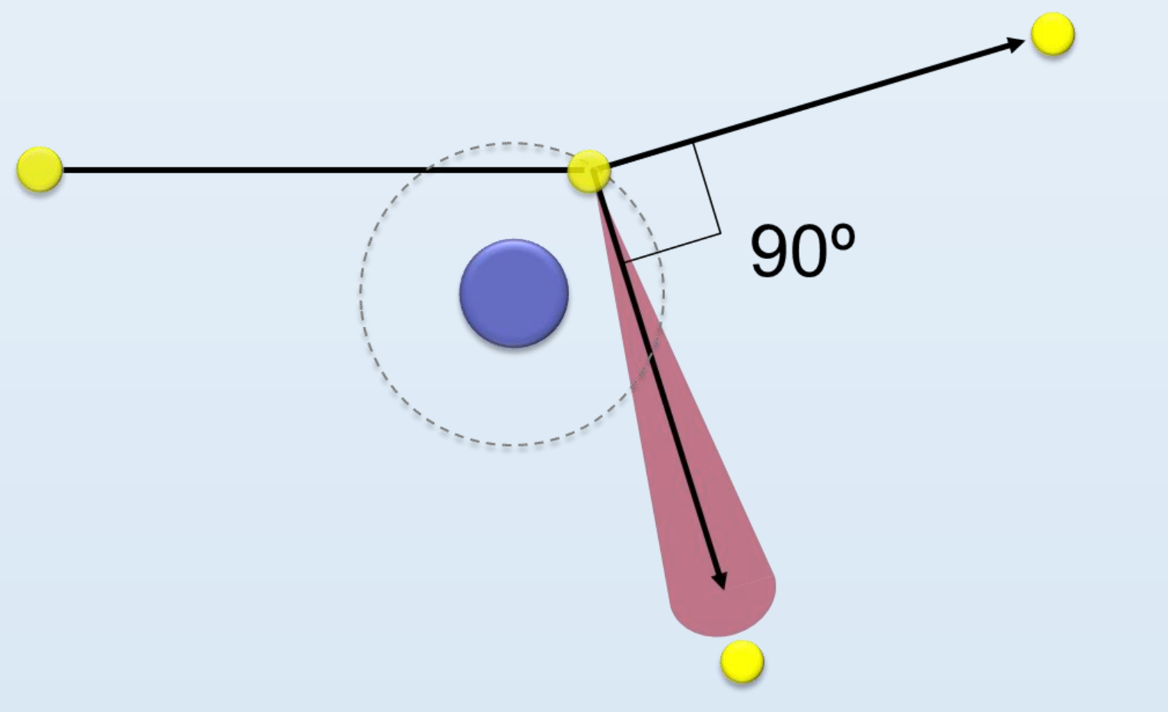
The scattered projectile's location following the collision is unspecified. The ionized electron leaves the collision at an angle θ_e.


