Setup for Precise Measurements of beta-decay in Optically Trapped Radioactive Na

Sohani, Moslem

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Chapter 6

The $\beta$-detector

The $\beta$-decay experiment is based on observing the recoiling ion along with the decay electron or positron. The measurement of the recoil-ion and $\beta$-particle momenta gives the kinematics of the decay. The detection of the $\beta$-particle is the start signal and it is necessary to reconstruct the recoil-ion momentum from the signals extracted from the MCP. In this chapter the design and the characteristics of the $\beta$-detector are discussed.

6.1 $\beta$-detector Requirements

The $\beta$-detector serves two main purposes. Firstly, it serves to resolve the momentum of the $\beta$-particle. Therefore it needs to give the direction and the energy of the $\beta$-particle. Secondly, it provides a start signal for a decay event, because the $\beta$-particle is much faster than the recoil-ion. The timing resolution of the $\beta$-detector is therefore crucial and should be in the ns region.

For the selection of a particular type of detector various practical issues and physical effects need to be considered. In particular the timing requirements, the electron backscattering effect, vacuum compatibility, and a window through which $\beta$-particles can leave the UHV chamber largely undisturbed, are considered.

6.1.1 Timing

The $\beta$-particles travel almost with the speed of light and reach the $\beta$-detector within ns after a $\beta$-decay, if it is located within a few 10 cm. The TOF of the recoil-ion through the reaction microscope is in the $\mu$s range, if they are accelerated to a few keV energy. The $\beta$-detector can thus serve as a trigger for
Table 6.1: The specifications of different possible detectors for $\beta$-particles.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Rise time</th>
<th>Decay time</th>
<th>Backscattering from bulk material</th>
<th>UHV compatibility</th>
<th>Energy resolution for 1 MeV $\beta$-particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-conductor</td>
<td>$\sim 10$ ns*</td>
<td>$&lt; 50 \mu$s**</td>
<td>$&gt;30%$</td>
<td>Yes</td>
<td>$&lt; 10$ keV</td>
</tr>
<tr>
<td>Plastic Scintillator</td>
<td>$&lt; 1$ ns</td>
<td>$1 - 3$ ns</td>
<td>$&lt;10%$</td>
<td>No</td>
<td>$&gt; 80$ keV</td>
</tr>
<tr>
<td>NaI Scintillator</td>
<td>$\sim 20$ ns</td>
<td>$230$ ns</td>
<td>$&gt;30%$</td>
<td>No</td>
<td>$&gt; 50$ keV</td>
</tr>
<tr>
<td>BaF$_2$ Fast Comp.</td>
<td>$&lt; 1$ ns</td>
<td>$&lt; 1$ ns</td>
<td>$&gt;30%$</td>
<td>Yes</td>
<td>$&gt; 80$ keV</td>
</tr>
<tr>
<td>Slow Comp.</td>
<td>$620$ ns</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*- Depends on the thickness of the detector.

**- Depends on the pre-amplifier.

data the reaction microscope, provided that it has a fast response. The resolution and the fall time of various materials that are commonly used to detect $\beta$-particles are tabulated in table 6.1. A steeply rising signal is favorable for the timing speed of a detector. At the same time a rapidly falling signal gives a rather short dead time of a detector. Plastic and BaF$_2$ scintillators thus seem to be the best suited materials. We have chosen fore NE104 plastic scintillator material, because it does not have a slow component.

6.1.2 Energy Measurement

As discussed in section 2.6.2 a momentum measurement of $\beta$-particles gives access to some sensitive parameters in the SM which calls for a good resolution in the measurement of the energy and the direction of the $\beta$-decay electrons and positrons.

Semi-conductor detectors have a good energy resolution for $\beta$-particle detection of $<1\%$ whereas scintillating detectors have only about $10\%$. This is mainly because of the statistical variation of the number of photo-electrons detected at photomultiplier tubes (PMT). Therefore semi-conductors are favored in terms of the energy resolution. However, their response to the signal and long decay time forces the use of a scintillating detector. Moreover, the detection system needs to cover a large area (180 mm diameter) with high efficiency which is hard and expensive with semi-conductor detectors. The resolution of the scintillating device should be optimized by maximizing the light collection, optimizing the PMT matching and minimizing the background. This includes the distortion due to inert material in front of the scintillator which not only affects the resolution, but also raises the minimum energy which the detector can observe. Therefore the amount of inert material in front of the detector should be minimized. Another
source of distortion of the energy spectrum is backscattering of the $\beta$-particles from the detector material which leads to incomplete energy deposition in the scintillator. These effects can be estimated through simulation. These aspects are discussed in the following paragraphs.

