Colliding-Beams Experiments for Studying Fundamental Atomic Processes

R A Phaneuf
Department of Physics, University of Nevada, Reno, Nevada 89557-0058, U.S.A.
Email: phaneuf@physics.unr.edu

Abstract. Following the pioneering experiment of Dolder, Harrison and Smith nearly a half-century ago, measurements based on the colliding-beams technique became a major source of fundamental data on the electronic structure and interactions of ions. The subsequent development of powerful new sources of highly charged ions and large-scale national facilities such as heavy-ion storage rings and synchrotron light sources provided new applications for established techniques and inspired the development of new interacting-beams methods to take advantage of their unique capabilities. This paper focuses on experimental developments within the last decade involving multiply charged ions using crossed, inclined and merged beams. Examples are presented to highlight such experiments and their impact on our knowledge of the atomic structure of multiply charged ions as well as their interactions in plasmas. Atomic processes considered are elastic scattering, excitation, ionisation, recombination and electron transfer.

1. Introduction
Nearly a half-century ago, Dolder, Harrison and Thoneman reported the first colliding-beams experiment with an accelerated ion beam [1]. With an absolute uncertainty of better than 10%, their pioneering measurement of electron-impact ionisation of He+ set a high standard for colliding-beams experiments that were to follow. Not until fourteen years later was the first colliding-beams measurement reported for a multiply charged ion: an absolute measurement of the cross section for 2s-2p excitation of C3+ [2]. To date, the colliding-beams method has been applied to hundreds of measurements of fundamental processes such as elastic scattering, excitation, ionisation and recombination. This paper presents an overview of such experiments that have been performed during the last decade with multiply charged ion beams.

2. Colliding-beams technique
A schematic diagram illustrating the colliding-beams technique is presented in figure 1. When two mass and charge selected beams are intersected at an angle \( \theta \), the relative collision energy in the center-of-mass frame is given by the expression

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E_{rel} = \frac{m_1 m_2}{m_1 + m_2} \left[ \frac{E_1}{m_1} + \frac{E_2}{m_2} - 2 \sqrt{\frac{E_1 E_2}{m_1 m_2}} \cos \theta \right],
\]
where $E_1$ and $E_2$ are the beam energies and $m_1$ and $m_2$ are their atomic masses. Highly energetic beams require a relativistic form of this equation that includes the Lorentz factor [3]. If the angle of intersection of the beams is $90^\circ$, the term crossed-beams is generally used, and the term merged-beams applies to the case when $\theta = 0$. The term inclined beams generally refers to other angles of intersection. In the special case when $\theta = 0$ and $E_1/m_1 = E_2/m_2$, the merged beams have the same speed and direction in the laboratory frame and the relative energy is zero [4]. The practical low-energy limit is determined by beam divergences and internal energy distributions. The colliding-beams method provides access to a wide range of collision energies and generally favors measurements of total rather than differential collision cross sections.

Colliding-beams experiments are particularly well suited to absolute measurements, which require quantification of the spatial overlaps of the two beams. This is generally accomplished by measuring the intensity distributions of the beams in their region of interaction using translating slits or apertures, and calculating the so-called form factor integral [5]. In the case of crossed or inclined beams, one-dimensional beam intensity profiles are measured in the direction perpendicular to their plane of intersection, whereas for merged beams, profiles in two dimensions are required. The animated or dynamic beams method [6] cleverly circumvents the need for profile measurements in crossed-beams experiments by recording the products as one beam is translated physically through the other. Products due to beam-beam interaction are separated from backgrounds due to interactions of either beam with residual gas or surfaces by beam-chopping or coincidence techniques that are unnecessary with the animated beams method. Space charge generally limits the maximum densities that are achievable in ion beams to the $10^6 - 10^7$ cm$^{-3}$ range, which is less than typical background gas densities in vacuum systems. Space charge forces are largest for highly charged ion beams, requiring ultra-high vacuum conditions in colliding-beams experiments.

3. Electron-ion collisions

During the last decade, collisions of electrons with multiply charged ions have been studied in at least nine different laboratories throughout the world using colliding-beams methods. A few illustrative examples of experimental setups and results for ionisation, excitation and recombination processes are given.

3.1. Electron-impact ionisation

A dynamic crossed-beams apparatus [7] developed at the University of Giessen, Germany for the measurement of electron-impact ionisation cross sections is shown schematically in figure 2. The general layout is typical for such experiments, which require careful attention to beam transport, differential pumping and collection/detection of collision products. Multiply charged ions are created by an electron-cyclotron-resonance (ECR) source that produces intense continuous ion beams, ideally suited to colliding-beams experiments.
Cross sections for electron-impact ionisation of multiply charged ions with occupied inner-electron shells often have significant contributions from the excitation of inner-shell electrons followed by autoionisation. An example presented in figure 3 is the measured cross section [8] for single ionisation of Ti$^{3+}$, which is dominated by unresolved excitations of the 3s and 3p subshells.

