The bubble chamber technique for low energy fragmentation processes in atomic, molecular, and surface physics.

COLTRIMS

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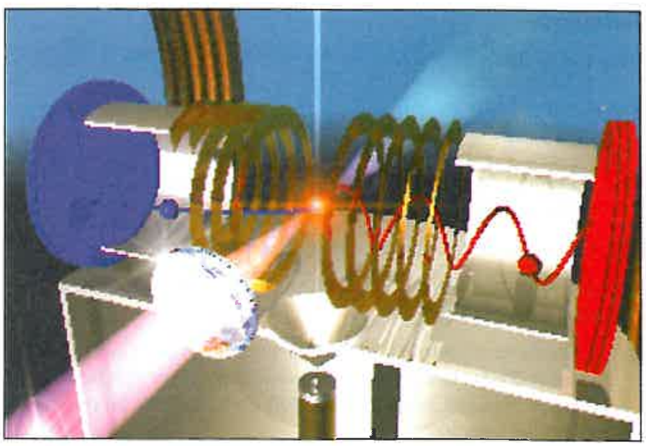
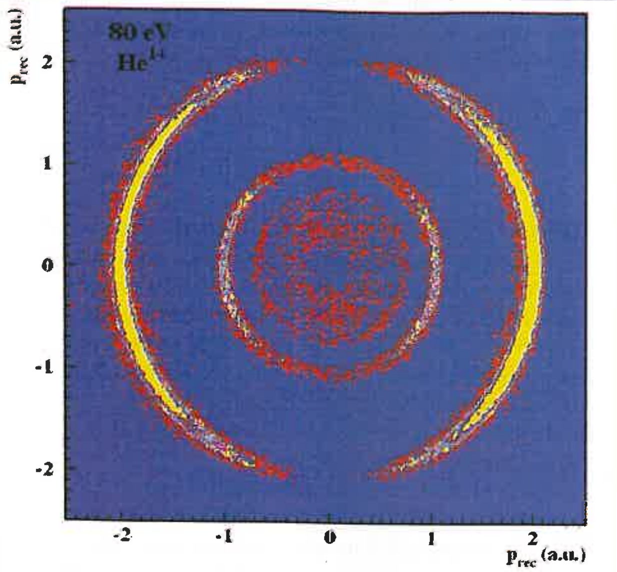
Correlated many-particle dynamics in Coulombic systems, which is one of the unsolved fundamental problems in physics, can now be experimentally approached with so far unprecedented completeness and precision. The recent development of the COLTRIMS technique (COLd Target Recoil Ion Momentum Spectroscopy) [1,2] provides a coincident multi-fragment imaging technique for eV and sub-eV fragment detection. In its completeness it is as powerful as the bubble chamber in high energy physics. Based on state-of-the-art cooling techniques (super sonic jets, MOT etc.) and nuclear physics imaging methods fragmentation processes of atoms, molecules, clusters, as well as of solid state surfaces induced by single photon or multi photon laser absorption, electron or ion impact can be explored completely in momentum space and, for ions, with micro-eV resolution. In recent benchmark experiments [1,2] quasi snapshots (duration as short an atto-sec) of the correlated dynamics between electrons and nuclei has been made for atomic and molecular objects. This new imaging technique has opened a powerful observation window into the hidden world of many-particle dynamics.

The principle of the method, namely measuring the momentum of the emitted charged particles from an atomic fragmentation process is as simple as determining the trajectory of a thrown stone. From knowing the position, from where the stone was slung and where it hits the target as well as measuring its time-of-flight, the trajectory of the stone and thus its initial velocity vector can precisely be determined. Furthermore, in order to achieve good precision we have to know whether the person, who throws the stone, was at rest in the frame of observation or with which relative velocity this person was moving. Thus to obtain optimal momentum resolution for the exploding fragments one has to bring the fragmenting object to a complete rest in the frame of measurement before the reaction occurs, i.e. if the object is a gas atom or molecule one has to cool it down to sub-milli Kelvin temperatures.

