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Vortex lines and surfaces in positron-atom ionization collisions

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Synopsis We study the appearance of quantum vortices in the ionization of atoms by positron impact. We avoid the standard restrictions on the final-state variables, in order to study vortices as submanifolds of codimension 2 in the multidimensional space of definition of the T-matrix element. In particular we demonstrate that three isolated vortices previously observed under a collinear geometry, actually correspond to a two-dimensional cut on a single vortex line.

In the fall of 1926, some few months after the publication of Schrödinger's seminal papers on wave mechanics, Erwin Madelung proposed an alternative but mathematically equivalent formulation where "Schrödinger equation for one-electron problems can be transformed into the form of hydrodynamical equations" [1]. The corresponding velocity field is shown to be irrotational everywhere, except at vortices where the density vanishes. These quantum vortices can appear during the evolution of an atomic scattering process, and even survive up to macroscopic distances so as to leave their imprints on the corresponding transition matrix element T in the form of isolated zeros. In recent years, certain sharp minima previously found in the electron momentum distribution for the ionization of atoms by the impact of electrons and positrons were demonstrated to be quantum vortices in the velocity field associated with T. They have also been observed in the photoionization of atoms, and in ionization collisions by the impact of protons and antiprotons (see [2, 3] and references therein).

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. However, vortices are submanifolds of codimension 2, and restrictive 2D geometries would provide only a glimpse of a much more complex structure. For instance, when tracked out of a collinear arrangement, a pair of vortices of opposite circulation previously observed in the ionization of Hydrogen (H) by positron impact [4], and a further vortex [2], which in a collinear geometry appears totally unrelated to them, turn out to correspond to a planar cut of a single vortex line, as shown in figure 1. Recently, a segment of a vortex line was also observed in a Coulomb-Born calculation of T for the electron-impact K-shell ionization of carbon [3]. Finally, in an effort to understand the topology of these quantum structures, we trace the vortices in the full multidimensional space of T for positron-atom ionization collisions, obtaining the first look of vortex surfaces, free of any restrictive geometry.

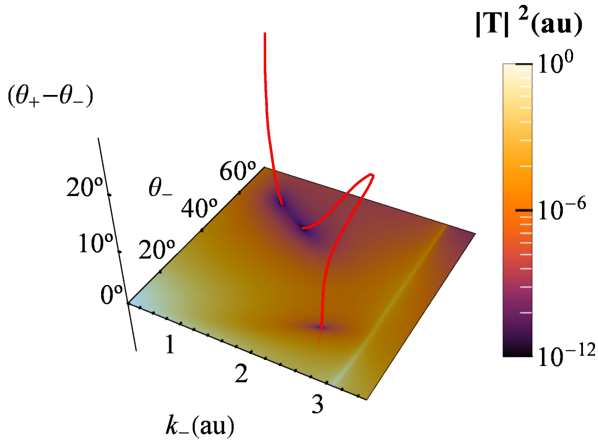

Figure 1. Vortex line (in red) of T for the 275eV ionization of H by positron impact. k_- and θ_- are the momentum and emision angle of the electron, and θ_+ is the emission angle of the positron. The density plot shows $|T|^2$ in the collinear geometry ($\theta_- = \theta_+$).

References

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