A compact Ultra-High Vacuum (UHV) compatible instrument for time of flight-energy measurements of slow heavy reaction products

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Abstract

A compact Ultra-High Vacuum (UHV) compatible instrument for time of flight – energy measurements of slow heavy reaction products from nuclear reactions has been designed and tested at the CELSIUS storage ring in Uppsala. The construction is based on MicroChannel Plate (MCP) time detectors of the electron mirror type and silicon p-i-n diodes, and permits the detectors to be stacked side-by-side to achieve large solid angle coverage. This kind of telescope measures the Time of Flight (ToF) and Energy (E) of the particle from which one can reconstruct mass. The combination of an ultra-thin cluster gas-jet target and thin carbon emitter foils allows one to measure heavy residues down to an energy of ~ 35 keV/nucleon from the interactions of 400 MeV/nucleon ^{16}O with ^{nat}Xe gas targets.

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1. Introduction

The availability of ultra-thin targets, 10^{13}-10^{14} atom/cm^2, high intensity beams and a large energy range of the heavy ion beams (25-470 MeV/nucleon) at the CELSIUS storage ring creates an ideal situation for studying the production of very slow heavy recoils in nuclear collisions. These recoil nuclei have energies less than 500 keV/nucleon, and are able to escape without energy loss from the interaction region. Thus they are in principle accessible for detection. These residues have however too low energy to be detected by conventional ΔE-E silicon telescopes because they would require a ΔE detector thickness of 0.2 μm or less [1,2]. Although gas ionization ΔE-E telescopes may in principle be used for detecting such low energy recoils, the gas diffusion through the entrance window prohibits their use in the Ultra-High Vacuum (UHV) system of a heavy ion storage ring. Time of flight telescopes are necessary, since they work in a typical energy range of 25 to

1000 keV/nucleon. This kind of telescope measures the Time of Flight (ToF) and Energy (E) of the particle from which one can reconstruct mass and energy. An instrument based on MicroChannel Plate (MCP) time detectors of the Busch electron mirror type [3] is the best one to measure the time of flight of heavy charged particles with insignificant energy losses. This instrument allows measurement of the fragment mass by also measuring energy of the particles with a silicon detector. This telescope type has been used for mass and energy identification of heavy ions [4] as well as heavy recoiling fragments of very low energy [5]. Unfortunately, conventional time of flight telescopes cannot be directly used in the ultra high vacuum chamber of the CELSIUS storage ring (at pressures of ~ 10^{-8} to 10^{-10} mbar) due to high outgassing from construction materials. Therefore, a UHV-compatible telescope system was developed and tested in a UHV environment. This system was designed to be compact, easily removable, with simple cable connections to minimize the number of feedthroughs needed.

2. Construction and principles of operation of the UHV compatible MCP based detector.

An MCP time detector of the electron mirror type was chosen as time detector due to its excellent time resolution and minimum distortion of the particle trajectory by the thin carbon foil. A schematic layout of the MCP mounting assembly is shown in Fig. 1. In this detector, based on the design by Busch et al. [1] the charged particles to be detected pass through a 20 $\mu g/cm^2$ carbon foil (10x20 mm) perpendicular to the charged particle direction. The emitted secondary electrons, mainly from the near surface of the foil, are accelerated to approximately 1 keV in the electric field generated by an accelerating harp placed at 5 mm distance from the carbon foil. The electrons are directed to an electrostatic mirror consisting of two parallel harps placed at 45 degrees to the particle's path and separated by 5 mm. The electrostatic field, existing between the harps of the electrostatic mirror, bends the electrons by 90 degree towards the MCPs, which are placed outside the heavy ion trajectories. The acceleration harp, the inner mirror harp and the channel plate input surface are held at the same potential (~ -2 kV) which allows the electrons to follow along straight lines in the electrical field free region. A front harp was added in front of the carbon foil and kept at the same potential as the accelerating harp to prevent foil deformation due to electrostatic force. Inside the central, electrical field-free volume, the accelerated electrons move along isochronous trajectories, which leads to negligible transit time spread. The MCP assembly consists of two plates mounted in a chevron configuration to achieve a gain around 10^7–10^8 and also to avoid after-pulses due to positive ion feedback [6]. These rectangular 10x22 mm MCPs were manufactured by special cutting from circular plates of 33 mm diameter made at the Vavilov State Optical Institute, St. Petersburg. The channel diameters are 10 µm with channel axes biased to an angle 7^o to the MCP input surface. The MCP thickness is 0.5 mm.

