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1 Tests of Micro-Pattern Gaseous Detectors for Active
2 Target Time Projection Chambers in nuclear physics

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9 **Abstract**

10 Active target detection systems, where the gas used as the detection medium
11 is also a target for nuclear reactions, have been used for a wide variety of
12 nuclear physics applications since the eighties. Improvements in MPGD (Mi-
13 cro Pattern Gaseous Detectors) and in micro-electronics achieved in the last
14 decade permit the development of a new generation of active targets with
15 higher granularity pad planes that allow spatial and time information to be
16 determined with unprecedented accuracy. A novel active target and time
17 projection chamber (ACTAR TPC), that will be used to study reactions
18 and decays of exotic nuclei at facilities such as SPIRAL2, is presently un-
19 der development and will be based on MPGD technology. Several MPGD
20 (Micromegas and Thick GEM) coupled to a 2×2 mm² pixellated pad plane
21 have been tested and their performances have been determined with differ-
22 ent gases over a wide range of pressures. Of particular interest for nuclear
23 physics experiments are the angular and energy resolutions. The angular
24 resolution has been determined to be better than 1° FWHM for short traces
25 of about 4 cm in length and the energy resolution deduced from the particle
26 range was found to be better than 5% for 5.5 MeV α particles. These per-
27 formances have been compared to Geant4 simulations. These experimental
28 results validate the use of these detectors for several applications in nuclear
29 physics.

30 *Keywords:* Active Target, Time Projection Chamber, Micromegas, Thick
31 GEM

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32 1. Introduction

33 With the ongoing improvements in radioactive ion beam production at
34 several facilities worldwide, new possibilities will soon be available for study-
35 ing the structure and decays of the most “exotic” nuclei, which are those
36 furthest from the line of beta stability [1]. The intensity of the most exotic
37 beams available remains however usually low. In this regard, the use of active
38 targets has become an attractive alternative to study the most exotic nuclei.
39 This type of detection setup, where the detection medium is also used as a
40 target presents several advantages. It allows the simultaneous detection and
41 identification of low-energy recoils that would stop in a classical solid target.
42 The effective target thickness can thus be increased (by adjusting the pres-
43 sure) to study nuclei produced at the lowest intensities, or to study reactions
44 with very negative Q-values where the recoils are emitted with low energies.
45 Active targets designed to study specific types of reactions are already in
46 existence. The IKAR active target [2] has been used to study the matter
47 distribution of very exotic light ions through proton inelastic scattering. The
48 CENBG TPC [3] is used to provide the three-dimensional reconstruction of
49 two-proton radioactivity events and was used to prove the existence of this
50 type of decay in ^{45}Fe . Other active targets like MAYA at GANIL [4] have
51 been built for more general use. With a solid angle coverage of about 2π ,
52 MAYA has been used for the study of transfer reactions with very exotic
53 beams [5, 6, 7] or giant resonances [8] in radioactive Ni isotopes.

54 With the upcoming availability of fission fragment beams at SPIRAL2,
55 there is an obvious need for active targets with higher dynamic range in or-
56 der to study, for example, the evolution of shell structure around the neutron
57 number $N=50$ and $N=82$ magic numbers via single neutron transfer reactions.
58 Higher granularity and higher counting-rate capabilities will permit the study
59 of giant resonances and key reactions for those nuclei situated in, or near,
60 the astrophysical rapid neutron and rapid-proton capture processes [9]. In
61 this framework, based on the concept of the active target MAYA, the more
62 efficient and versatile ACTAR TPC (ACTIVE TARget and Time Projection
63 Chamber) is being developed. This detector will consist of a gas-filled volume
64 of approximately $25\times 25\times 20\text{ cm}^3$. As in the MAYA active target, the ion-
65 ization electrons produced along the charged particles tracks, *i.e.* the beam
66 or the charged recoils produced in the reactions of interest between projec-
67 tiles with the gas atoms, drift under the influence of an electric field to an
68 amplification gap. The latter will consist of either Micromegas [10] (as used

69 in the AT-TPC at MSU [11]) or ThGEM (Thick GEM) [12, 13], chosen for
70 their robustness and high-rate counting purposes. The amplification system
71 will be coupled to a high granularity pad plane with 2×2 mm² pixels, which
72 will allow events to be reconstructed with good angular resolution even for
73 short track lengths and with an excellent spatial resolution on the stopping
74 points and hence a good energy resolution.

75 Regarding the foreseen geometry, several validation tests have been per-
76 formed using one ThGEM of 600 microns (with 0.4 mm diameter holes and
77 0.7 mm pitch) and two Micromegas detectors of 128 and 256 microns ampli-
78 fication gaps, respectively. These tests consisted of several angular resolution
79 and stopping-point measurements using a pixellated pad plane with 2×2
80 mm² pads. The setup consisted of an α source and a silicon strip detector
81 to select α trajectories above the pad plane. The entire ensemble was in-
82 stalled in the existing drift-field cage of MAYA. Gases at different pressures
83 (He+CF₄(2%) from 400 to 800 mbar and iC₄H₁₀ from 25 to 75 mbar) were
84 used. Another gas, Ar+CF₄(2%), was used to stop the alpha-particles over
85 the pad plane and determine the energy and range resolutions.

86 In section 2 and 3, the experimental set-up and the data analysis are
87 presented in detail. Section 4 is devoted to the results of angular resolution
88 with the different conditions of gas and pressure. The stopping point mea-
89 surements are described in section 5. Experimental results are then compared
90 to simulations in section 6.