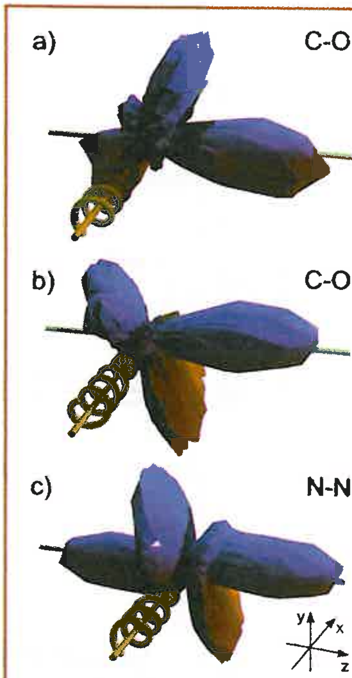


▲ Fig. 1: Artist view of the COLTRIMS imaging system [1,2].



▲ Fig. 2: Recoil-ion momentum distribution for single ionization of He induced by a single photon of 80eV [1,2].

In figure 1 the principle of the new reaction microscope (synonym: COLTRIMS) is presented. In a well designed electric field configuration (static or pulsed) the positively as well as the negatively charged fragments are projected (typically with 4π solid angle) on two position-sensitive detectors. Measuring the impact position on the detector (typically < 0,1mm resolution) and the time-of-flight of the fragment (TOF) between the moment of fragmentation till hitting the detector, the particle trajectory, and thus the particle momentum after fragmentation, can be determined. To improve its momentum resolution electrostatic lenses can be incorporated into the projection system, such that the influence of the unknown size of the target region, from where the fragments originate, can completely be eliminated [1-4]. To detect also the higher energetic electrons, magnetic fields, superimposed over the electric field [1-3]), as well as pulsed electric fields can be used. If



▲ Fig. 3: Angular distribution for K photo electron emission in diatomic molecules after K shell ionization by a circular polarized photon of 300eV [5].

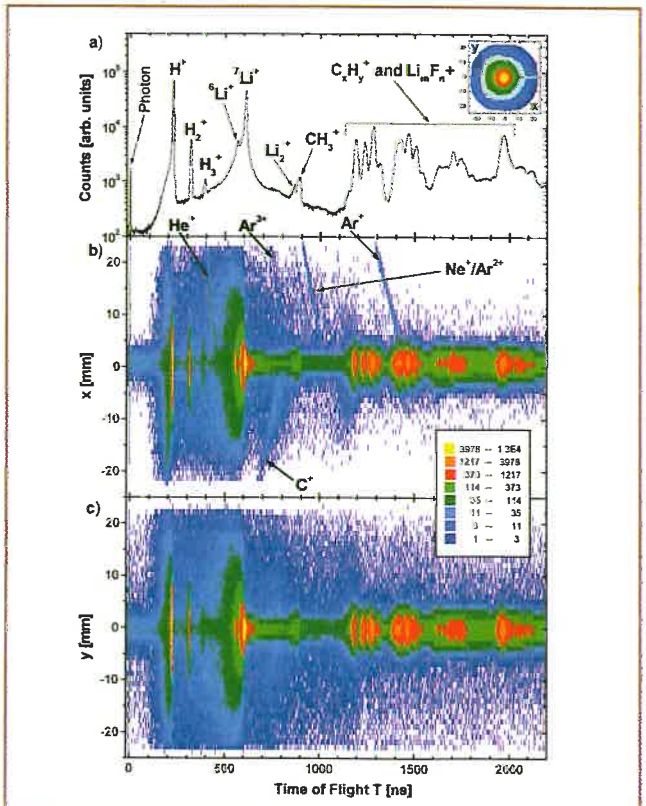
particle detectors based on fast delay-line position read-out are used multi-hit detection is possible. Even two particles hitting the detector at the "same" instant ($\Delta t <$ 1nano-sec) can simultaneously be detected. The number of detected multi-hits is practically only limited by the electronics needed to store in event mode all information. In future even up to 100 particles per microsec might be detectable if fast transient recorder units with channel resolution of about 0,1 nano-sec become available. Thus, for low energy particles (micro-eV to hundreds of eV) the COLTRIMS method is indeed as powerful as advanced bubble chamber systems for high energetic (mega-eV) particles. It is even comparable with modern TPC systems used in high energy physics. Furthermore the rate of fragmentation processes per second can exceed several 100kHz.