UHV requirements prescribe the use of UHV compatible materials such as stainless steel, Vespel® SP-1 and ceramics as insulators. Moreover, the use of any soldering, glue and ordinary cable with plastic isolation was rejected due to outgassing problems. Special UHV innovations include the development of very thin, soft contacts to provide high

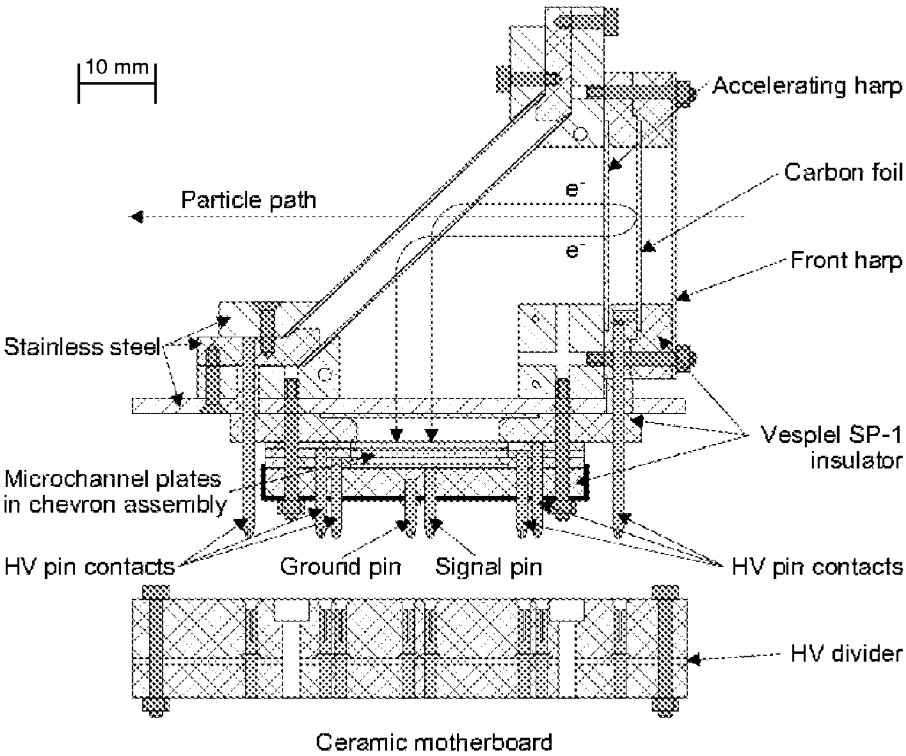

Figure 1. A layout (side) view of the microchannel plate mounting assembly with pin contacts.

voltage for the MCPs, the production of highly transparent welded harps using precise welding techniques, and the design and use of a ceramic High Voltage (HV) divider with distribution pins (Fig. 1). The special soft contact is needed because the normal contact area of the MCP was removed by the cutting process. The MCP contact was made from 30 µm thick Cu-Be plate in the shape of a fork bent in a small angle. The contact is an important point, especially for our small, rectangular MCPs that are mounted in a compact assembly, because of the small (a few mm in our case) available space for the contact. Moreover, it has to be soft in order not to crack the glass base, but on the other hand it must be sufficiently stiff to provide good and permanent electrical contact. All harps have 98.7% transparency and were built by tack-welding of gold plated 15 µm tungsten wire to a stainless steel holder with 1 mm separation. Instead of providing six different high voltage potentials on each MCP based detector, we designed a UHV compatible HV divider, a ceramic socket and distribution pins (as shown in Fig. 1). This allowed us to use only one HV cable per time detector (Kapton® cable KAP2 type by Caburn-MDC Ltd.). The HV divider was made on a 1 mm thick ceramic plate using thin-film printed circuit board technique by Monolitsystem AB. The total resistance of the divider is around 43 MΩ. A maximum applied negative HV of 4.3 kV is distributed by the resistor chain: 4.3 kV to the electrostatic mirror; 3.3 kV to the carbon foil; 2.3 kV to the accelerating harp; 1 kV per MCP with 0.1 kV intermediate, between the plates, and