In the case of Li-like ions, the simplest with an inner shell, such a measurement is capable of resolving excitation-autoionisation (EA) contributions as well as features due to resonant-excitation double-autoionisation (REDA) and resonant excitation-auto-double ionisation (READI). The measured cross section [9] for electron-impact ionisation of O$^{5+}$ in the energy region where 1s excitations occur is presented as an example in figure 4.

Measurements of electron-impact single and multiple ionisation of highly charged Ni ions measured by the Louvain-la-Neuve group [10] indicate substantial EA contributions in the single ionisation of Ni$^{12+}$ and Ni$^{14+}$, whereas multiple ionisation is dominated by inner-shell ionisation followed by single or double autoionisation.
3.2. Electron-impact excitation
A merged-beams electron-energy loss technique has been developed and implemented for near-threshold measurements of cross sections for electron-impact excitation of multiply charged ions at both the Oak Ridge and Jet Propulsion Laboratories. The JILA-ORNL setup [11] is shown in figure 5.

The electron beam is merged with and demerged from the ion beam by trochoidal $\mathbf{E \times B}$ analysers. A position-sensitive detector registers electrons that have lost a fixed amount of energy. A novel filter lens developed at JPL separates elastically and inelastically scattered electrons, extending the energy range of the technique. Typical results from the JPL group [12] for $2s^2 \, ^1S \rightarrow 2s2p \, ^1P$ excitation of $\mathrm{O}^{4+}$ are compared with ORNL measurements and theory in figure 6.
3.3. Electron-ion recombination

Intense, well-characterized electron-cooler beams in heavy-ion storage rings provide ideal merged-beams setups for high-resolution measurements of electron-ion recombination. Such processes involving highly charged ions have been studied extensively in storage rings in Heidelberg (TSR), Darmstadt (ESR) and Stockholm (CRYRING). The speed of the electron beam matches that of the ion beam during cooling and is intermittently stepped to access a range of electron-ion collision energies. Radiative recombination dominates at low energies, whereas Rydberg series of dielectronic recombination resonances characterize the process at higher energies. Figure 7 presents an example from the ESR storage ring of electron recombination with Li-like Pb\(^{79+}\) from which precise determination of the 2s\(^{1/2}\) – 2p\(^{1/2}\) energy splitting provides a stringent test of QED in intense electric fields and of the influence of nuclear size [3].

4. Heavy-particle collisions

Colliding-beams methods have been applied primarily to the study of electron-transfer processes in heavy-particle collisions involving highly charged ions. A merged-beams apparatus at Oak Ridge, shown in figure 8, has permitted electron capture by multiply charged ions from atomic hydrogen to be studied at relative energies ranging from 0.1 eV/u up to several keV/u. Typical results shown in figure 9 for electron capture by Ne\(^{14+}\) ions from atomic hydrogen show a rise with decreasing energy below 1 eV/u that is attributed to trajectory effects resulting from the attractive ion induced dipole interaction [13].

*Figure 6.* Merged-beams electron-energy-loss measurements of 2s\(^{1}\)S \(\rightarrow\) 2s2p\(^{1}\)P excitation of O\(^{14+}\) are compared with R-matrix theory [12]. The theory curve in the right panel has been convoluted with a Gaussian of FWHM 0.2 eV to match the energy resolution of the experiments. The open squares were measured at ORNL and the solid circles at JPL.

*Figure 7.* Electron-ion recombination measurements for Li-like ions at the ESR heavy-ion storage ring provide stringent tests of nuclear size effects in QED [3].
An inclined-beams technique has been developed in Giessen for the study of electron transfer in ion-ion collisions [14]. The technique has been applied to a variety of collision systems involving multiply charged ions. The setup features two ECR ion sources and coincident detection of both charge-changed product ions. Typical results for electron capture by He\textsuperscript{2+} ions from multiply charged Li-like ions [14] are shown in figure 10.
5. Photon-ion collisions

The implementation of so-called third-generation synchrotron light sources throughout the world has facilitated high-resolution quantitative studies of photoionisation of multiply charged ions using merged-beams and photoion-yield spectroscopy [15]. A typical endstation used at the Advanced Light Source is shown in figure 11. Similar set-ups exist at ASTRID (Århus), Super ACO (Orsay), Spring-8 (Hyogo) and the Photon Factory (Tsukuba). Typical results for photoionisation of Xe\(^{6+}\) from three independent experiments [16, 17] are presented in figure 12 and compared to theoretical estimates.

The photoionization cross section is dominated by strong resonances due to 4d \(\rightarrow\) np (n \(\geq\) 5) and 4d \(\rightarrow\) nf (n \(\geq\) 4) excitations. Since the active electrons are all in the same shell, the 4d \(\rightarrow\) 4f resonance decays by an extremely fast Super-Coster-Kronig transition and is therefore broad.
6. Summary and Outlook

Colliding-beams techniques are versatile and when coupled with an ECR ion source, provide absolute data on many fundamental atomic processes involving highly charged ions. The power of such techniques is amplified when coupled with major facilities such as heavy-ion storage rings and synchrotron light sources. Free-electron-lasers that are just coming on line or are under development promise to open exciting new windows on highly charged ions and their interactions.

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