# High Resolution Recoil Ion Momentum Spectroscopy

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### Abstract

A newly developed spectroscopy technique is presented to study the kinematics of many-particle atomic collision processes with high momentum resolution and high detection efficiency. These goals are achieved by detecting the low energetic recoil ion in coincidence with the emitted electrons or scattered projectiles. The low energetic recoil ions can be detected with nearly 100% efficiency by projecting them with a weak electrostatic field on a position-sensitive detector. The high momentum resolution for the recoil ion is obtained by using a very cold super- sonic gas-jet as target and measuring the recoil-ion trajectory and its time-of-flight with a position-sensitive multichannel plate detector. The basic components of the experimental set-up for **COLTRIMS** (**COL**d **T**arget **R**ecoil **I**on **M**omentum **S**pectroscopy) and first results obtained with this technique are presented. First results for target and projectile ionization in fast ion-atom collisions and photo ionization processes are described. Future applications of **COLTRIMS**, e.g. in the field of photon induced ionization processes for the investigation of subatomic many electron dynamics are discussed.

## 1 Introduction

High-resolution spectroscopy techniques in atomic collision physics in general suffer from the restriction of small detection efficiency. Thus the coincident detection of several reaction products to study e.g. many-particle effects becomes extremely difficult. This is one of the reasons for the lack of systematic experimental data on the many-particle momentum exchange in atomic collision processes. Only very few data have been published so far in the literature (Coplan *et al.* 94, Schwarzkopf *et al.* 93, Huetz *et al.* 95), e.g. for (e,2e) and ($\gamma$,2e) reactions. In these experiments the traditional electron-electron-coincidence technique was used for ionization processes. In case of three electrons in the continuum final state, such triple e-e-e coincidence techniques yield extremely low coincidence detection efficiency, particularly if high momentum resolution is required. To our knowledge only two groups have reported on experiments in the literature (Lahmam-Bennani *et al.* 92, Ford *et al.* 95).

In case of detecting the recoil ion instead of electrons, however, this recoil ion can be detected with high resolution and nearly 100% efficiency. To achieve high resolution the initial thermal motion of the target atoms (i.e. target temperature) has to be strongly reduced and the recoil-ion trajectory and its time-of-flight (TOF) must precisely be measured. Using standard super-sonic target devices, for helium as target gas an initial target temperature of 0.2K was obtained which is equivalent to a momentum distribution width of approximately $0.2 a.u.$. To reach better resolution we use a precooling for the helium gas down to 10 K before the supersonic expansion, in the second generation gas-jets. With this technique an internal gas temperature of 10mK can be reached. Depending on the size and the geometry of the recoil-ion spectrometer a relative resolution below 1% can be achieved for the recoil-ion momentum. Thus for small recoil-ion momenta a resolution of $0.02 a.u.$ is feasible with a relatively small detection device. In not too far future Laser-cooled gas targets may even provide lower target temperatures and by using large scale detection devices a relative momentum resolution of $10^{-3}$ is achievable. The ultimate limit of momentum resolution obtainable with presently thinkable techniques may approach 0.001 a.u.

For fast ion-atom collision processes, as will be shown below, the recoil-ion transverse (with respect to the incoming beam) momentum component is a good measure for the impact parameter like the projectile scattering angle, and its longitudinal component reflects the Q-value (inelasticity due to electronic excitation and ionization) and the mass exchange (number of transferred electrons) in such collisions. Thus the measurement of the longitudinal momentum is equivalent to an energy-gain spectroscopy and it can provide for the projectile energy gain or loss in fast ion atom collisions a relative resolution even in the $10^{-9}$ regime (Mergel *et al.* 95). Thus recoil-ion momentum spectroscopy is a tool which yields even in GeV ion-atom collisions precise information on the electronic transitions. Furthermore also for (e,2e) or (e,3e) or ($\gamma$,2e) measurements **COLTRIMS** provides a very efficient way to study the complete momentum exchange between the electrons and nuclei in such collision processes. For a recoil-electron coincidence an overall coincidence efficiency of 10 to 20% is easily feasible. Furthermore **COLTRIMS** is not limited to any spatial direction thus complete angular distributions are obtained.

In section 2 the experimental technique is explained. In section 3 of this paper first results (Dörner *et al.* 94, Spielberger *et al.* 95) for different collision processes are presented and the power of the new technique is discussed.