0.2 kV between the second plate and anode. The current through the divider is around 100 μA which dissipates a power of almost 0.5 watt. This construction has thermal contact to the main metallic board, which prevents overheating of the HV divider.

The ceramic socket consists of two ceramic plates, 6.5 and 8.5 mm thick, an HV divider plate placed in the middle of the assembly, standard female pins by Caburn-MDC Ltd. and stainless steel springs of 1.6 mm internal diameter to keep good electrical contact between the pins and the gold-plated HV divider contacts. All male pins were made from stainless steel with threads on the end, which allows us to use them as bolts and to compress the soft MCP Cu-Be contacts and harp, to provide all necessary HV potentials without soldering or gluing. Another advantage of this construction is that it is easy to remove an individual detector from the socket. Two pins (marked ground and signal in Fig. 1) and a 50 Ω KAP50 cable by Caburn-MDC Ltd. were used to extract fast signals from the anode of the MCP assembly. Good contact between the signal pin and anode copper plate is achieved by using the thread on the pin.

3. Construction of the time of flight energy telescope.

Each of these telescopes consists of two MCP based time detectors described above (to measure the start and stop time for the time of flight (ToF) of heavy charged particles) and a silicon p-i-n diode (to measure the energy (E) of the heavy charged particles). A photo of a time module is shown in Fig. 2, while two fully mounted ToF-E telescopes are shown in Fig. 3. The carbon foil of the start MCP detector faces towards the target. A stop time detector is placed in reverse direction to the first one, which means that the particle enters from the electrostatic mirror side. This geometry allows us to maximize the time of flight path between two carbon foils and to place the p-i-n diode surface as close as possible to the carbon foil of the stop time detector. The number of secondary electrons emitted from the side of the foil, facing the incoming particles source (in our case the stop time detector), is approximately 0.5 times smaller than that observed on the emergence side (case of the start time detector) according to measurements by J. Girard et al. [7]. This is important for the detection probability of a light charged particle, because the yield of electrons from the passage of an ion through a carbon foil range from approximately 10 for natural alpha particles to about 100 for fission fragments [8]. The detection probability of the ToF-E telescope varies smoothly [9] ~ 10% for alpha particles and ~ 99% for fission fragments from a ^{252}Cf source. The thickness of the carbon foil was chosen as 20 μg/cm^2 for both the start and stop detectors. The main reason for this thickness was its mechanical strength, which allows easy transportation, mounting and fast pump-down. Moreover, the secondary electron yield of this foil is higher than a 10 μg/cm^2 thick carbon foil [7]. The time of flight path (distance between two carbon foils) was 20 cm. According to the investigation in [5] a time of flight path of less than 0.2 m is sufficient for detection of heavy recoil nuclei with an energy of 100 keV/nucleon for time detector pair resolution of around 170 ps (400 ps (FWHM)). A 300 μm thick, fully depleted, 20x20 mm active area, UHV compatible p-i-n diode detector from Micron Semiconductor Ltd was used for energy measurements of charged particles. The energy detector is placed as close as its mechanical frame allows (~10 mm) away from the carbon foil of the stop time detector. The typical bias voltage working potential