### 6.1.3 Backscattering

The $\beta$-particles (electrons or positrons) passing through a medium are affected strongly by the medium’s atoms because of their electric charge and because of their small mass. Scattering of $\beta$-particles from atoms may happen at scattering angles ranging from 0 to 180 degree. Along its propagation through matter the direction of the $\beta$-particle can change drastically and frequently. This may lead to redirecting the particle backward out of the sensitive material of a detector, before it has released all its energy. $\beta$-backscattering is more severe for heavier materials (see Fig. 6.1 and [Mar06, Mas93, Cha04]). The use of lighter detector materials is thus favorable. Plastic scintillator is one of the lightest detection materials that can be used as a $\beta$-detector. Heavier materials such as NaI and BaF$_2$ crystals, would have more backscattering especially for low energy $\beta$-particles. In addition, also the composition of the materials surrounding the detector, such as the window in front of the detector, must be carefully considered. The $\beta$-particles have to pass through the window material before entering the $\Delta E$-detector. This backscatters some of the particles depending on the sort and thickness of the window material. Backscattering off the window will prevent particles from reaching the $\Delta E$- and E-detectors. The window should therefore be as thin as possible and also be made of low-Z material. E.g. beryllium windows have been used for Phoswich $\beta$-detectors to reduce the backscattering effect [Sci03].

The material of the mounting flange for the $\beta$-window also can scatter particles into the detector and its amount must therefore be minimized. The fact that electrons are slightly more backscattered than positrons due to the identical electric charge as the electron gas (indistinguishable particles) in the material is of no significant importance.

### 6.1.4 $\beta$-Window

The detectors in the MOT-RIMS setup (Sec. 4.16) are located around a MOT cloud that requires ultra high vacuum (UHV). Ideally the detector should be
placed directly in the UHV region around the MOT to minimize the amount of inert material in front of the $\beta$-detector. This is impossible for plastic scintillators as plastics are UHV incompatible. Therefore the scintillator material has to be separated from the main vacuum by a window which is thin enough to let the $\beta$-particles pass with minimum distortion. Furthermore, this window should be able to withstand a pressure difference up to 1 bar to allow the scintillators to be reached without venting the UHV section. The material of the window should be UHV compatible. Low-Z materials are favored to reduce the amount of $\beta$-particle backscattering. Also the mounting material of the foil scatters $\beta$-particles towards the detector and acts as a source of background. Minimization of the mounting material can be achieved using direct welding of a foil to a vacuum stainless steel tube. Appropriate welding techniques were developed together with the mechanical workshop at KVI and outside companies. For details see appendix B.

A well established model to explain the behavior of membranes under pressure was modified to account for pressure dependent changes of elastic parameters. In particular an effective constant of elasticity was introduced, the use of which provides sufficient accuracy to predict the elastic behaviour of thin foil windows. A series of measurements with small models were used to establish sufficient
understanding of the behaviour of the foil and its weld and to find the relevant operational parameters. As a result, an arc welded 75 $\mu$m stainless steel foil is approved as the first $\beta$-window in our setup (see Fig. B.6).

### 6.1.5 Particle Identification

The main source of background on the $\beta$-detectors is $\gamma$-radiation from positron annihilation. For the $^{21}$Na decay two 511 keV $\gamma$-rays from annihilation and 350 keV secondary $\gamma$-ray emission after decay to an excited state of the daughter nucleus $^{21}$Ne (see Fig. 2.4) contribute to the events in the $\beta$-detector. Also Compton scattered photons and x-rays produced by the charged particles following an original $\gamma$-ray event add to the background. To suppress these $\gamma$ events a two layer setup is used, consisting of a thin layer in front and a thick block behind it. Charged particles produce a signal in both layers, whereas $\gamma$-rays most likely only fire the thick layer because of their low interaction probability particularly with low Z materials such as plastic scintillators. By requiring a coincidence between both layers, the background can be largely reduced. The two detectors can be made out of the same material (e.g. plastic scintillator) or two different detection materials (e.g. plastic scintillator and silicon). The lowest energy electrons will be stopped in the thin detector before reaching the thick one. Higher energy electrons will only loose a small fraction $\Delta E$ of their energy in the thin detector and deposit nearly all their energy $E$ in the thick detector. Calibration of the $\Delta E$- and E-detectors using radioactive sources of known particle spectrum allows to reconstruct the initial energy of the $\beta$-particles and to distinguish between $\gamma$’s and electrons.