91 **2. Experimental set-up**

92 The prototype MPGDs were mounted on a circular PCB pad plane of 5.6
93 cm diameter with square pads of 2 mm side length that totaled 576 channels.
94 As only 288 channels could be read using a single AFTER card (electronics
95 previously developed for the T2K experiment [14]), only a fraction of the
96 total pads could be connected while all others were grounded. The AFTER
97 card was placed either below the pad plane in the gas or outside the chamber
98 depending on the thermal conductivity of the gas. Two bulk Micromegas
99 [15] were tested on this pad plane, one with an amplification gap of 128
100 μm and the other with 256 μm . A ThGEM foil of 600 μm thick was also
101 tested and was positioned at a height of 2 mm above of the pad plane. The
102 detection system was inserted at the bottom of the MAYA drift field cage
103 and was surrounded by a copper plate that was biased at the micromesh
104 or the ThGEM voltage to maintain the homogeneity of the electric drift

105 field. The field cage is composed of printed circuit board with copper strips
 106 (with 3 mm pitch) on the front and side panels and a wire plane on the
 107 back panel to allow particles to escape [4]. As shown in figure 1, a DSSSD
 108 (Double Sided Silicon Strip Detector) with 16 channels on each side and a
 109 strip pitch of 3.12 mm was placed at the end of the chamber. A mask with
 110 16 slits of $10 \times 0.6 \text{ mm}^2$ was positioned in front of the DSSSD. A mixed alpha
 111 source (3 alpha-particles with energies of 5.1 MeV, 5.5 MeV and 5.8 MeV
 112 from ^{239}Pu , ^{241}Am and ^{244}Cm , respectively) was inserted at a distance of 184
 113 mm from the Si detector and at a height of 10 cm above the MPGD pad
 114 plane. In the horizontal direction, the source was 13 mm from the start of
 115 the active area of the detector. The source has a diameter of 5 mm and can
 116 be collimated. The data acquisition system was triggered by the detection of
 117 an alpha-particle in the Si detector and the charge signals on the pad plane
 118 were used to reconstruct the alpha trajectory. The slits of the Si mask were
 119 positioned either vertically or horizontally depending on the desired angular
 120 resolution measurement.

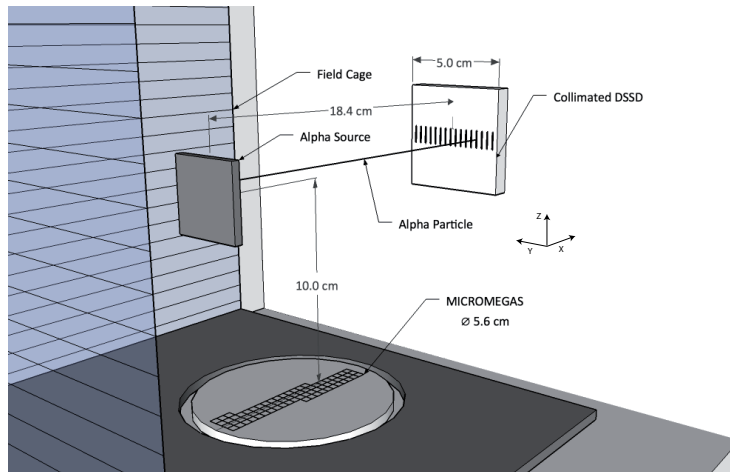


Figure 1: Schematic view of the complete setup for horizontal measurements. For vertical measurements the DSSSD and the mask were rotated by 90° .

121 The filling gas used in the chamber was supplied through a gas regulation
 122 system that ensured a constant flow and pressure. The $128 \mu\text{m}$ Micromegas
 123 prototype was tested in $\text{He}+\text{CF}_4(2\%)$ at 500, 600 and 800 mbar whereas the
 124 $256 \mu\text{m}$ detector was tested at 400, 500 and 600 mbar and in pure iC_4H_{10}
 125 at 25, 50 and 70 mbar. The ThGEM was only tested in pure iC_4H_{10} at

126 25, 50 and 75 mbar. The maximum pressures (800 mbar in the He mixture
127 and 75 mbar in isobutane) were chosen so that the alpha particles could
128 reach the silicon detector. The lower pressures were adapted to the different
129 amplification systems and their own sparking limits and gain properties. For
130 this reason, the 256 μm Micromegas was preferred to the 128 μm in isobutane
131 [16]. The values of voltages are specified for each result given later in this
132 article. For Micromegas, they are given as: $V_{\text{mesh}}/V_{\text{drift}}$ with V_{mesh} the
133 micromesh voltage and V_{drift} the voltage applied to the drift cathode. For
134 the ThGEM, they are given as: $V_{\text{down}}/V_{\text{up}}/V_{\text{drift}}$ with V_{down} the voltage
135 applied to the bottom electrode in front of the pad plane (generally called
136 extraction voltage) and V_{up} the voltage applied to the top electrode.

137 3. Data analysis and trace reconstruction

138 Figure 2.a shows a schematic view of how the pads were connected to the
139 electronics card (288 total channels from sectors 1,2,3 and 4). The AFTER
140 card is equipped with one preamplifier and shaping amplifier per channel.
141 Signals are sampled at a maximum rate of 100 MHz and registered in a 12 bit
142 ADC on trigger request. Parameters such as the dynamic range, the shaping
143 time and the sampling rate can all be modified in software. In general, a
144 shaping time of 400 ns and a sampling rate of 100 MHz were used. The
145 dynamic range was typically 120 fC but could be increased to 240 or 360 fC
146 if the detector gain or the energy deposition was too high. The homogeneity
147 of the pad response was studied by injecting a pulser on the mesh of the
148 Micromegas detector and it was found to be better than 2%. The analysis
149 program utilises the main characteristics of the event-by-event signals such
150 as the channel number, the baseline and the noise (standard deviation of
151 the baseline), the signal amplitude and the times (start, maximum and stop
152 times). Only those channels whose total collected charge exceeded a specified
153 threshold were recorded. This threshold was typically chosen to be 10 times
154 the noise level. The mean standard deviation of the baseline (noise level)
155 was around 4 ADC channels (for short cables of less than 10 cm length and
156 a dynamic range of 120 fC) which corresponds to less than 800 electrons. An
157 example of a 2D histogram with the signal amplitude of the channels versus
158 their X and Y spatial coordinates for a single projected trace is shown in
159 figure 2.b. Due to the influence of the transverse diffusion of the electrons in
160 the drift gap, the traces have a transverse multiplicity that is larger than a
161 single pad. The start time of each pad was calculated using a software CFD

162 (Constant Fraction Discrimination at 30%) method on the sampled signals.