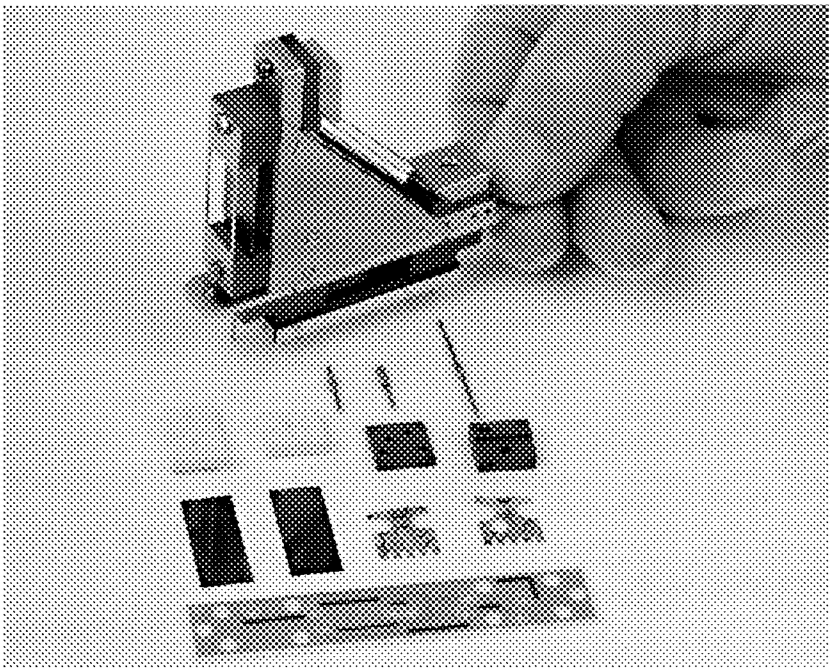

Figure 2. A photo of a time module and some of its components, incl. MCPs, contacts and the HV divider.

ranged from 40 to 70 volts. Both time detectors and the p-i-n diode detector were shielded by a 1mm thick Al box with 10x20 mm collimator window. This box served to shield: a) the channel plates against a flux of energetic δ-electrons from the target region; b) all insulator parts, mainly the ones made from ceramics against charged ions originating from the cluster-jet target to prevent discharging of the collected static electricity through the MCP; c) the insulator against a discharge which could cause damage; d) the p-i-n diode against the ultraviolet light coming from the interaction region.

When mounting the detector, the Kapton® HV and signal cables were fixed into the female pins of the ceramic socket by crimping, subsequently the sockets were fixed on an aluminum baseplate. The grounding point of the fast signal from the MCP was put as close as possible to the central signal cable (50 Ω) and fixed into the base aluminum plate. The HV divider was grounded at the same ground point. Special efforts have been made to ground the signal cables of the start and stop time detectors on the inner side of the vacuum flange as a replacement for very bulky and much more expensive floating ground 50 Ω UHV feedthroughs. There were two reasons for this: a) to minimize the cross talk between complementary start-stop time detectors, and b) to minimize the signal reflection on the inner connector.

As a result we used three independent grounding points on the inner side of the vacuum flange for both time detectors and for the p-i-n diode. In an experiment the fast signal from the p-i-n detector (as a master trigger) was applied to minimize background due to the cross-talk between the time detectors. During a test run and a real experiment, the