Scattered Projectile

Proton

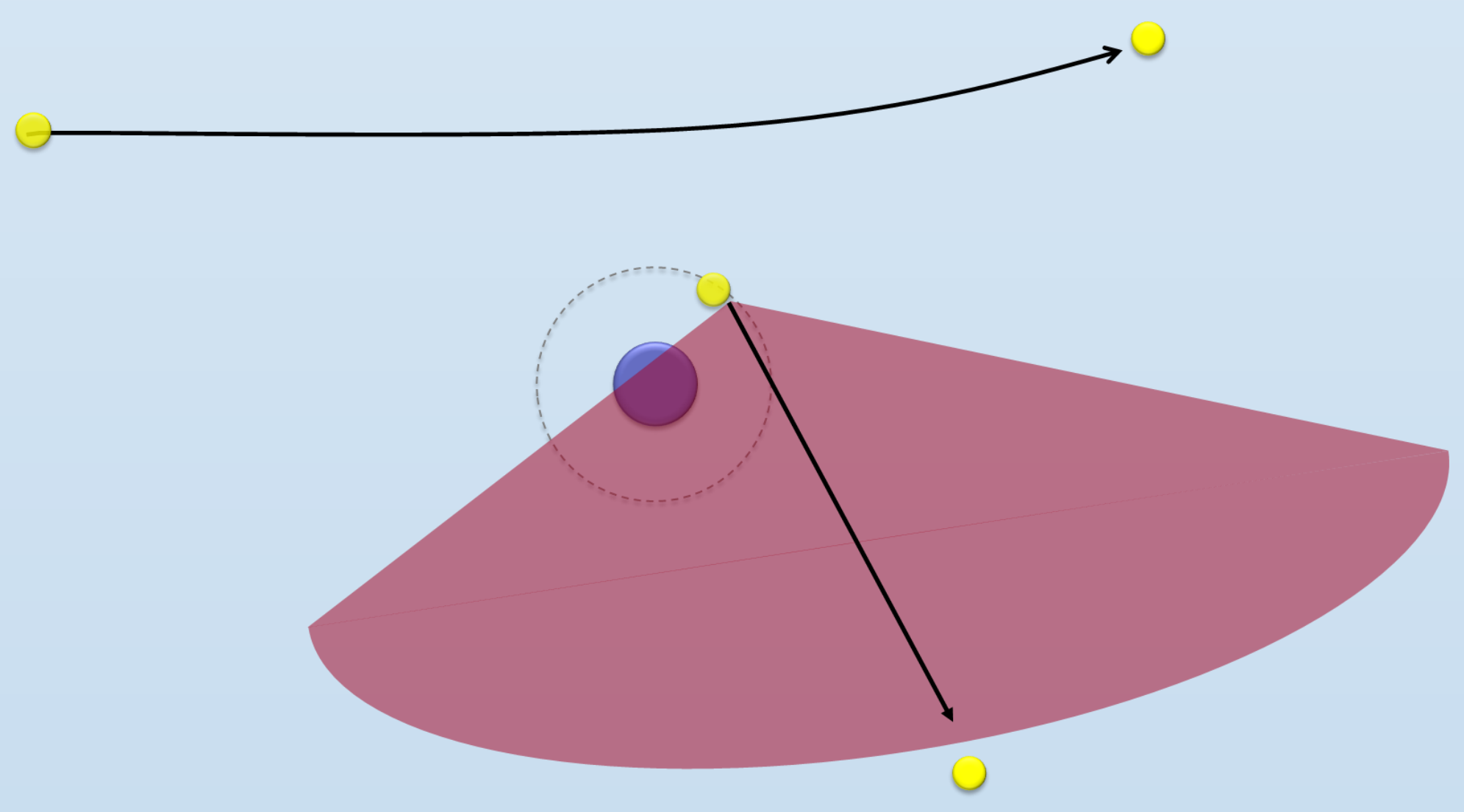
Ionized electron

Double Differential Cross Sections Indicate Collision Mechanism



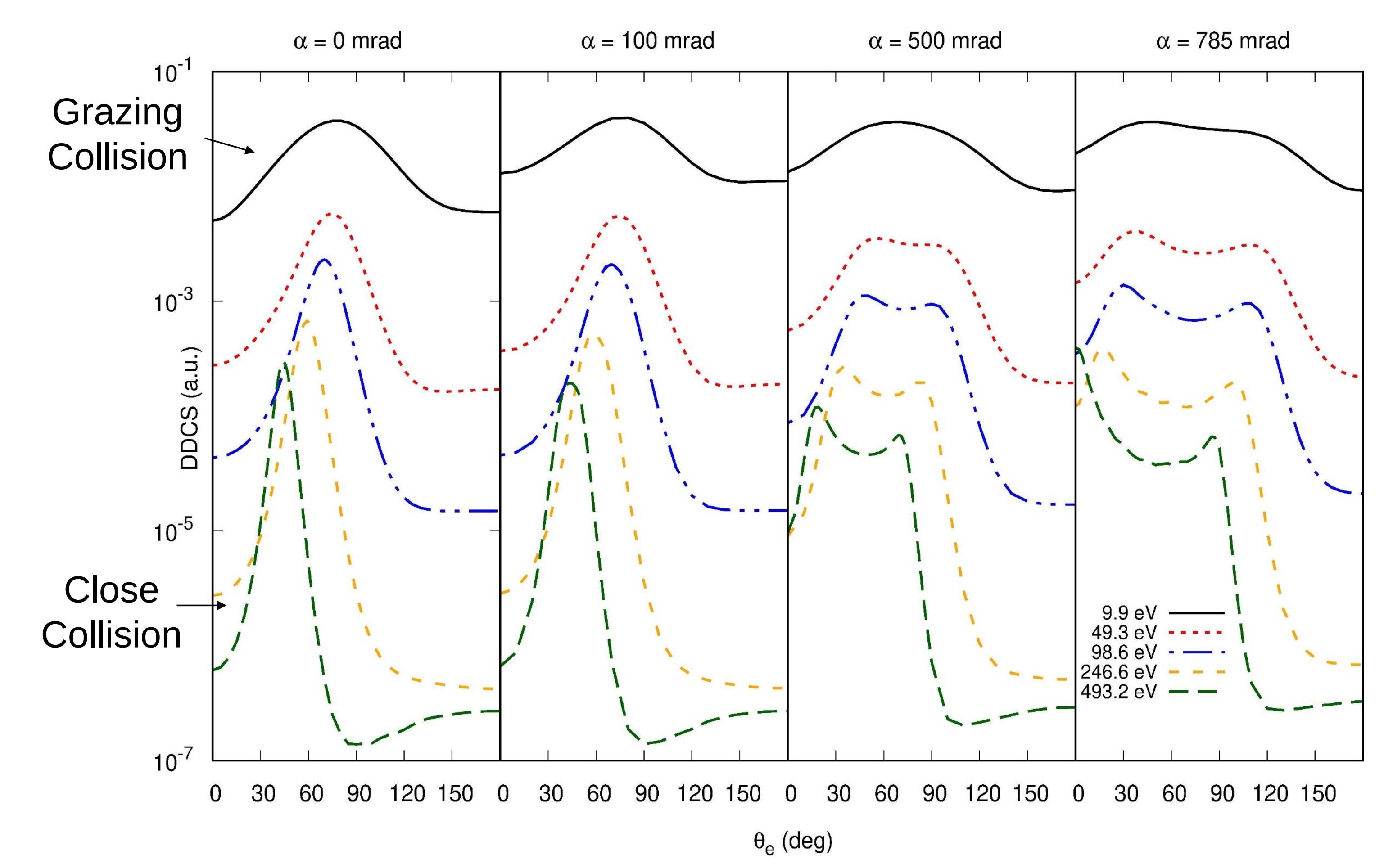
A close collision between the projectile and target electron results in a large momentum transfer with both electrons leaving at 90º relative to each other. The DDCS exhibit a sharp binary peak where the electrons are ejected.

In a grazing collision, the momentum transfer is small, and the target electron momentum density plays a dominant role. The DDCS show a broad, nearly uniform distribution.



Momentum Uncertainty Broadens Binary Peak

Low energy ejected electrons result from grazing collisions, while close collisions yield higher energy ejected electrons. For vortex projectiles, we observe a broadening of the binary peak due to the momentum uncertainty of the incident projectile. A splitting of the binary peak is also observed for the two largest opening angles.



