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COLTRIMS studies on singly ionizing ion-atom collisions: The roles of the projectile and target coherence

Konstantin A. Kouzakov[*1]

[*] Department of Nuclear Physics and Quantum Theory of Collisions, Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia

Synopsis A theoretical analysis of the so-called projectile and target coherence in COLTRIMS experiments on single ionization of atoms by fast ions is presented. Using time-dependent quantum scattering theory, it is shown that the projectile coherence has no serious impact on the measured fully differential cross sections. In contrast, the effects of the target coherence might be of greater importance in the discussed experiments.

Cold target recoil ion momentum spectroscopy (COLTRIMS) is a reaction microscope that allows high-precision measurement of fully differential cross sections (FDCS) of various atomic fragmentation processes. Of special interest are the COLTRIMS experiments on single ionization of helium by fast ionic projectiles [1, 2, 3], particularly due to the claim that for explaining their results one should account for the projectile-coherence effects.

As formulated by Wang et al. [2], in analogy to classical optics and in accordance with Huygens' principle, the projectile transverse coherence length is given by $\Delta x \approx \lambda L/2a$, where a and L are the width of the collimating slit and its distance to the target, respectively, and λ is the de Broglie wavelength of the projectile. If the projectile coherence length is larger (smaller) than the size of the target atom, the projectile is coherent (incoherent). For example, the transverse coherence length of the projectile beam in the 100-MeV/u C^{6+}+He experiment [1] was estimated as $\Delta x \approx 10^{-3}$ a.u. [2], thus suggesting that the C^{6+} projectiles were strongly incoherent in that experiment. From this fact it follows that the usual time-independent quantum scattering theory is not directly applicable, because this theory is based on the assumption that the projectile wave packet is much broader than the spatial extent of the target.

The proper theoretical framework for inspecting the effects of the projectile coherence is quantum scattering theory of wave packets. It treats a time-dependent collision of the projectile and target wave packets, as opposed to the time-independent formulation of scattering theory that deals with stationary plane waves. The time-independent formulation follows from the time-dependent one in the limit of the perfect localization of wave packets in momentum space. Suppose that the initial state of the ionic projectile in momentum space, as it is prepared in a COLTRIMS experiment, is given by the wave packet $\Phi_p(\mathbf{q}_p)$. The projectile coherence is directly related to the properties of this wave packet, namely the projectile becomes fully coherent when $|\Phi_p(\mathbf{q}_p)|^2 \to (2\pi)^3\delta(\mathbf{q}_p - \mathbf{k}_p)$, where $\mathbf{k}_p$ is the centroid of the wave packet. The same consideration applies to the target coherence, which is determined by the initial wave packet $\Phi_t(\mathbf{q}_t)$ that describes the state of the center of mass of the He atomic target in momentum space.

The performed theoretical analysis [4] involves general arguments based on quantum scattering theory of wave packets. The general formula for FDCS has been derived, where the projectile wave packet appears to be canceled. In other words, it does not support the claim that the projectile-coherence effects play an important role in atomic ionization by fast ions studied with COLTRIMS. In contrast, the incoherent effects can arise only due to the target center-of-mass wave packet. The detailed properties of this wave packet depend on experimental procedures employed for creation of a cooled atomic beam. This reflects the fact that it constitutes a part of experimental uncertainties pertinent to the COLTRIMS technique.

For accurate quantitative comparisons with experiment, one must further convolute the FDCS with a distribution of the target wave packets in a supersonic jet over the mean velocities, $\mathbf{v}_t = \mathbf{k}_t/M_t$, where M_t is the atomic mass, and with finite energy and angular resolutions of the detectors. In the case of weak collimation of the projectile beam, it is necessary to carry out an additional averaging due to the spread of the mean velocities $\mathbf{v}_p$ of the projectile wave packets. Thus, singling out the effects of the target center-of-mass wave packet in the measured FDCS is not a straightforward task in general.

[1]E-mail: kouzakov@srd.sinp.msu.ru

References

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