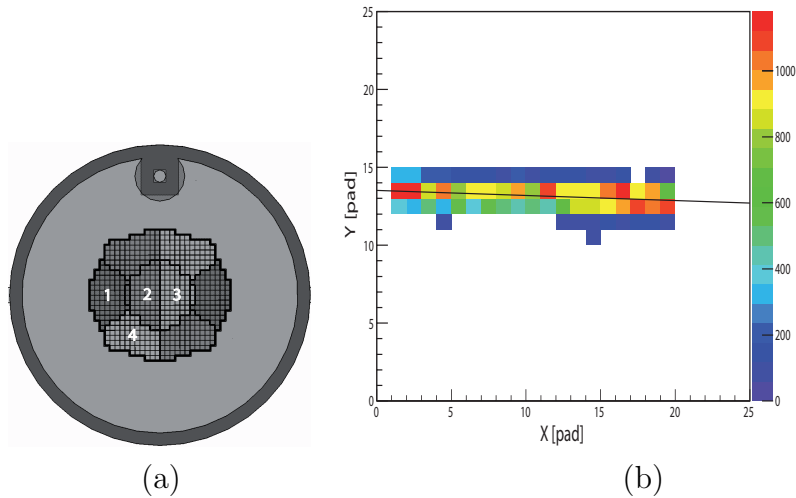


Figure 2: (a) The pad plane was divided into eight sectors of 36 pixels of $2 \times 2 \text{ mm}^2$ and sectors 1,2,3 and 4 were connected to a single 288 channels AFTER card. (b) Representative 2D histogram of the charge signal amplitude in ADC values using Micromegas versus the X and Y spatial coordinates and resulting best-fit trajectory (solid line).

163 A two-step track reconstruction analysis was performed on an event-by-
 164 event basis. The horizontal angle of the projected 2D alpha trace was first
 165 calculated using a linear fit. The vertical angle was then evaluated using the
 166 time differences between the pads along the trajectory. The horizontal mea-
 167 surement is absolute, the real position of the projected track is reconstructed
 168 and it was not necessary to collimate the source. However, the vertical angle
 169 measurement is relative. The angle is calculated but the absolute height of
 170 the particle is not known. It was therefore necessary in this case to use a
 171 collimated source.

172 For horizontal angles, the trajectories are determined from a χ^2 minimiza-
 173 tion between the fit and the pad centers in the X and Y directions weighted
 174 by their individual collected charge [17]. The result is a straight line that
 175 gives the direction and the origin of the track as plotted in figure 2.b. Once
 176 the straight line parameters (slope and origin) are known, the final Y co-
 177 ordinate of the track at the position of the Si detector can be extrapolated
 178 using the known physical geometry of the setup. One can then obtain the
 179 angle considering a point-like source. From the connected sectors shown in

180 figure 2.a, the maximum track length corresponds to the first 3 sectors of the
181 detector. This implies that the linear fits could be performed using charge
182 distributions with a maximum length of 4.2 cm (3 sectors with 7 pads of 2
183 mm length per sector). In practice, the first and last rows of the pad planes
184 were removed from the analysis to remove observed edge effects. Resolutions
185 were thus calculated using a maximum trace length of 3.8 cm. For compari-
186 son, MAYA pads are 8.9 mm length and traces of at least 5 cm in length are
187 required to deduce the horizontal direction.

188 For vertical angles, the setup restricted traces to angles that were pri-
189 marily parallel to the X-axis (horizontal angles $\theta_h < 7^\circ$ for the most external
190 silicon strips). The traces were divided into pad rows and it was the start
191 time of the pads with the maximum charge in that particular row that was
192 used in the analysis. This minimizes the influence of transverse diffusion of
193 the ionization electrons on the time determination. A linear fit of the start
194 time of each row versus the row was then performed. From these fits, and
195 using the drift speed of the gas obtained from GARFIELD simulations [18],
196 the relative vertical angles θ_v of the traces can be determined.

197 4. Angular resolution results

198 Four slits of the Si detector out of the 16 total were used to trigger the
199 electronics. Well separated slits such as 1, 5, 9 and 13 were used to increase
200 the total counting rate and ensured the distributions could be resolved. Plots
201 of the reconstructed slit positions were obtained (figure 3) and the angular
202 resolution was deduced using a gaussian fit to the collected distribution of
203 each slit. The contribution to the total resolution from the slits themselves
204 was less than 0.2° (FWHM) and was negligible compared to the overall resolu-
205 tions obtained. Results of the angular resolution measurements (in FWHM)
206 are provided in figure 4. The results shown are the average values of the
207 widths of the four reconstructed slits. This corresponds to angles between
208 $\pm 7^\circ$ in the horizontal and the vertical directions.

209 The first set of measurements were performed in He+CF₄(2%) using the
210 two Micromegas detectors at several pressures (figure 4.a). Voltages of -
211 190/-2000, -210/-2000 and -250/-2000 V were applied to the 128 μm detector
212 for 500, 600 and 800 mbar of pressure, respectively. Voltages of -250/-2000,
213 -260/-2000 and -270/-2000 V were applied to the 256 μm detector for 400,
214 500 and 600 mbar of pressure, respectively. The horizontal resolutions are of
215 order 1° and are comparable between the two detectors. This confirms that

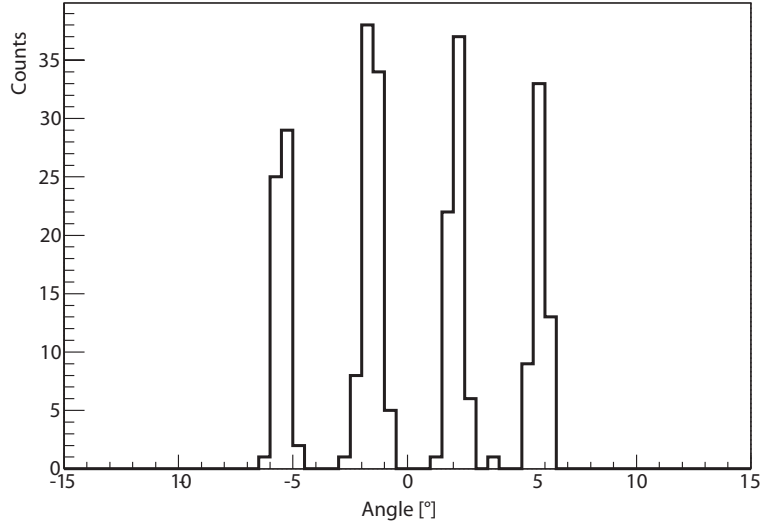


Figure 3: Histogram of the slit reconstruction in degrees.