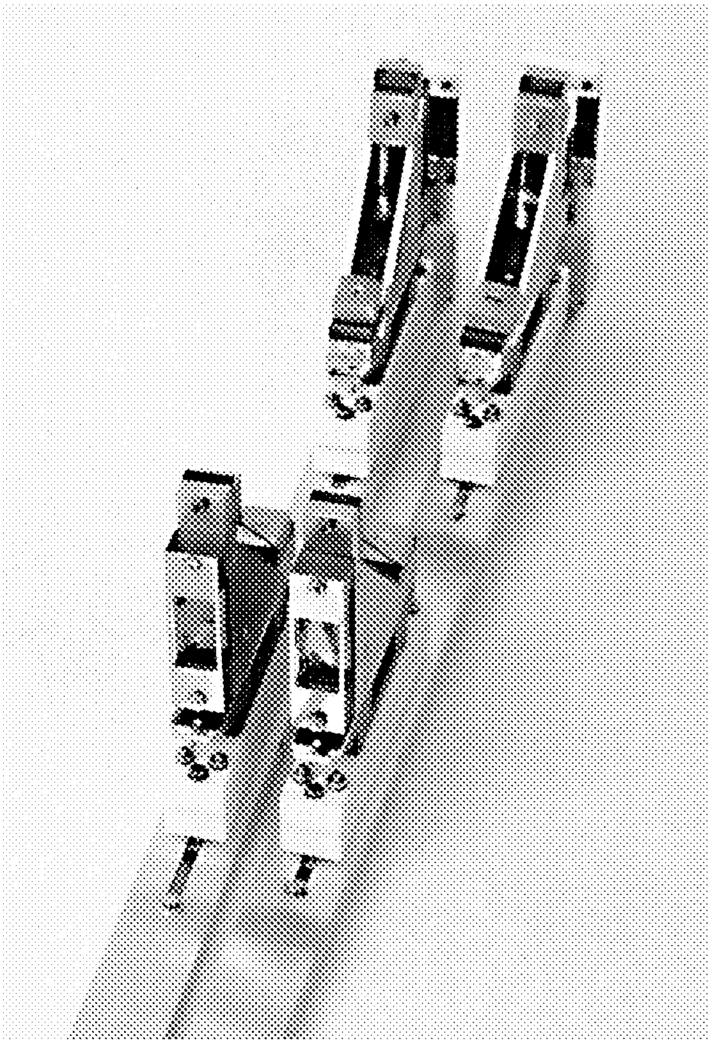

Figure 3. Photo of two fully mounted ToF-E telescopes.

minimum distance between the start time detector and the maximum extension of the beam was ~ 1 cm, at a distance of 10 cm from the target. At present we have collected data from telescopes placed at 10^{o} and 50^{o} with respect to the beam direction, while the final system will consist of 15 telescopes to detect residues in the angular range 10^{o} to 50^{o} with high efficiency. In Fig. 4., we show a top view of the new CELSIUS cluster-jet reaction chamber with the CHICSi multi detector system [10,11], ToF-E recoil telescopes inside the chamber and a possible future forward wall of plastic and CsI detectors outside the vacuum chamber, in the forward direction.

4. Results and discussion

Two ToF-E telescopes have been tested off-line using fission and alpha sources as well as under experimental conditions inside the CELSIUS cluster-jet target chamber [12]. It was found in [5] that the mass resolution of the telescope, similar to the one described above,

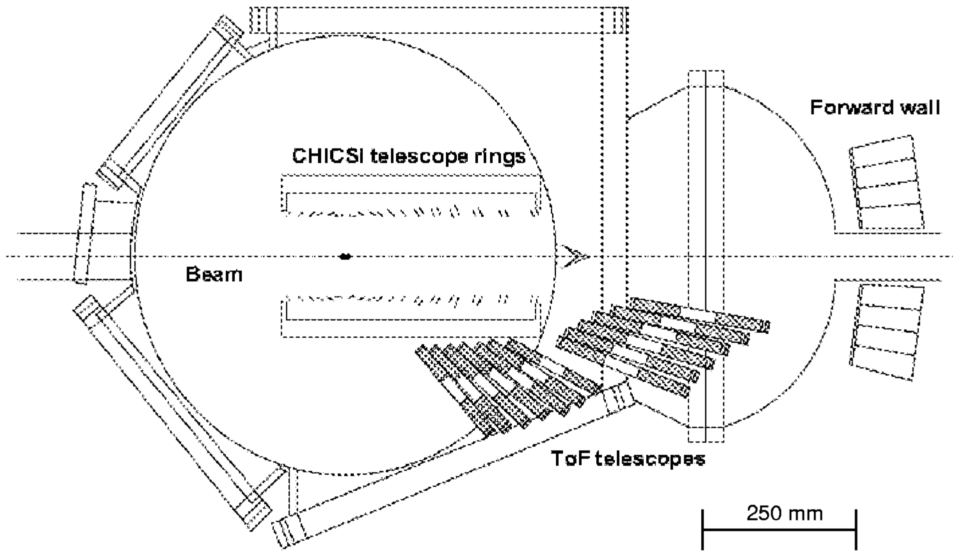

Figure 4. Top view of the new cluster-jet CELSIUS reaction chamber with CHICSi telescope rings [10,11], ToF-E recoil telescopes inside the chamber, and a forward wall for projectile fragments outside the chamber.