### 6.1.6 Position Sensitivity

The momentum of the $\beta$-particle can be reconstructed from its energy and the directional information from the $\beta$-detector. As the $\beta$-particles are emitted from a small source (MOT cloud), it is sufficient to reconstruct the impact position.

### 6.2 Simulations

To understand the behavior of the setup, particle trajectory simulations were performed using the GEANT4 software package [Ago03]. We have modelled an atomic source in front of a detection setup consisting of a window foil (75 $\mu$m
stainless steel), a 2 mm thin scintillator as ∆E-detector and a 20 mm thick scintillator as E-detector. The source was $^{21}$Na with its natural β-decay properties, in particular its life-time and β-energy spectrum. The model also includes two 511 keV γ-rays after positron annihilation.

Figure 6.2 shows the energy deposition in the ∆E- and E-detector. The energy cutoff due to the β-window and the ∆E-detector is visible. The window reduces the minimum detectable particle energy to 40 keV. The ∆E-detector stops β-particles with energies below 700 keV.

The response of the β-detector was further qualified by comparing the total deposited energy (sum of the ∆E- and E-detector) distribution to the initial energy from a homogenous source. For that the atomic source was replaced with a β-particle source with a flat distribution of energies between 0 and 2.5 MeV (the energy range of the β-particles from $^{21}$Na decay). Although the response spectra have the shape of a Landau distribution, we fitted a gaussian function as an approximation. The resolution of the spectra are shown in figure 6.3(a). Typically the resolution is 8%. Note that the PMT photo efficiency (∼10%) and photon statistics (100 eV/photon) alone leads to an energy resolution of at least in the order of 3%. The fraction of events in the peak (2σ) of the total deposited energy distribution is shown in figure 6.3(b). The fraction of events with an energy definition within the 8% resolution is in the order of 60%.

The influence of the β-particle energy on the backscattering probability was also investigated using a homogenous source. Figure 6.4 shows the fraction of positrons which are backscattered from the thick E-detector depending on the initial energy of the positrons. The backscattered events are events where the positrons exit the thick E-detector from the same side where they entered. Therefore there are events from high energy positrons which deposit part of their energy in the E-detector before they are scattered backward. The probability of backscattering is higher for positrons with low energy. Comparing this result to the backscattering probability of β-particles from bulk material in normal entrance (see the C backscattering shown in Fig. 6.1) shows a higher backscattering fraction. The reason is that not all positrons enter the detector at angles perpendicular to the surface. Due to the angular straggling in the β-window and ∆E-detector, this will be even more important when entering the E-detector.

The considerations above show the importance of simulations in the analysis of correlation measurements.
Fig. 6.2: Simulated energy deposition by positrons from $^{21}$Na decay in (a) the E-detector and (b) the $\Delta$E-detector. The energy cut off due to the $\beta$-window and the $\Delta$E-detector are visible.
Fig. 6.3: (a) The energy resolution of the \( \beta \)-detector is defined as \( \frac{\sigma}{E_{\text{dep}}} \) where \( \sigma \) is the standard deviation of the total deposited energy distribution and \( E_{\text{dep}} \) is the peak center of this distribution. (b) The fraction of events in the peak (2\( \sigma \)) of the deposited energy distribution.
6.2 Simulations

Fig. 6.4: The fraction of positrons which are backscattered from the E-detector as a function of the initial energy of the positrons. The positron source is at the position of the MOT and emits positrons randomly in all directions with a flat energy distribution between 0 and 2.5 MeV. Backscattered positrons are those which left the detector through the same side as they entered.