As a typical example for COLTRIMS data, figure 2 shows the recoil-ion momentum distribution of He^+ ions from the photo-electric effect at a single atom (the electric field vector of the linear polarized photon is parallel to the horizontal direction). This data set is simultaneously obtained for all momenta. Using COLTRIMS, the typical duration of such measurements is less than one hour for data sets. The physics of these data is discussed in ref. [1,2].

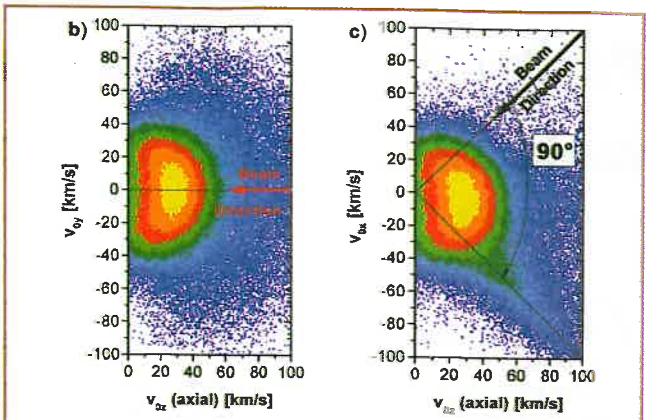
In figure 3 the angular distribution for K photo electron emission for the reaction

$$\gamma\text{(circular polarized)} + AB \Rightarrow A^+ + B^+ + e_\gamma + e_{K\text{-Auger}}$$

is shown. The molecular axis is oriented parallel to the electric field vector (z-axis). The circular polarization and the impact direction of the photon are indicated by the arrow. In this measurement both photo electron and recoil-ion momentum



▲ Fig. 4: Secondary ion distribution from a LiF+Al surface after 25keV/u Ar^{0+}impact (see text).



▲ Fig. 5: Secondary H^+ ion velocity distribution (see figure 4 and text).

distribution are detected in coincidence and the digitized data are stored in list-mode technique.

The COLTRIMS imaging method can be applied also to surface fragmentation processes. In figure 4a the time-of- flight (TOF) spectrum for ion emission from a surface after single ion impact (25keV/u Ar^{0+} on LiF+Al) is shown, the insert in figure 4a shows the ion position distribution on the detector.

In figures 4b and c the ion TOF distribution (perpendicular to the surface, z direction) as function of the x and y directions are presented. X and y direction are parallel to the surface, where the x axis is the projection of the incoming fast ion direction. In figure 5 for H^+ ions the velocity distributions are shown for the x, y, and z directions. In one measurement the whole momentum distribution of all emitted ions is detected with high momentum resolution. Details of the physical interpretation of these data are given in ref. [6].

Many new applications for COLTRIMS in different areas of AMOP physics are under way. Experiments of atomic and molecular fragmentation processes in strong femtosec laser pulses have recently been performed yielding precise information on sub femto-sec dynamics of the correlated motion of electrons and nuclei in strong laser pulses. The detection of fragmentation of BE condensates is in preparation. Last not least the fragmentation of biological species is an interesting application for the COLTRIMS imaging method.

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References:

[1] J. Ullrich, *et al.*, J. Phys. B 30 (1997) 2917, "Topical Review"
[2] R. Dörner, *et al.*, Physics Reports 330 (2000) 95-192
[3] R. Moshammer, *et al.*, NIMB 108 425 (1996)
[4] V. Mergel, PHD thesis University Frankfurt 1996
[5] T.Jahnke, *et al.*, PRL 88 (2002) 073002
[6] T.Jalowy, PHD thesis University Frankfurt, 2002