for low energy (less than 300 keV/nucleon) recoils depends mainly on the contribution associated with the energy detector resolution (Intertechnique IPB 150-100-16 detector).

A time of flight spectrum of alpha particles and fission fragments emitted from a ^{252}Cf spontaneous fission source is shown in Fig. 5. The FWHM of the alpha particle peak is ~400 ps. This value includes a) the transit time spread of electrons (~160 ps (FWHM) according to [5], mainly associated with mechanical tolerance of the detectors (~3%)); b) the time resolution of an MCP assembly for both start and stop time detectors (which is around 100 ps (FWHM) for one MCP assembly); c) the time jitter of electronics (which is ~70 ps for monoenergetic alpha particles from the source but has a maximum value of ~180 ps (FWHM) with 1:100 dynamical range of signal amplitude); d) the difference in flight path (~220 ps (FWHM)). We consider that the differences in flight path are significant contributions to the widening of the alpha peak in Fig. 5. Since a) we used an uncollimated source placed close to the first foil which leads to maximum differences in flight path of ~ 1 mm corresponding to 130 ps (FWHM) of the contribution to the peak spread ; b) carbon foil distortion (±1 mm) and the deviation of both foils from a parallel plane (±1 mm) are also contributing to the peak spread (~130 ps (FWHM) for each). Estimations of the telescope mass resolution for an ion of 100 u and 100 keV/nucleon shows that the contribution to the relative mass resolution from the time resolution of the telescope and the time spread due to differences in flight path is less than 2% for a 20 cm flight path. The relative energy resolution was assumed to be 2% according to [5], although it is less than 1% for alpha particles at 5 MeV. Thus, the relative, total mass resolution of the telescope (contributions from both time, and energy resolution, and difference in flight path) was estimated to ~ 3%. This value is quite adequate for our purpose since we are hardly going to investigate distributions, which require complete mass resolution. The calibration of the telescope must contain both time and energy. The time scale (see Fig. 5) was calibrated by introducing fixed delay lines, and known velocities of ^{252}Cf alpha particles and fission fragments [13]. Using alpha and fission source as well as a scattered beam we performed the calibration of the energy scale of the p-i-n diode detector.

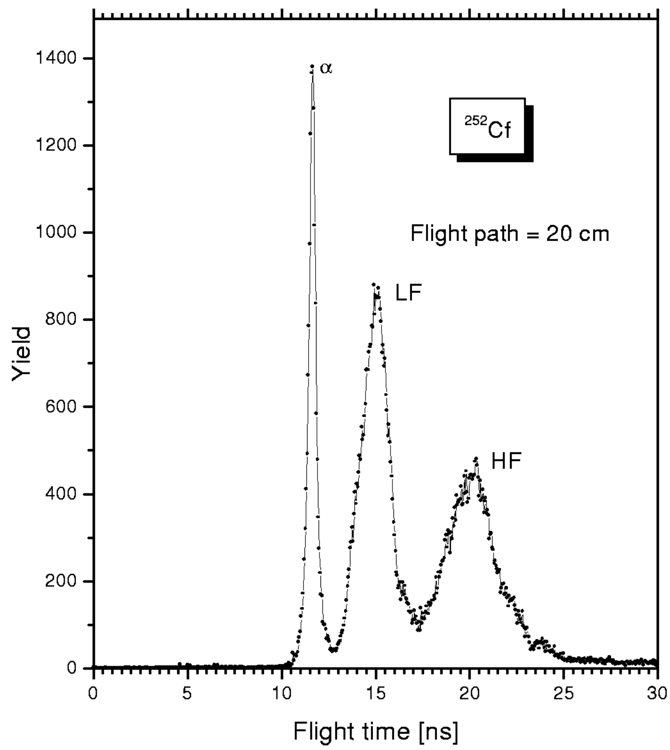

Figure 5. Calibration of the recoil telescope by a ^{252}Cf fission source: Time of flight spectrum from a ^{252}Cf source. The flight path is 20 cm.