Fig. 6.5: Simulation of the magnetic field strength at the center of the detection chamber. The minimum is shifted by the effect of the magnetic PMT shields of the $\beta$-detector.
6.3 Influence of Magnetic Fields

The magnetic quadrupole field produced by the MOT coils, which are mounted on the detection chamber, distorts not only the particle trajectories but also it can affect the functioning of the detectors. If PMTs are used for the ΔE- and E-detectors, they need to be shielded from the magnetic field of the MOT coils using μ-metal tubes. At the same time these shields react back on the MOT magnetic field. Therefore the position of these tubes and the distortion they cause must be considered. Placing the PMTs far away would reduce this shift. However, the light detection efficiency for scintillation light depends on the length of the light-guide due to attenuation in them. This prefers the PMTs to be placed closer to the MOT. A COMSOL simulation shows that the μ-metal shields of the ΔE-detector in the configuration chosen for an experiment (see Sec. 6.4) causes a shift of the position of the field minimum by 10 mm (see Fig. 6.5). A similar effect is anticipated for the E-detector. With appropriate currents in the correction coil set the position of the field minimum for the MOT can be moved back to center of the setup.

6.4 Mechanical Setup of the β-Detector

There are three mounting positions foreseen in the detection chamber for a β-detector: one along the axis of the reaction microscope and two others orthogonal to this axis. Each β-detector is mounted on a 200CF flange inside its own vacuum container (see Fig. 6.6). This vacuum housing separates a low vacuum region near the β-detector from the UHV required for the MOT. This vessel has a 75 μm stainless steel foil window to provide vacuum separation. This foil is arc welded to the body of the scintillator vacuum. It stands one bar pressure difference (see Fig. B.6 and for more details see appendix B). This vacuum housing is mounted on the 200CF flange on the detection chamber and has a 190 mm diameter KF mount for the β-detector assembly. The thin ΔE-detector and the thick E-detector of the β-detector are separately mountable in the vacuum housing. The ΔE-detector consists of a thin scintillator, a sixfold segmented light-guide connected each to one photomultiplier tube (PMT). The PMTs are mounted together on a single Aluminum head. This head mounts the ΔE-detector on the KF seal of the β-detector vacuum housing. It has also a mounting flange for the E-detector.

The ΔE-detector is a 2 mm NE104 plastic scintillator with 170 mm diameter
Fig. 6.6: a) Vacuum housing of the $\beta$-detector. b) Sketch of the location of the $\beta$-detector in the detection setup relative to the reaction microscope.
which is connected to the six fold segmented Perspex (polymethyl methacrylate) [Kha01] cylinder light-guide from the edge (see Fig. 6.7(a) and 6.8(b)). The scintillator sheet is clamped between these 6 segments. A 45° edge on the light-guide reflects the light by 90° into the light-guide cylinder (see Fig. 6.7(b)). Each of these segments is adiabatically coupled to a PMT with a set of 4 twisted strips. The PMT tubes are mounted in iron tubes with a µ-metal tube layer inside to shield the PMT tubes from external magnetic fields (see Fig. 6.8(a)). After mounting, the thin scintillator is positioned about 1 mm from the thin foil vacuum window which is about 120 mm away from the MOT cloud in the detection chamber. The solid angle for ∆E-detector is $9 \cdot 10^{-2}$ sr. The design of the E-detector is not yet finalized. The design goal is to provide maximum light collection with position sensitivity to resolve the momentum vector of the β-particle. The E-detector will be a 3 cm thick NE104 cylinder mounted inside the ∆E-detector’s light-guides.

The six PMTs of the ∆E-detector are 25 mm diameter HAMAMATSU R7449 tubes, which have ultra violet transparent quartz windows. The tubes are each connected to a socket base (C9028-01), which includes a built-in high voltage (HV) generator. The bases require 15 V DC power and their HV can be remotely controlled with low DC control voltage. A set of measurements were performed to estimate the characteristics of these PMTs. This includes measurement of the dark-current, finding the single photon line and estimating the gain and the background count rate [Sil07] (see Tab. 6.2). The parameters of this tube (R7449) are well suited for our use.

**Table 6.2: Specifications of R7449 PMT. For these measurements we used a high voltage of 1150 V.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain (measured)</td>
<td>$2 \times 10^6$</td>
</tr>
<tr>
<td>Gain (catalogue)</td>
<td>$2.1 \times 10^6$</td>
</tr>
<tr>
<td>Background rate (bare tube)</td>
<td>209 s$^{-1}$</td>
</tr>
<tr>
<td>Background rate (tube + Scintillator)</td>
<td>746 s$^{-1}$</td>
</tr>
<tr>
<td>Spectral response</td>
<td>185 to 650 nm</td>
</tr>
<tr>
<td>Maximum Response at</td>
<td>420 nm</td>
</tr>
<tr>
<td>Photocathode material</td>
<td>Bialkali</td>
</tr>
<tr>
<td>effective diameter</td>
<td>25 mm</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>11% @ 400 nm</td>
</tr>
<tr>
<td>Pulse width</td>
<td>$&lt; 5$ ns</td>
</tr>
</tbody>
</table>