# 2 Experimental Set-up

The measurement of the momentum transfers between different atomic reaction products is always performed by determining the final and the defining initial momenta of these products. Furthermore the accuracy of the measurement of the transfered momentum is generally better, when the transfered momentum is of the order of the final or large compared to the initial momentum. The measurement of the initial momenta, however, becomes even obsolet when it is very small compared to the transfered momentum. These requirements are perfectly fulfilled in the COLTRIMS spectroscopy technique.

The main components of **COLTRIMS** are the very cold target gas jet and the recoil-ion spectrometer with a position-sensitive detector (see figure 2). In the center of the recoil-ion spectrometer the incoming projectiles collide with the cold target atoms.

In the presently used **COLTRIMS**- systems a supersonic helium gas jet, with an internal temperature of about 10 mK, provides the rather cold thin gas target. The helium gas expands through a $30\mu$m hole. The gas source is mounted on the cold finger of a cryo pump and is cooled down to a temperature of 10 to 35K. The gas jet is collimated at a distance of about 10mm from the expansion hole by a skimmer of 0.3mm diameter. The gas jet leaves the collision chamber through a hole of about 1cm diameter into a jet dump, pumped by a small turbomolecular pump (260 or 360l/sec) to reduce the helium residual gas pressure in the scattering chamber to $10^{-8}$mbar. Typical pressures are: 400mbar on the high pressure side of the $30\mu$m hole and $5 \times 10^{-4}$mbar in the source chamber (preskimmer stage). Both chambers are separately pumped by two small (260 or 360l/sec) turbomolecular pumps. At the collision region, 30mm above the skimmer, the helium gas jet has a diameter of 1 to 2mm and a local density of $1 \ldots 5 \times 10^{11} cm^{-2}$. The internal temperature is lower than 0.1K in the jet direction (Brusdeylins *et al.* 89). Perpendicular to the jet the atoms have a momentum spread of $\pm 0.02 a.u.$ given by the velocity of the jet and the skimming geometry. Figure 2 shows the gas jet device with the target and source chamber.

The recoil ions created in the intersection region of the gas jet with the ion beam are extracted by a weak homogenous electrostatic field varying between 0.1 to about 10V/cm depending on the detected recoil-ion momenta. After passing a field-free drift region they are post accelerated onto a position-sensitive channel-plate detector with a position resolution of $< 0.2mm$. Great care has been taken to assure proper field conditions in the spectrometer area.

In the second generation **COLTRIMS** spectrometers (Mergel 96) the drift region was separated from the extraction region by a woven mesh of 0.25mm mesh width. A stack of two of these meshes with 1mm spacing shields the drift region from the strong postaccelaration field just in front of the detector. On all parts, including the meshes, a thin layer of carbon is evaporated to avoid contact potentials. However, recent tests with improved spectrometers (Dörner *et al.* 95, Mergel 96) have shown, that all meshes influence somewhat the recoil-ion trajectory and are thus limiting the

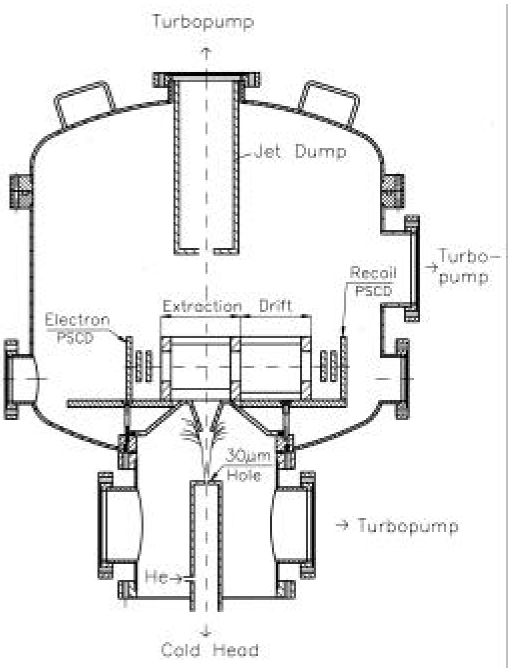

Figure 1: The upper part shows the target chamber with the recoil ion spectrometer, the lower part the source chamber where the gas jet is created by expanding through the $30\mu m$ nozzle, mounted on the cold head of a cryogenic system.

resolution to about 0.15a.u.. Therefore in the most recent spectrometers the electrostatic fields are created without using meshes between extraction and drift region. The structure width of the mesh in front of the channelplate is now chosen to be 0.05mm. A homogeneous field in the extraction region is obtained by shielding this area from external potentials e.g. with a carbon fiber. One thin carbon fiber of $7\mu$m diameter and 10m length (or in some cases a thin metallic wire, see e.g. Kambara *et al.*95) is wound around four supporting germanium coated insulator screws. The fiber defines the potential in the extraction region and divides the voltage. Figure 2 shows a schematic of the third generation recoil-ion spectrometer. A sudden potential change in the extraction region provides a field geometry, which focuses recoil ions with the same momentum but created at different target positions onto the same position on the detector.