Since the energy calibration is the most crucial point in a mass-energy reconstruction procedure we performed separate measurements of the dead layer of the p-i-n diode, and the Pulse Height Defect (PHD). The dead layer was measured by using a ^{226}Ra source placed at different angles with respect to the surface of the diode. It was found to be 200 nm thick. The energy loss inside this dead layer is approximately the same as the one in both carbon foils. The PHD according the definition by Moulton et al. in [14] is the difference between the energy deposited by a heavy ions and the alpha particles excluding the energy loss in the detector surface dead layer. We have measured the PHD in the p-i-n silicon detector by means of elastically scattered Al, Cu, Xe and Au ions from a thick target. The PHD ranged from 10% (Al of 10 MeV total energy) to 30% (Au of 5 MeV total energy) and it depends both on mass and energy of the heavy ions.

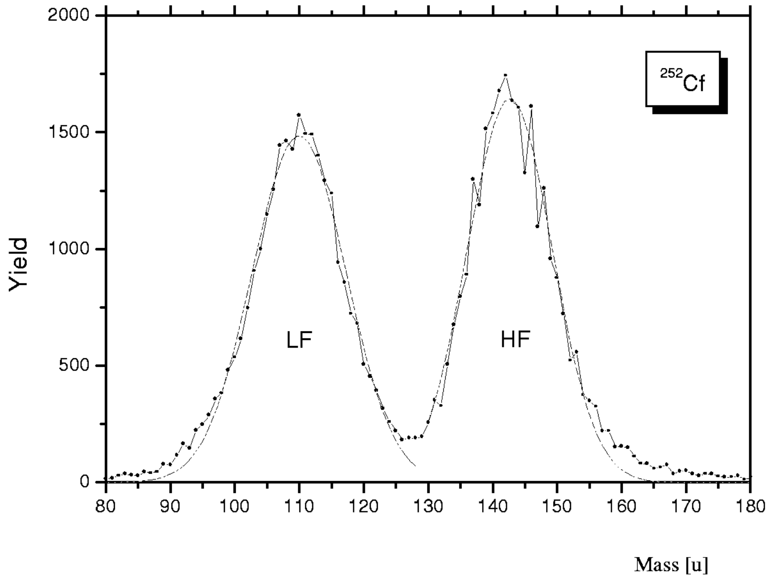

Figure 6. Mass spectrum of light and heavy fission fragments from a ^{252}Cf fission source.

To validate the telescope calibration we reconstructed the mass from the measured energy and velocity spectra from a ^{252}Cf source. The mass distribution of the fission fragments is shown in Fig. 6. Gaussian fits to the reconstructed spectrum yielded mean fragment (post neutron emission) masses of 4, 110 and 143 u with standard deviations of the peaks 0.5, 7.3 and 6.7 u for alpha particles, light fragments and heavy fragments, respectively. These are in good agreement with previously measured average fission fragment masses from [14] of 108.9, 143.1 u with standard deviations of 7.6 u. The reconstructed energies (and standard deviations) of alpha particles, heavy fragments and light fragments were 6 (0.4), 75 (10.) and 102 (7.) MeV, respectively. This is in agreement with data from [15] for heavy 78.3 (8.5) and light fragments 103.5 (5.8) MeV. The reconstructed velocities (standard deviations of the peaks) of the alpha particles, light fragments and heavy fragments were 1.72 (0.03), 1.33 (0.07), 1.00 (0.08) cm/ns, respectively in agreement with data from [9] for fission fragments of 1.369 (0.064) and 1.035 (0.078) cm/ns.