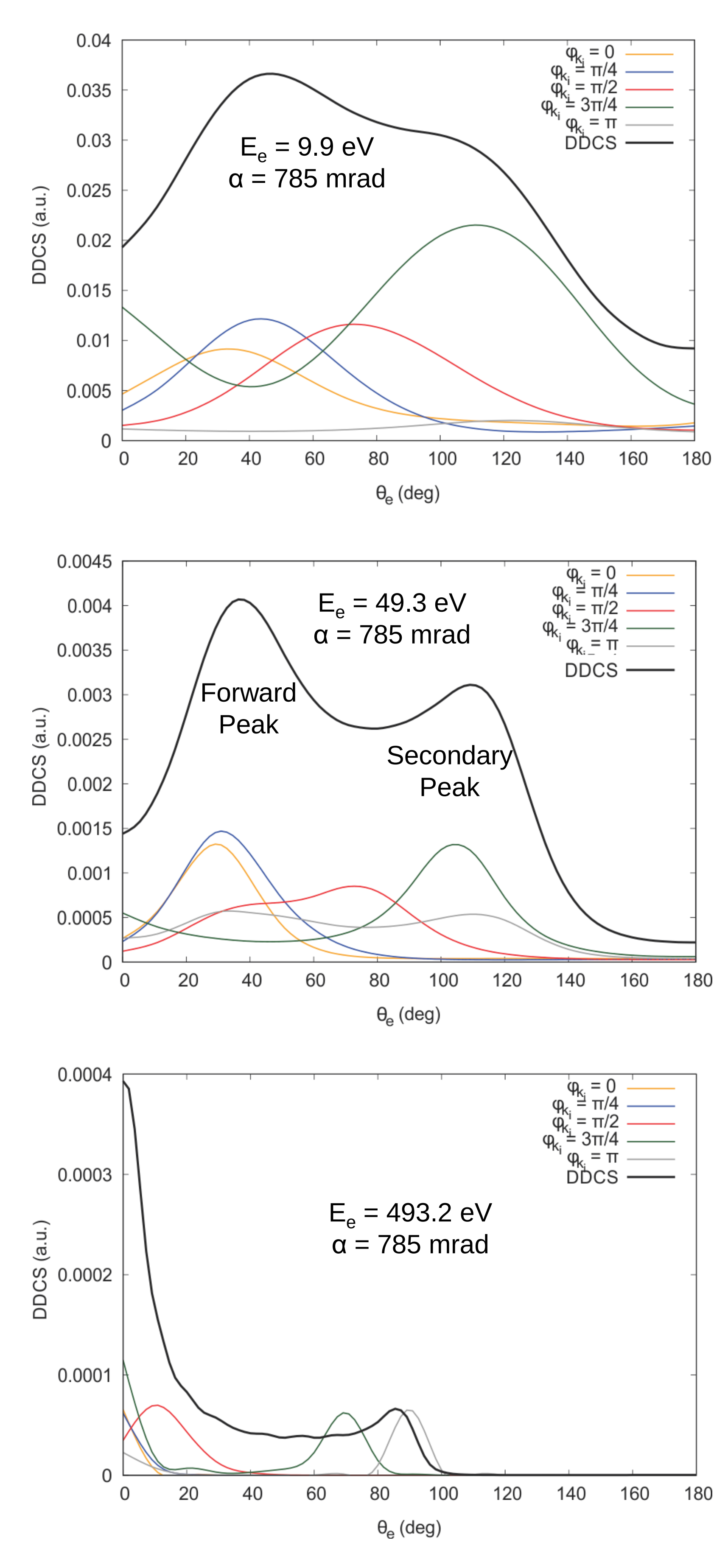
Out-of-Plane Projectiles cause Binary Peak Splitting

For vortex projectiles, many different incident momentum azimuthal angles contribute to the DDCS and cause a splitting of the binary peak.

The forward scattering peak results from incident momenta with azimuthal angles $\phi_{k_i} < \frac{\pi}{2}$ and $\phi_{k_i} > \frac{3\pi}{2}$. In this region, the momentum transfer direction is primarily longitudinal.

The secondary peak results from $\frac{\pi}{2} < \phi_{k_i} < \frac{3\pi}{2}$, in which the momentum transfer direction is primarily transverse. This indicates the projectile's momentum uncertainty is the source of the binary peak splitting.

The splitting is enhanced for large energies because the close collision mechanism results in larger momentum transfer values and greater sensitivity to projectile momentum uncertainty.



Conclusions

Vortex projectiles possess an inherent uncertainty in the incident momentum that leads to an uncertainty in the momentum transfer. This uncertainty leads to a broadening and splitting of the DDCS binary peak. DDCS for close collisions with large ionized electron energies are more sensitive to the projectile momentum uncertainty and show enhanced peak splitting.

References

[1] A Plumadore and A L Harris 2020 J. Phys. B: At.. Mol Opt. Phys. 53 205205
[2] A L Harris et al 2019 J. Phys. B: At. Mol. Opt. Phys. 52 094001