216 the slit widths can be neglected. The mean transverse multiplicities were 3.5
 217 pads for both detectors. This is larger than what would be expected from the
 218 amplification gap alone and is thus a result of the electron diffusion in the
 219 drift gap. From GARFIELD simulations, a strong variation of the transverse
 220 diffusion coefficient is not expected for pressures between 500 mbar and 800
 221 mbar (about $400 \mu\text{m}/\sqrt{\text{cm}}$ with 10% variation). The transverse multiplicity
 222 can increase to ~ 4 pads in certain conditions (higher gains for example) but
 223 this has a negligible influence on the angular resolution for trace lengths ex-
 224 ceeding 3 cm. Straggling effects calculated with TRIM [19] for a trace length
 225 of 184 mm and with 5.5 MeV alpha particles are also indicated in figure
 226 4. The long distance of 184 mm between the source and the Si detector is
 227 clearly a drawback of the present set-up. Each event is affected by straggling
 228 along this entire length and not just the 3.8 cm that the detector is sensi-
 229 tive to. The slight degradation of the horizontal resolution with increasing
 230 pressure is consistent with straggling. The measured angular resolutions are
 231 however bigger than the effect of straggling given by TRIM. The straggling
 232 given by TRIM could be underestimated and this could explain the difference
 233 between straggling curves and measurements. Since the horizontal angular
 234 reconstruction relies on the individual charge of the pads, the angular reso-
 235 lution could also be degraded compared to straggling because of the energy

236 resolution of the pads (see section 6).

237 Variations in the vertical resolution are similarly influenced by straggling.
238 However, as explained above, the drift time is relative between channels.
239 The exact heights of the alpha particles are unknown and thus only their
240 angles can be deduced. It was therefore necessary to restrict the emission
241 angles of the source using a 2-mm diameter collimator that corresponds to
242 a broadening of the vertical angular distribution of 0.5° FWHM. The time
243 resolution of the electronics and the CFD method has been estimated to 7 ns
244 FWHM by injecting pulses on the micromesh and reading the corresponding
245 signals on the pads. For a drift speed of $1 \text{ cm}/\mu\text{s}$ and taking into the account
246 the number of pads used in the vertical angle analysis, the time resolution
247 of the electronics leads to an additional angular uncertainty of $\sim 0.1^\circ$. The
248 overall vertical resolution of $\sim 1^\circ$ is thus primarily limited from straggling
249 effects and the diameter of the collimator.

250 Figure 4.b shows complementary results to figure 4.a but for low pressures
251 of pure isobutane for the $256 \mu\text{m}$ Micromegas detector and the ThGEM.
252 Voltages of -380/-2000, -410/-2200 and -380/-2500 V were applied to the
253 $256 \mu\text{m}$ detector for 25, 50 and 75 mbar of pressure, respectively (the voltage
254 at 75 mbar was kept lower to avoid the saturation of the electronics). The
255 voltages of the ThGEM were -200/-700/-1700, -60/-700/-1700, and -350/-
256 1050/-2500 for 25, 50 and 75 mbar of pressure, respectively. The results are
257 also compared to straggling calculations from TRIM. Angular resolutions are
258 comparable to He+CF₄(2%) and are equivalent between the two detector
259 types. However, vertical angular resolutions (close to 1.3°) at low pressure
260 are slightly degraded relative to the horizontal resolutions due (partially)
261 to the increased drift speed of the gas. The estimated uncertainty of the
262 time resolution of the electronics with a drift speed of $5 \text{ cm}/\mu\text{s}$ in isobutane
263 leads to a vertical angular uncertainty of $\sim 0.5^\circ$. This is five times larger
264 than the corresponding uncertainty in the helium mixture at higher pressure.
265 However, the time uncertainty is not sufficient to explain the degradation of
266 the vertical angle resolution at low pressures and it is probable that this time
267 uncertainty has been under evaluated (see section 6).

268 The influence of the total trace length on the resulting angular resolution
269 is particularly important for the reconstruction of low-energy particles. For
270 example, a 100 keV proton will have a range of less than 8 mm in 50 mbar of
271 isobutane. Short trace-length events were investigated by removing data in
272 software from the 3.8 cm tracks in successive intervals of 0.4 cm (2 pads) and
273 the analysis described above was repeated. Angular resolutions (horizontal