* HAMAMATSU R7449 PMT catalogue.
†- Count rate including and above single electron peak.
Fig. 6.7: a) ΔE-detector in its vacuum housing. b) Details of the coupling of the thin scintillator to the light-guide.
Fig. 6.8: a) Arrangement of the PMTs and light guides in the ∆E-detector. b) One of the light-guide sections in the ∆E-detector made of Perspex (F. Mul).


6.5 ΔE-detector Performance

For test measurements the detector was mounted on a light-tight tube with a 75 μm stainless steel foil in front of the scintillator. A $^{90}$Sr source was put at several locations on the front foil. The individual PMT high voltages were set to achieve similar pulse amplitudes from each PMT by putting the source in the center of the detector.

The end point of the $\beta$-particles from $^{90}$Sr decay is 546 keV and its daughter $^{90}$Y 2.26 MeV. As seen from figure 6.2 most events will have similar energy deposited in the detector. Consequently, the PMT output is determined by the photon-statistics of the photocathodes rather than the energy distribution. The spectra are typical Landau spectra (see Fig. 6.10). From the width of the recorded distributions, the number of photo-electrons was extracted to be 6 photons on average per tube. The number of photons is somewhat below the approximately 15 expected from a crude ray tracing simulation [Ond07a] and can be improved by applying reflective tape on the bevelled edge of the light-guide.

A second test modelled the position dependence of the light output. The source was positioned at various well defined locations (see Fig. 6.9(a)) across the detector surface. In figure 6.9(b) the average output of PMT 1 is shown for the source at various positions. During this measurement the source was moved around the outer ring and finally to the center of the detector (C). Other PMTs showed identical behaviour within the experimental error margins. Each PMT has its maximum output when the source is directly in front of it. It gradually decreases when the source is moved across the middle towards the opposite side of the scintillator. A PMT has a minimal signal when the source is positioned in front of the nearest neighbors (see Fig. 6.9(b)). In this case, the photons enter the light-guide with large angles and easily escape because the light rays hit the light-guide surface at an angle smaller than the total reflection limit angle.

This observed position dependence was the starting point for investigating the design of a robust and high efficiency trigger using the outputs of the six PMTs and investigated the possibility to obtain position sensitivity.

Data were taken with a low-bias trigger corresponding to at least 1 photo-electron in one of the PMTs. The pulses coming from each of the six PMTs were recorded using a QDC (charge to digital converter). The pedestals were determined by sending gates to the QDC at random times. From those data, several more complicated trigger conditions were simulated and compared in software, including the effect of raising the discriminator threshold.
First, the efficiency of a majority trigger was explored. For example, “majority one”, is equivalent to the OR-of-six trigger with which the data was taken, whereas “majority six” is equivalent to an AND-of-six trigger.

Second, a “smart-trigger” based on the observed position-dependent PMT output was simulated. The position scans showed that for each source position, four PMTs have the largest signals. A simultaneous hit in each of the four PMTs that are expected to have a large signal (i.e. an AND-of-4, e.g. PMT-1 & PMT-3 & PMT-4 & PMT-5) defined a sub-trigger. For each of the six most prominent positions directly in front of the PMTs (positions P1 through P6 as defined in figure 6.9(a)) such a condition was implemented. The OR of these six sub-triggers defined the final trigger.

The number of accepted events drops steadily when requiring higher multiplicity and applying higher thresholds. The efficiency is defined as the fraction of events that survive when applying a certain trigger condition. In table 6.3, the efficiency is reported for the various majority requirements, first averaged over all positions, then for the center position and finally for one of the positions right in front of a single PMT. For a threshold at 25% of the maximum in the QDC spectra, the lowest efficiency is 97% for any trigger. For a threshold at 50% of the location of the maximum, only for a sixfold coincidence requirement does the efficiency drop below 90%. An efficiency of 95% can be obtained by reducing the PMT threshold from 89% of the peak position for multiplicity two, down to a little over 30% of the peak position for majority six.