The time-of-flight of the recoil ions is measured by a coincidence with projectiles, electrons or the machine pulse, when using a pulsed beam. From the time-of-flight and the position on the channel-plate detector the three momentum components of the recoil ion can be calculated.

Important components of the **COLTRIMS** system are the position-sensitive recoil-ion or electron detectors. The standard size detector is a 50 mm diameter chevron or Z-stack channelplate electron multiplier with an active area of typically 47mm diameter. The position information is obtained either from charge division us-

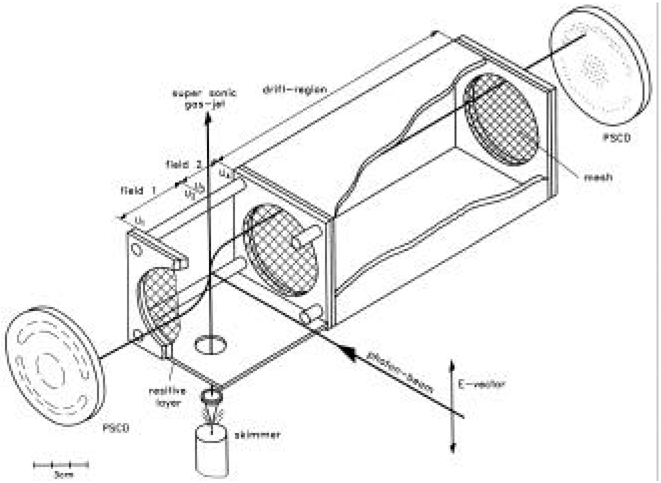

Figure 2: High-resolution recoil-ion momentum spectrometer with threedimensional focusing and the precooled supersonic gas jet target.

ing "wedge-and-strip" anode structures or from time measurements using "delay-line" anode structures. Both position readout systems can yield a position resolution better than 0.1 mm depending on the electronic moduls (preamplifiers, constant fractions, analog digital or time digital converters etc.) available. It might worth to notice that the use of a Z-stack channelplate system yields, even for electron detection, signals far separated from noise pulses providing even with "standard electronic moduls" very good position resolution.

The resolution e.g. of the apparatus (figure 2) used by Dörner et al. 95 for $p_{||R}$ is $0.07 a.u.$ (FWHM). This resolution is limited by the precooling target temperature of about 30 K.

Opposite to the detector for the recoil ions a second position-sensitive detector for electrons is located. For the same given momentum the electrons are much faster than the recoil ions due to the lighter mass. Thus, they are nearly unaffected by the weak electrostatic extraction field. The solid angle for electron detection is determined for the high energetic electrons by the geometry of this device and can reach for the present spectrometer (Dörner *et al.* 95) about 15%, for low energetic electrons (less than about 5eV kinetic energy) the solid angle approaches nearly 100%.

## 3 Experimental Results and Discussion

The kinematical calculations for the recoil ion in fast ion-atom collisions become most simple if the momentum transfer between the collision partners is small compared with the initial momentum in the center-of-mass system. In this case the longitudinal momentum of the recoil ion depends only on the inelastic energy gain or loss of the collision process (i.e. electronic excitation, emission of Bremsstrahlung etc.) and on the mass transfer in electron capture collisions; while the transverse momentum of the recoil ion reflects in "close" encounters the nuclear impact parameter. The condition of small momentum transfer is fulfilled in most of all atomic reactions of interest here. A detailed deriviation of the important formulas for the recoil-ion kinematics is presented in ref. (Mergel 94 and Ullmann *et al.* 95 ).

In the case of absorption of a single photon the approximation of small momentum and energy transfer is certainly no longer valid. On the contrary, for single ionization the electron absorbs all the photon energy and gets the momentum $p_e = \sqrt{2E_\gamma - E_B}$. The recoil ion has to compensate this momentum. So the ions are also distributed on a momentum sphere of a radius $p_R = \sqrt{2E_\gamma - E_B}$ in the center-of-mass system, where $E_\gamma$ is the photon energy. Because of the momentum of the incoming photon ($p_\gamma$) this sphere is shifted in the Lab system by $p_\gamma = E_\gamma/c$.