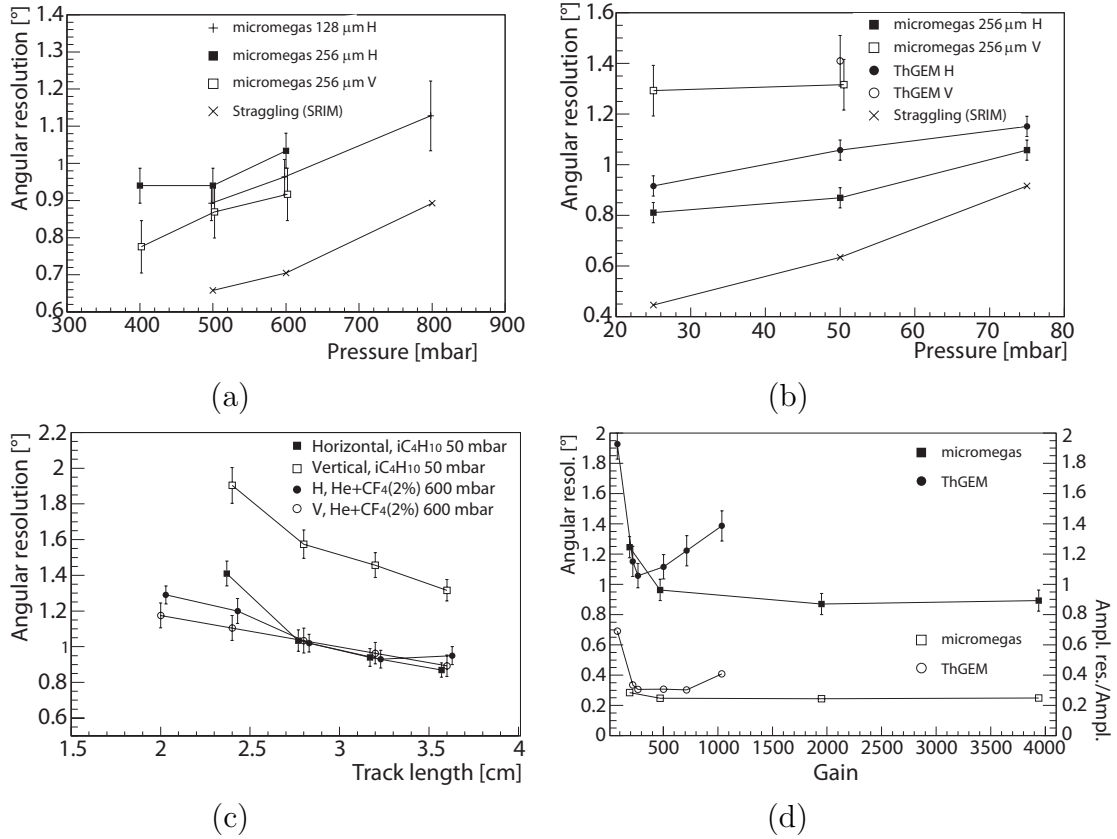


Figure 4: Experimental angular resolution results. (a) Angular resolution (in FWHM) in $\text{He}+\text{CF}_4(2\%)$ (H for horizontal and V for vertical) for the two Micromegas detectors, (b) angular resolution in $i\text{C}_4\text{H}_{10}$ for the 256 μm Micromegas and the ThGEM, (c) angular resolution versus track length for the 256 μm Micromegas detector in $\text{He}+\text{CF}_4(2\%)$ at 600 mbar and $i\text{C}_4\text{H}_{10}$ at 50 mbar, and (d) angular resolution (solid symbols, axis on the left) and the energy resolution (open symbols, axis on the right) versus the amplification gain in $i\text{C}_4\text{H}_{10}$ at 50 mbar.

274 and vertical) versus the trace length are provided in figure 4.c for the 256
275 μm Micromegas in 50 mbar of $i\text{C}_4\text{H}_{10}$ and $\text{He}+\text{CF}_4(2\%)$ at 600 mbar. A
276 degradation of the resolution in both horizontal and vertical directions with
277 the track length is observed in both gases. For trace lengths larger than 2.5
278 cm, angular resolutions are comparable with the exception of the vertical
279 resolution in low-pressure isobutane. As described above, this is primarily
280 due to the high drift speed at low pressure coupled with the time resolution of
281 the electronics. Vertical resolutions follow the trend imposed by the coupling
282 of this time resolution and the track length (number of pads used for the
283 time fitting). The degradation of the horizontal resolution for shorter track
284 lengths can have two origins. Besides the straggling effects inherent to the set-
285 up, the ratio between the track length and the transverse multiplicity has a
286 direct influence on the accuracy of the straight line fit used to reconstruct the
287 direction of the tracks. Gases with low transverse diffusion coefficients should
288 be used when events with short ranges must be reconstructed or, at least,
289 since the choice of the gas and pressure are imposed by the nuclear reaction,
290 the drift voltage or the quencher percentage should be adapted to minimize
291 the transverse diffusion. However, the mean transverse multiplicity must be
292 larger than 2 pads to keep a good angular resolution in every direction.

293 Measurements with different detector gains were performed in 50 mbar
294 of pure isobutane with the 256 μm Micromegas and the ThGEM detectors
295 and results are shown in figure 4.d. The Micromegas voltage was varied
296 from -300/-2000 to -420/-2000 V. The THGEM voltages were varied from
297 -20/-660/-1500 to -190/-830/-1700 V keeping a constant difference between
298 V_{down} and V_{up} . It was not the gain of the foil that was varied but rather
299 the extraction field (the field applied between the bottom of the ThGEM and
300 the pad plane). Angular resolutions and energy resolutions are plotted versus
301 the amplification gain and both show similar trends. The horizontal angle
302 reconstruction is weighted by the amplitude of the signal collected on the
303 individual pads. The energy resolution therefore influences the determination
304 of the reconstructed trajectory. The energy resolution of 22% (FWHM),
305 for gains higher than 500 in the Micromegas detector, was calculated from
306 the dispersion of the mean amplitudes on several rows of the pad plane.
307 It includes the variations in the number of electrons produced during the
308 ionization and the avalanche processes, the electronic noise contribution and
309 the energy straggling of the alphas, which is the main contribution at high
310 gains. The energy deposition of the alpha-particles was ~ 25 keV/pad in
311 $i\text{C}_4\text{H}_{10}$ at 50 mbar. Amplification gains were calculated using the mean

Radioactive species	Alpha energies	SRIM Range	LISE Straggling
^{239}Pu	5.15 MeV	36.5 mm	0.35 mm
^{241}Am	5.48 MeV	40 mm	0.4 mm
^{244}Cm	5.8 MeV	43.5 mm	0.45 mm

Table 1: Characteristics of the 3α source, ranges and associated straggling in Ar+CF₄(2%) at 1100 mbar.