6.6 E-detector Performance

In order to determine the possibilities of a plastic scintillator as an energy calorimeter we have measured the performance of a 2 cm thick disk of NE104 material. It was coupled to a HAMAMATSU R7449 PMT. We recorded electron-spectra from a $^{207}$Bi source (see Fig. 6.11). The spectrum is a composite of various contributions of $\gamma$-rays and conversion electrons. The main $\gamma$-rays are at 570 and 1064 keV. They are seen as Compton scattering events. The K and L conversion electrons are at 1048 and 576 keV respectively. The composite spectrum therefore allows to give an upper limit for the resolution of 21%. At present the best way to achieve position resolution is investigated. Among the possibilities are a segmented scintillator or a scintillator coupled to a position sensitive PMT (HAMAMATSU R2486-02).
Table 6.3: Efficiency for various trigger majority requirements or the smart-trigger (labeled “s.t.”). The efficiencies are for discriminator threshold at 25% and 50% of the PMT signal height position at which the maximum single rate is observed (around 100 QDC channels).

<table>
<thead>
<tr>
<th>Source location</th>
<th>Average over all the positions</th>
<th>At the center</th>
<th>In front of a single PMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Majority</td>
<td>2 3 4 5 6 s.t.</td>
<td>2 3 4 5 6 s.t.</td>
<td>2 3 4 5 6 s.t.</td>
</tr>
<tr>
<td>Efficiency [threshold at 25% of peak]</td>
<td>99.9 99.9 99.8 97.3 99.9 99.9 99.8 99.6 97.9 99.7</td>
<td>99.9 99.9 99.8 99.6 97.9 99.7</td>
<td>99.9 99.9 99.8 99.5 96.7 99.7</td>
</tr>
<tr>
<td>Efficiency [threshold at 50% of peak]</td>
<td>99.5 99.0 97.9 94.9 83.7 96.6 99.4 98.9 97.7 94.8 84.4 96.4</td>
<td>99.5 98.8 97.3 92.7 77.1 95.9</td>
<td></td>
</tr>
<tr>
<td>Threshold [efficiency of 95%]</td>
<td>89% 76% 64% 51% 36% 56%</td>
<td>88% 73% 63% 51% 36% 56%</td>
<td>89% 74% 61% 49% 31% 54%</td>
</tr>
</tbody>
</table>
Fig. 6.9: a) Pattern used for positioning the $^{90}$Sr source across the $\Delta E$-detector in the performance measurements. Position 1-6 are in front of the center of the light-guide which couples to the PMT 1-6, respectively. b) The relative pulse height of the PMT 1 (position P1 in the pattern) when the $^{90}$Sr was in front of the other PMTs and at the center of the detector surface. The PMT signal decreases if the source is moved across the center of the detector to the opposite side. It has the lowest signal when the source is in front of the direct neighbor PMTs.
Fig. 6.10: A typical $\beta$-spectrum of a $^{90}$Sr source observed in one of the PMTs of the $\Delta E$-detector.

Fig. 6.11: Energy spectrum of a $^{207}$Bi source taken with a 2 cm thick NE104 plastic scintillator coupled to a HAMAMATSU R7449 PMT. The resolution of the detector is about 21%, which is calculated from the 1 MeV $\beta$-$\gamma$ composite peak around the channel 950.
6.7 Conclusion

The β-detector setup consists of a telescope with an ΔE- and E-detector. They are mounted in a vacuum housing. This setup is designed particularly,

a) to work in combination with a reaction microscope in UHV, which is needed for a MOT cloud of radioactive atoms. For this a vacuum housing with a 75 µm thick stainless steel β-window was developed which separates the UHV MOT region from the β-detector where rough vacuum is sufficient.

b) to distinguish β-particle events from γ-ray events. A combination of a 2 mm thick plastic scintillator ΔE-detector coupled to a 6-fold segmented light-guide system in front of a 20 mm thick plastic scintillator E-detector provides the particle identification.

c) to provide a start signal for the reaction microscope. For this the detectors are chosen to be of NE104 plastic scintillator material with less than 1 ns signal rise time.

d) to resolve the full kinematics of the β-particle. A position sensitive energy detector using a segmented PMT (HAMAMATSU R2486-02) which can resolve both energy and direction of the β-particles is under way. The ΔE-detector has position resolution for ensemble of decays. Position sensitivity in the ΔE-detector for individual events would require improvement of the photon statistics, which could be achieved, e.g. by the choice of a thicker ΔE-detector on expense of lower E×ΔE coincidence rate.