In figure 3 the measured recoil-ion momenta in the x-y-plane are plotted. x and y are the directions of the electric field vector and of the momentum of the incoming photon, respectively. One can see two kinematic circles: the one with the larger radius corresponds to the emission of one K-electron, where the other remains in the He ground state; the one with the smaller radius corresponds to ionization of one K-electron and simultanious excitation of the second He electron to the L-shell.

In this chapter the following ionization processes investigated by **COLTRIMS** will be discussed:

1. $He^{1+} + He \rightarrow He^{2+} + He^{1+} + 2e$

2. $\gamma + He \rightarrow \gamma' + He^{2+} + 2e$

In reaction 1 (Dörner *et al.* 94 and Wu *et al.* 94) the projectile and the target are simultaneously ionized either by nucleus-electron or by electron-electron interaction. Both interaction processes yield different recoil-ion momentum distributions and can, indeed, be experimentally separated by **COLTRIMS**. In reaction 2 He-double ionization has been investigated for high-energy photon Compton scattering (Spielberger *et al.* 95). Measuring the recoil-momentum, the Compton scattering and photo-effect processes were separated.

Reaction 1: It is generally assumed that in fast ion-atom ionization processes the target ionization is due to a target-electron projectile-nucleus interaction. However, if the projectile is not fully stripped its remaining electrons can also contribute to the target ionization process via a pure electron-electron interaction (Montenegro *et al.* 92, Montenegro *et al.* 93, Dörner *et al.* 94, Wu *et al.*94). In recent times the importance of these e-e contributions were discussed by comparing total ionization cross sections with theory (Hülskötter *et al.* 91, Montenegro *et al.* 93). So far it has been rather difficult to separate these different ionization mechanisms by traditional experimental detection techniques. **COLTRIMS**, however, provides a new experimental tool, to separate the different mechanisms by the very small differences in their final

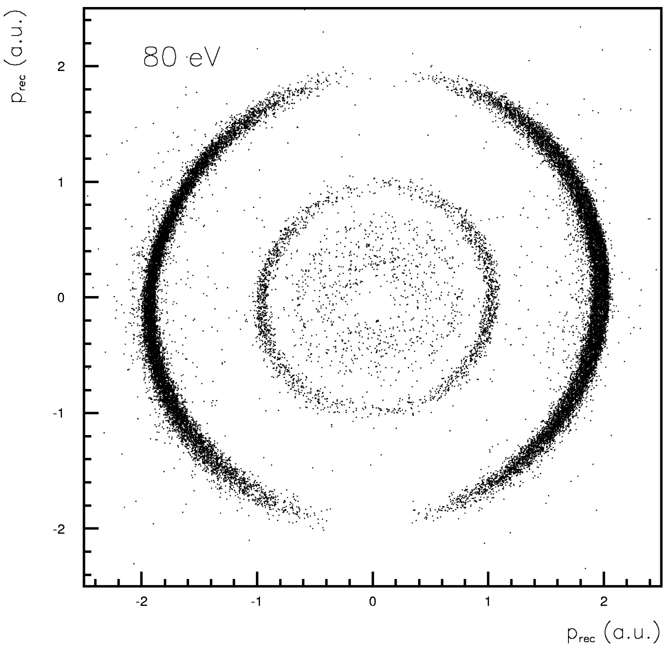

Figure 3: Recoil-ion momentum distribution for the He($\gamma$,e)He$^{1+*}$ reaction, induced by linearly polarized light. The x-axis is parallel to the electric field vector of the photon. The photon beam direction is perpendicular to the figure plane.

