Vortex surfaces in the ionization of atoms by positron impact

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Synopsis: We studied the morphology of quantum vortex surfaces in positron-atom ionization collisions. By conducting a detailed calculation of the position of vortices in the final momentum space with no kinematic restrictions, we could analyze the characteristics of the full four-dimensional vortex structure. This is the first time that these structures are fully calculated for positron-atom collisions. Quantum vortices have been scrutinized both theoretically and experimentally over the last decade for the ionization of atomic and molecular targets by the impact of proton, electron, and positron projectiles. Because they are submanifolds of co-dimension 2 on the phase space of the T-matrix element of the collision, they appear as points in twodimensions, lines in three dimensions, and surfaces in four dimensions. A previous exhaustive study of the ionization of atoms for different positron impact energies allowed us to show how these structures emerge in a collinear geometry as pairs of isolated points. In a subsequent work, weproved that many structures that appeared isolated when studied in two dimensions were part of a single vortex ring. In the current study, we were able to trace the full vortex structure surface.

INTRODUCCIÓN

Back in the early 1990's, a deep minimum was experimentally observed in the differential cross section of the (e,2e) process in helium [1]. A similar minimum was theoretically found by Brauner and Briggs [2] for the ionization of hydrogen by the impact of positrons. Two decades later, these minima were shown to be isolated zeroes, and recognized as quantum vortices [3, 4, 5].

QUANTUM VORTICES

Quantum vortices are submanifolds of co-dimension 2 on the phase space of the T-matrix element of the collision. This means that they appear as points in two dimensions, and as lines in three dimensions. The *velocity field* associated with T exhibits a solenoidal field like that of irrotational vortices in Fluid Dynamics

QUANTUM VORTICES AS ISOLATED ZEROES

Usually, quantum vortices in ionization processes are studied as isolated zeroes on two-dimensionally constrained regions of the phase space of the multidimensional T-matrix element. These reductions are customarily achieved through restrictive geometries, as for instance the collinear arrangement, where the emitted electron and the projectile move along the same direction in the final state [4]. In figure 1 these structures emerge as pairs of isolated points with a velocity field of opposite circulation to each other.

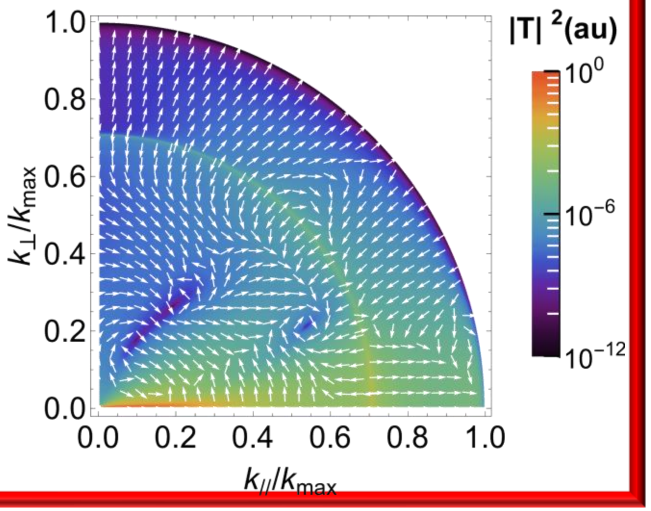
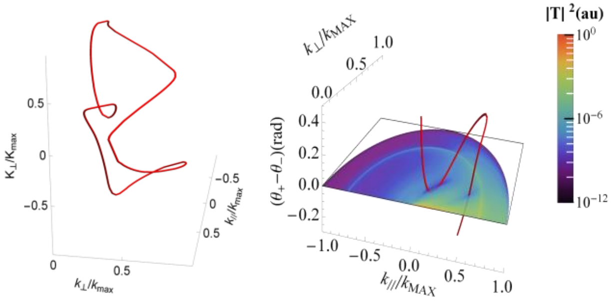


Figure 1: Ionization T matrix for the ionization of H the impact of by 275 eV positron impact in a collinear geometry. $k_\parallel$ and $k_\perp$ are the components of the momentum $\boldsymbol{k}$ of the electron, parallel and perpendicular to the initial velocity $\boldsymbol{v}$ of the positron, respectively. These components are normalized to the maximum momentum $k_{max} \approx \sqrt{mv^2 + 2\epsilon}$, where ϵ is the first ionization energy of the hydrogen atom. The density plot displays the modulus of T, while the arrows represent the generalized velocity field $\boldsymbol{u} = \mathrm{Im}\,\nabla_k \ln T$ All the quantities are expressed in atomic units.

VORTEX RING

When tracked out of a collinear (but still coplanar) geometry, the three vortices in figure 1 turn out to correspond to a planar cut of a single vortex line [6,7].

Figure 2. Same as figure 1. On the **right figure** θ_- and θ_+ are the emission angles of the electron and the positron, respectively. The density plot shows $|T|^2$ in the collinear geometry. On the **left figure** $K_\perp$ is the component of the positron momentum $\boldsymbol{K}$ perpendicular to the initial velocity of the positron.



VORTEX SURFACE

Now, since the T matrix element depends of four independent variables, it is not unreasonable to assume that the previous argument can be applied again, and that the vortex ring would in fact be the cut of a vortex surface. To track such multidimensional structure, it is necessary to take into account the geometry in a correct way since the beginning. Towards that aim we found useful a new representation of quantum vortices. In Figure 3 we represent a quantum vortex ring at 100 eV positron impact, but instead of starting from collinear geometry like in Figure 2, this time we fix the final polar angle of the positron and calculate in all the electron momenta space, in coplanar geometry. We think this is the correct way to "cut" the 4D surface is by representing the results as a function of the polar angle of the positron in this combined cartesian-polar plot.

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