The same formalism and calibration was used for the reconstruction of mass and energy spectra of heavy residues and fragments measured by the ToF-E telescopes from intermediate energy nuclear reactions at the CELSIUS storage ring in Uppsala. A 2-Dimensional (2-D) plot of energy vs. mass from 400 MeV/nucleon ^{16}O on a ^{nat}Xe target is shown in Fig. 7. The thick line shows the telescope threshold curve. One can see that the low energy threshold measured for residue detection is 35 keV/nucleon for mass

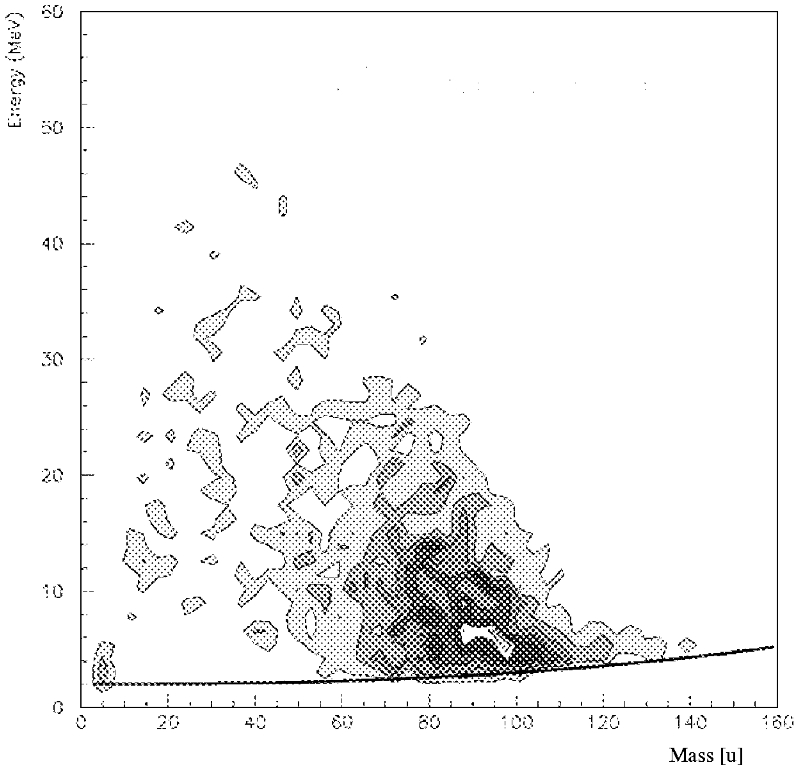

Figure 7. 2-D energy vs. mass distribution from 400 MeV/nucleon ^{16}O on a ^{nat}Xe target. The low-energy detection threshold is denoted by a thick solid line.

100 u. It is very important to reach these low energies since the peak in the 2-D energy versus mass spectrum occurs at 100 keV/nucleon and even lower for high energy beams (400 MeV/nucleon). Similar energy-mass spectra of heavy residues are found for all beam energies that we studied, 25, 75, 150, 200, and even at 400 MeV/nucleon. This result shows a persistence of fusion-like collision (relatively large momentum transfer) up to and including 400 MeV/nucleon of projectile energy [12]. This result, obtained by the telescopes described above, is new and not yet fully understood.

5. Conclusion

A compact, UHV compatible construction for time of flight and energy measurements of slow heavy reaction products from nuclear reactions has been designed and successfully tested in the CELSIUS storage ring. The combination of an ultra-thin cluster-jet target and thin carbon emitter foil MCP time detectors allows us to reach a very low energy threshold, less than 35 keV/nucleon. The energy calibration of the energy detector (p-i-n diode) is the most crucial point in the mass-energy reconstruction procedure from these data. The PHD correction in the energy detector is significant for low energy heavy ions. It is our experience that lowering the grid voltages from over 6 kV in our first prototypes to 4.3 kV in the final one has resulted in a much more stable operation.

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