312 signal amplitude over several rows, the charge dynamic range of the electronic
313 channels, the average energy deposited and the pair energy creation (~ 20
314 eV). The maximum gain of the ThGEM is lower than the Micromegas at 50
315 mbar but the ThGEM used was probably too thin for this pressure.

316 5. Stopping point measurements

317 To obtain Bragg-peak events with 5.5 MeV α particles within the 4.2 cm
318 active length of the detectors, Ar gas with 2% CF₄ at 1100 mbar was em-
319 ployed. In table 1, energies and ranges of the 3 main alphas of the source are
320 summarized for this particular gas mixture. Range studies were performed
321 using the 256 μm Micromegas detector with a voltage of -350/-3350 V.

322 The micromesh signal, rather than the Si detector, was used as trigger for
323 the electronics card. Reconstruction of the individual tracks on the pad plane
324 were performed using the analysis techniques described above. An example of
325 the amplitude of the signals on the pads projected in the transverse direction
326 with respect to the alpha trace is presented in figure 5. The resulting Bragg
327 peak is in good agreement with SRIM calculations. However, the energy loss
328 at the beginning of the trace is larger than expected and is likely due to edge
329 effects in the electrostatic field of the drift region.

330 Bragg-peak distributions were fitted on an event-by-event basis using cu-
331 bic spline interpolation. The maxima were deduced, and the ranges de-
332 termined using the position where the amplitude equals one fourth of the
333 maximum. This is an empirical method that depends upon the particular
334 detector and the diffusion of the gas, but it is sufficiently accurate in this
335 context. Once the projected length is determined, the horizontal and verti-
336 cal angles allow the total track length to be deduced in 3 dimensions. Figure
337 6 shows the calculated end points of several reconstructed α -particles. A
338 clear separation of the 3 alpha energies confirms the accuracy of this analysis
339 procedure.

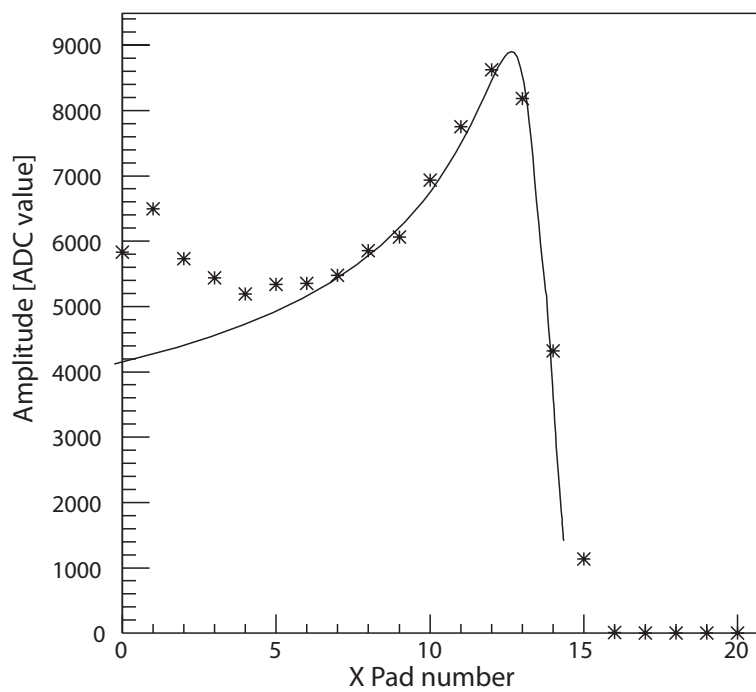


Figure 5: Amplitude signals versus track length and expected distribution from SRIM for a 5.5 MeV alpha in 1100 mbar of Ar+CF₄(5%).

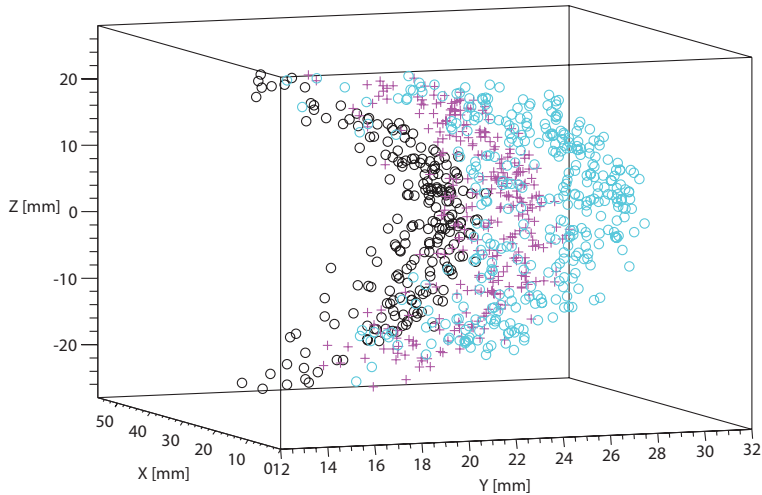


Figure 6: Plot of the reconstructed ranges for the 3 α -particles (black Pu, red Am and blue Cm).

340 Amplitude and range resolutions obtained at angles restricted to $\pm 10^\circ$ in
 341 vertical and $\pm 5^\circ$ in horizontal are shown in figure 7 and the 3 peaks are very
 342 well separated. From the total amplitude of the signals registered on the pads,
 343 the energy resolution obtained for these three peaks (from lowest to highest
 344 energy) are 5%, 4.5% and 6% (FWHM) respectively. The energy resolution
 345 is degraded for the highest alpha energy. Its stopping point was located
 346 between two sectors of the pad plane and thus two different AFTER chips.
 347 This resolution could be improved with a better calibration of the system.
 348 The reconstructed ranges are 36.7 ± 0.4 mm, 39.9 ± 0.4 mm and 43.3 ± 0.4 mm
 349 for the 3 peaks, respectively. These values are in excellent agreement with
 350 the SRIM values shown in table 1. The range resolution on the stopping
 351 points are 2.4%, 2.3% and 2.2% (FWHM), respectively. In terms of energy
 352 resolution, a 2.5% FWHM range corresponds to 2% for a 5.8 MeV α -particle.
 353 The detector behaves as expected and the energy resolution is consistent with
 354 results obtained in [20].