momentum states. In the case of a nucleus-electron interaction the projectile nucleus has to penetrate the target atom in a "close" collision yielding a transverse momentum exchange between the projectile and the target nuclei of more than $1 a.u.$. In case of e-e interaction only the two electrons in the projectile and target have to approach each other and the nuclei are mostly distant spectators. Thus in these collisions a smaller transverse momentum is given to the recoiling target ion. Also the longitudinal momentum of the recoil ion in the case of e-e interaction should be smaller than for the nucleus-electron ionization process. In figure 3 for different projectile bombarding energies for He$^{1+}$ on He the measured recoil momentum distributions as function of the transverse and the longitudinal momentum components are given. For experimental reasons the reaction channel with simultaneous target and projectile ionization was separated by a recoil-projectile coincidence, since in this channel the e-e contribution is easily visible. Figure 3 shows that the distributions show two separate peak positions whose relative strengths vary with projectile energy. The peak near zero-recoil-momentum is indeed resulting from e-e interactions, whereas the peak at larger recoil momentum is due to nucleus-electron ionization processes. Both contributions show the expected projectile energy ($E_p$) dependence. The n-e interaction decreases with $E_p^{-2}$, whereas the e-e decreases with $E_p^{-1}$ towards higher projectile energies. The e-e contribution is only observable above the expected threshold velocity. In figure 3 the recoil-ion momentum distribution for $130 eV$ electron impact on helium is also shown. This distribution agrees nicely with the e-e contribution at 1MeV Helium impact energy (i.e. the same projectile velocity). Using the same recoil detection technique (Wu *et al.* 94) could recently separate for $F^{8+}$ on helium the e-e and n-e contributions as well and determine the absolute cross sections for both ionization mechanisms.

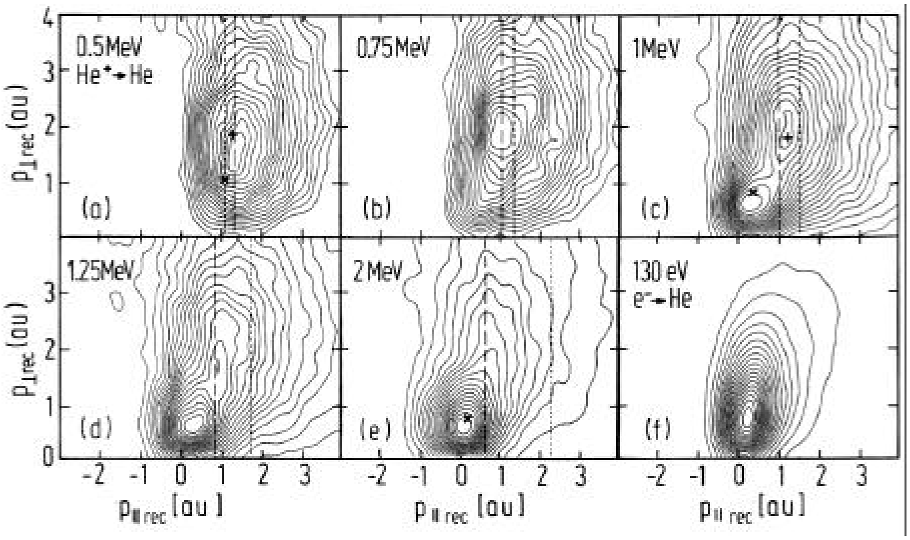

Figure 4: Doubly differential cross sections for reaction 1. The y axis shows the recoil transverse, the x axis the recoil longitudinal momentum. The contour lines represent a linear plot. Part f shows the recoil ion distribution for 130 eV electron impact.

Reaction 2: **COLTRIMS** is a powerful technique for "complete" experiments of photon induced ionization processes. For example, $(\gamma 2e)$ reactions can very efficiently be investigated by recoil-electron coincidence detection systems replacing the traditional low efficiency electron-electron coincidence technique. Since the absolute value of the recoil-ion momentum vector can be detected with nearly 100% efficiency and high resolution, only the emission angle of one electron has to be measured using large solid angle position-sensitive electron detectors. Thus a nearly 20% total coincidence efficiency is obtained. (Vogt *et al.* 95) have applied **COLTRIMS** recently, measuring the complete momentum balance in $(\gamma, 2e)$ reactions for different photon energies at HASYLAB in Hamburg and at the ALS in Berkeley. They achieved a coincidence rate for the He-double ionization channel of about 100 coincidences per sec. In particular **COLTRIMS** will be a very powerful technique to study the angular distributions of the reaction products near the photo-ionization threshold. It can be applied to atomic as well to molecular targets.

