Chapter 4

Kinematically Complete Measurements of Single Ionization of He

In the following chapter, we present the final set of experiments of this dissertation. It is here that we realize the full power of the momentum imaging technique. Using a 3rd generation version of the spectrometer and gas jet, we have measured low energy continuum electrons ejected in single ionization of helium atoms. We used bare projectiles of various velocities (between 6 and 14 a.u.) and charge states (from 1 to 9). By measuring the complete momentum vectors of both the ejected electron and recoiling target ion, we were able to infer the full change in the projectile momentum vector. Because we know the momentum of each body in the collision, the experiment is kinematically complete. The goal of the analysis was

to discern what two-body interactions play a dominant role in the three-body collision as we varied the collision system parameters.

We will begin the chapter by showing a simple derivation of the momentum transfer in the longitudinal direction between the projectile, recoil ion, and electron. This derivation shows the longitudinal momentum transfer to the projectile to be usually restricted to very small values due to the very small projectile scattering angles in these collisions. However, such restrictions do not apply to the transverse momentum exchanged in the collision. It is by measuring the correlated two-body motion in the transverse direction that we can discern the ionization mechanism; this is where all of the "action" is. To place our work in context, we will present some related work by other groups and identify the dominant two-body interactions evident in their data. Finally, we will describe the apparatus in some detail and present the results of our experiments.

4.1 Small Momentum Transfer

The smallest projectile momentum in our experiments was in excess of 10^4 atomic units. However, as shown in previous chapters, we measure only the low-energy continuum electrons produced in the collision. In this case, the recoil ion and electron momentum that we measure are *both* of the order of one atomic unit. Therefore, the projectile scattering angle for single ionization is quite small (~10^{-5} radians), and the projectile trajectory can be approximated as a straight line. It is straightforward to derive the restrictions placed on the momentum changes of the interacting particles.

4.1.1 Longitudinal Momentum and Q-value

Due to the virtually straight-line beam trajectory involved, it is straightforward to show that for a given energy transfer in the collision (Q-value) there is a well defined longitudinal momentum transfer to the projectile. We begin with conservation of energy.

$$\varepsilon_i + \frac{1}{2m_p}(\vec{P}_p^{\,i})^2 = \frac{1}{2m_p}(\vec{P}_P^{\,f})^2 + \frac{1}{2m_R}(\vec{P}_R)^2 + \frac{1}{2m_e}(\vec{P}_e)^2 \tag{4.1}$$

where ε_i is the helium electron energy, and the subscripts denote the projectile, recoil ion and electron. Because the recoil ion has a large mass but small momentum, its energy term may be neglected, and a rearrangement yields the following:

$$\frac{1}{2m_p}(\vec{P}_P^{\,f})^2 - \frac{1}{2m_p}(\vec{P}_p^{\,i})^2 = \varepsilon_i - \frac{1}{2}m_e v_e^{\,2} \tag{4.2}$$

$$\frac{1}{2m_p}(\vec{P}_P^{\,f} - \vec{P}_p^{\,i}) \bullet (\vec{P}_P^{\,f} + \vec{P}_p^{\,i}) = \varepsilon_i - \frac{1}{2}m_e v_e^{\,2} \tag{4.3}$$

With an approximation and projection,

$$\vec{P}_P^{\,f} + \vec{P}_p^{\,i} \cong 2m_p \vec{v}_p \tag{4.4}$$

$$v_p \times \Delta P_{//p} = \varepsilon_i - \frac{1}{2}m_e v_e^{\,2} = Q \tag{4.5}$$

we see that the energy conservation forces a restriction on the momentum change of the projectile in the longitudinal direction. Further, because of momentum conservation,

$$\vec{P}_p^{\,i} = \vec{P}_P^{\,f} + \vec{P}_R + \vec{P}_e \tag{4.6}$$

$$-v_p(P_{//R} + P_{//e}) = \varepsilon_i - \frac{1}{2}m_e v_e^{\,2} = Q \tag{4.7}$$

where the sum of longitudinal momenta for the recoil ion and electron must be a constant (within the energy distribution of the electron). Because Q ~ 1 a.u., and $v_p \geq$ 6 a.u. for all cases presented in this thesis, the following equivalent conditions are imposed. From eq. 4.5, we see that the longitudinal momentum transferred from the projectile ( ) is essentially fixed at a small value of less than 1/6 of an atomic unit.

This implies, from eq. 4.7, that the longitudinal momenta of the electron and recoil ion must balance within 1/6 of an atomic unit.

Although the sum of the electron and recoil longitudinal momentum is nearly kinematically determined, their individual magnitudes are not. It is here that we must introduce the concept of "post-collision" interaction, which allows us to visualize some of the mechanics of the collision. For a given collision, one can imagine that shortly after the target is ionized, the recoil and electron both see the electric field due to the receding projectile. The electrons are then pulled forward by this field, while the recoil ions are pushed backward along the beam direction. As we vary the projectile's velocity and charge, we might expect this effect to change accordingly.

4.1.2 Transverse Momentum

We now turn our attention to the transverse momentum transferred between each pair of the three bodies in the collision. The motion in the direction perpendicular to the ion beam is not so tightly restricted as that of the parallel direction. The vector sum of the transverse momenta transferred to all participants in the collision must be zero. However, the relative magnitudes among the three vectors can vary from collision to collision. It is useful to classify individual collisions into three categories based on the strength of the interaction between two of the bodies. To avoid confusion with similar work in the literature, we will attempt to associate the labels we have chosen for our categories with others that are commonly used.

If the projectile has a hard collision with the target nucleus, then it must have an equal and opposite transverse momentum to compared to that of the nucleus. If the dominant transverse momentum exchange is between the projectile and recoil ion, we will refer to this scattering as being strongly "nuclear" in nature. In a similar fashion, the projectile may have a hard collision with the target electron, and there must exist a transverse momentum balance between the electron and projectile. As in the case of nuclear scattering. these collisions are sometimes referred to as two-body for obvious reasons. To avoid confusion, we will adopt the standard electron spectroscopy terminology and refer to these events as “binary-encounter” collisions. The final case corresponds to events where, at larger impact parameters, the atom as a whole receives a fast electric field pulse (or virtual photon). Then the projectile gains little transverse momentum, and the recoil ion and electron must have equal and opposite transverse momenta. We will refer to this type of scattering as photoionization-like, although other labels for this ionization mechanism have included “three-body” or “dipole”. One of the goals of this experiment is to discern the strength of the contribution from each of these interactions to the total transverse momentum transferred to (or from) each of the three bodies.