355 Charge and range resolutions were also obtained when the angular restric-
 356 tion is removed taking into account the set-up geometry ($\pm 50^\circ$ in vertical and
 357 $\pm 18^\circ$ in horizontal) and results are shown in figure 8 for the charge (a) and
 358 range (b) measurements respectively. From the signal amplitudes, the en-

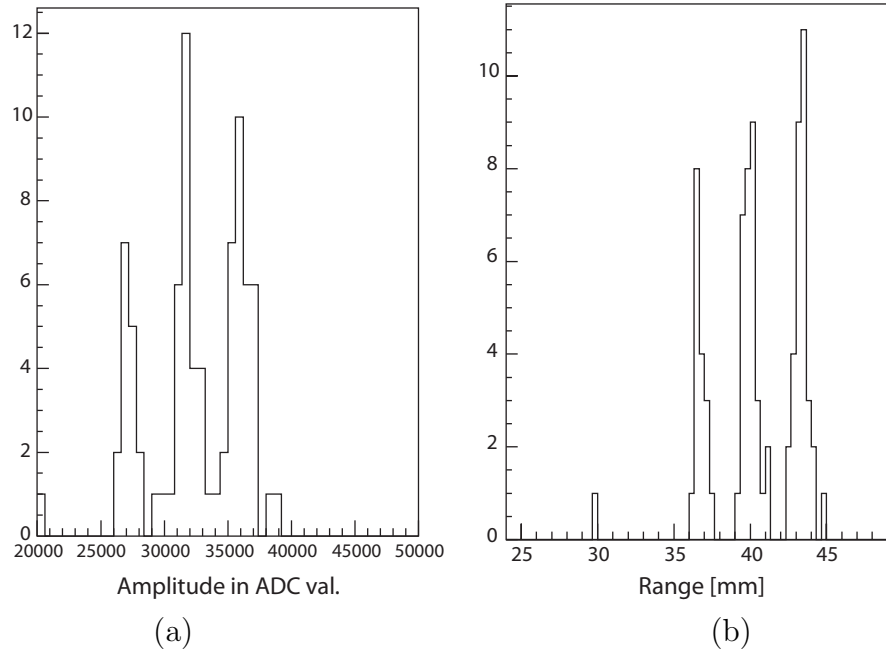


Figure 7: Signal amplitude (a) and range (b) resolutions at closed angles.

359 energy resolution is degraded relative to the results at restricted angles and is
 360 likely due to the distance between the source and the active pad plane that
 361 is more significant for larger angles. In terms of the total range, the resolu-
 362 tion on the trace lengths (from lowest to highest energy) are 4.6%, 5.5% and
 363 4.27% (FWHM), respectively. The reconstructed ranges are 36.8 ± 0.7 mm,
 364 40.2 ± 0.9 mm and 43.7 ± 0.8 mm for the 3 peaks. The energy resolution from
 365 the range analysis is, to a large extent, preserved since the 5% FWHM range
 366 corresponds to 4% in energy resolution for a 5.8 MeV α -particle.

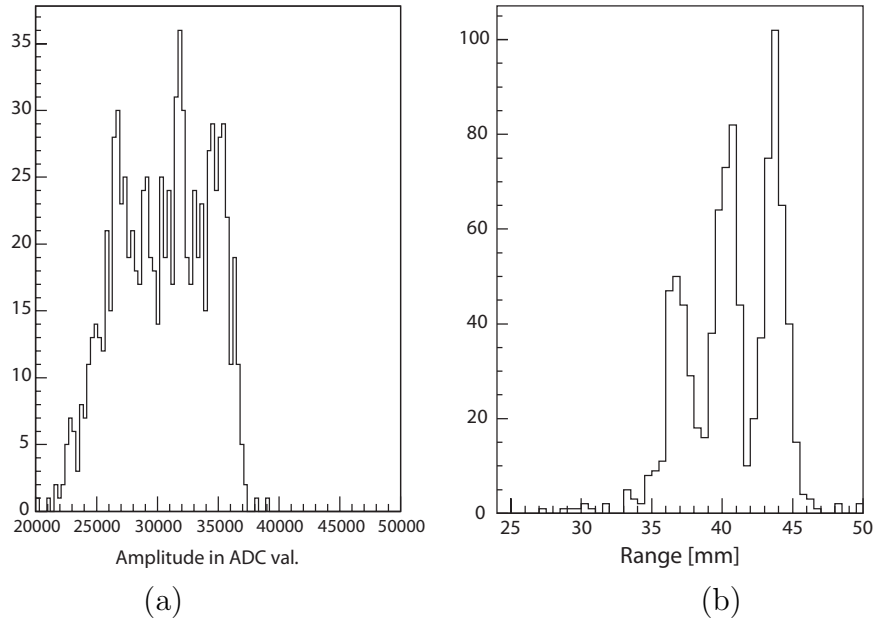


Figure 8: Signal amplitude (a) and track length (b) resolutions at open angles.

367 6. Simulations

368 The complete experimental setup was simulated using a dedicated pro-
 369 gram based on the ROOT data analysis framework [21] and the Geant4
 370 toolkit [22]. The program employed GEANT4 to describe the interactions
 371 of the particles with the atoms or molecules of the gas and for the deter-
 372 mination of the energy deposited at each interaction position along their
 373 trajectories. The precise physical geometry of the setup including the Si
 374 strip detector that was used as the trigger detector in the experiment (for

375 the angular resolution measurements) were also defined in Geant4. Because
376 the ionization electrons produced along the trajectories of the α particles,
377 their transportation through the drift gap under an applied electric field,
378 electron amplification in the Micromegas, and the subsequent charge collec-
379 tion on the position-sensitive pad plane cannot be specified in Geant4, it
380 was necessary to include these processes within a set of macros developed in
381 ROOT. A description of these processes, how they were combined with the
382 GEANT4 simulated energy deposition and position information, and com-
383 parison between the simulation and the experimental results are presented
384 below.