(Spielberger *et al.* 95) have recently used **COLTRIMS** to measure the ratio of total cross sections of He double to single ionization by high-energy photon impact $(\hbar\omega = 9keV)$. **COLTRIMS** provides a clean method to separate the photo-effect and Compton-effect induced ionization processes. In case of photo-ionization the recoil-ion momentum is large $(\sqrt{2E_\gamma - E_B})$. For a photon energy of 9 keV the recoil momentum this is approximately $25a.u.$. In case of Compton scattering the recoil ion is mostly a spectator and its final momentum is not very different from that in its initial state, and typically of the order of $1a.u.$. Using a "warm" super-sonic jet expansion (Jagutzki *et al.* 94) with a target density of about $5 \times 10^{12}$atoms/$cm^2$ the corresponding cross section ratios of single to double ionization of helium for photo-effect and Compton-effect could separately be measured (see Spielberger et al 95). Furthermore the Compton profile (*i.e.* the three-dimensional momentum distribution of the recoil ions for the Compton scattering process) could be determined with very good statistics too. In figure 3 the density plot of the measured recoil-momentum distribution for $He^{1+}$ ionization is presented. The outer ring distribution is due to photo-effect ionization and the inner spot is due to the Compton scattering process. Since in this experiment the photon beam had a broad energy distribution (parasitic experiment at the direct beam at the HASYLAB undulator beam line) the photo-effect distribution must show a large momentum width too.

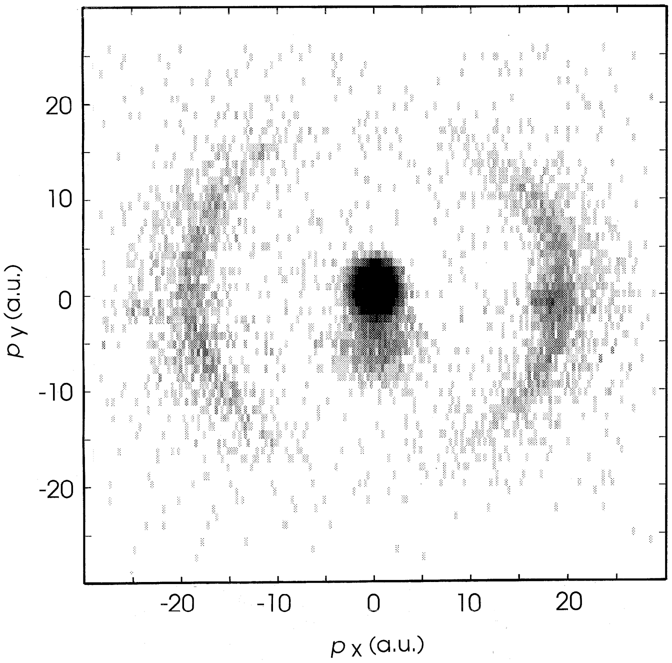

Figure 5: Measured momentum distribution of $He^{1+}$-ions created by 9keV photons. The x-axis shows the recoil momentum in the direction of the polarization axis of the photons. The direction of the photon beam is perpendicular to the figure plane. The peak in the center results from comtpon scattering, the ring around from photoabsorption.

## 4 Outlook and Perspectives

Because of its momentum resolution and high detection efficiency for slow recoil ions **COLTRIMS** is an excellent technique to study the momentum exchange in many-particle atomic collision processes. It is well suited to investigate the dynamics of subatomic many-electron processes by electron-recoil coincidence methods particularly for photo-ionization processes. Its application is, however, not restricted to the field of atomic collision physics. It may open new detection windows for other fields in physics, *e.g.* nuclear physics, where *e.g.* $\beta$-decay can be investigated with this method. The angular correlation between electron and neutrino and even the neutrino mass can be determined with improved precision. Using super-sonic gas jets or in the near future even laser cooled target devices, a recoil momentum resolution of 0.01 or even $0.001 a.u.$ may be feasible, if the recoil-ion trajectory and the recoil-ion TOF can be measured with the required precision. This requires large position-sensitive detection devices which can be developed from existing technology. The momentum of the emitted electron has to be measured as well (emission angle and TOF) with equivalent precision. These angular correlation measurements provide detailed information on the electron-neutrino angular correlation. With sufficiently large detection devices (several meters diameter) a neutrino-momentum resolution of a few eV/c seems feasible. One notes that in such a measurement the neutrino mass can, in principle, be derived from one single decay event. Using laser cooled targets even polarized target nuclei can be provided.

Last but not least, using very cold molecular targets, the Coulomb explosion of interesting molecules can be investigated. The momenta of all emitting fragments can be measured with high precision by using multi-hit detection devices, if all of these fragments are ionized (except one). Also here a momentum resolution of $0.02 a.u.$ seems feasible.

## 5 Acknowledgement

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