385 *6.1. Gas ionization and detector response*

386 The ionization of the gas and the drift of the resulting electrons were
387 treated as follows. At each Geant4 interaction point, the mean number of
388 electrons was calculated from the ratio between the energy deposited and
389 the average energy required to produce an electron-ion pair ($W \sim 30$ eV) [23].
390 Fluctuations to this mean number are then included using a Poisson distri-
391 bution. In order to reproduce the charge spread that arises from diffusion
392 along the vertical drift length (considering an ideal electrostatic drift field),
393 the arrival point of the electrons at the amplification plane was obtained
394 using a Gaussian randomization of the horizontal coordinates with respect
395 to the initial interaction point. The width of this Gaussian distribution is
396 given by $\sqrt{2Dh/v}$ where D is the diffusion coefficient of the gas, h the ver-
397 tical height of the interaction point with respect to the pad plane and v the
398 electron drift velocity. The parametrization of each gas was calculated using
399 MAGBOLTZ [24] that uses as inputs the gas species, pressure, and the elec-
400 tric field applied across the drift region. Pressures used in the simulations
401 were the same as for the experiment: 600 mbar for He+CF₄(2%), 50 mbar
402 for iC₄H₁₀) and 1100 mbar of Ar+CF₄(2%) for range determinations. The
403 time required for the electrons to reach the anode (the time projection) was
404 obtained at each position using the (vertical) position coordinate and the
405 constant drift velocity in the gas (with a drift electric field of 100 V/cm). A
406 time resolution of 3 ns (corresponding to 1 standard deviation) was added
407 according to the experimental results.

408 The microscopic details of the avalanche process in the Micromegas were
409 not included in the simulations. Instead, an overall multiplicative gain factor
410 was applied to every electron that was selected with a probability according
411 to a Polya distribution [25, 26]. Fluctuations on this gain, that arise from

412 the statistical nature of the avalanche, are therefore intrinsically included
413 with this approach ($\theta = 2.2$ was chosen for the Polya parameter [26]). For
414 an entire simulated α particle trajectory, which corresponds to many Geant4
415 single-interaction points, the total charge collected on each pad was obtained
416 from the sum of all of the individual electron contributions to that pad. A
417 software threshold of 8000 electrons was then applied to the simulated data
418 to be consistent with the experimental results described above in Sec. 3. No
419 additional effects (such as noise) were included in the simulations. The charge
420 resolution obtained with this method was $\sim 35\%$ (FWHM). This value is
421 larger than the experimental resolution given in figure 4.d (which was $\sim 22\%$)
422 indicating that the energy straggling in Geant4 is likely overestimated.

423 *6.2. Angular resolution simulation results*

424 To distinguish between the relative contributions of straggling effects in
425 the experimental results obtained for the angular resolution, two different
426 simulations were performed. The first used the identical physical geometry
427 and analysis methods as employed in the experiment. The Si detector was
428 placed a total distance of 184 mm from the α source and results were ob-
429 tained from fits applied to only the first few cm of each simulated trajectory.
430 The angular resolutions obtained from these simulations are shown in figure 9
431 (squares) for both gases versus the length of the fitted trace. Qualitatively,
432 the trends observed in the simulated results are in excellent agreement with
433 with experimental data. The simulated data reproduce both the increased
434 horizontal resolution for short traces and the difference between the vertical
435 angular resolution between the helium and isobutane gases (open squares)
436 that arise from differences in their drift velocities as described above. It was
437 even possible to show that a time resolution degraded to 6 ns (sigma, instead
438 of 3 ns) was enough to reproduce the difference between the helium mixture
439 and the isobutane in vertical angular resolution (see figure 4.c). Quantita-
440 tively, the simulated results are systematically lower than the experimental
441 data of figure 4 by $\sim 20\%$. It should be emphasized that the angular res-
442 olutions are completely dominated by lateral straggling of the particles in
443 the gas. In the simulations, these effects are described by Geant4 libraries
444 that were found to be consistent with SRIM calculations. The decreased
445 resolution observed experimentally therefore indicates that lateral straggling
446 effects are likely underestimated in Geant4 and SRIM. This has been ob-
447 served previously in Ref. [27], for example, where precise measurements of
448 lateral straggling from a highly-collimated beam of protons and α particles

449 (at energies similar to those in our study) were also underestimated in SRIM
 450 by approximately 40%.

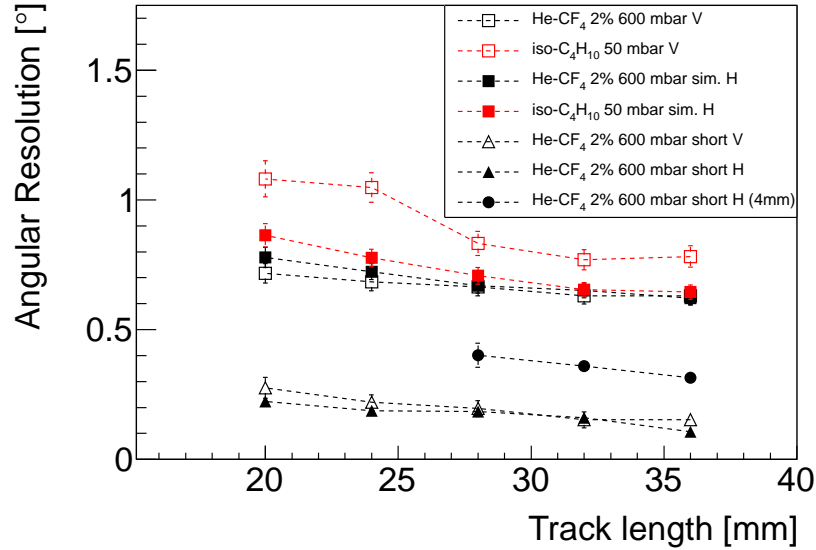


Figure 9: Results of the simulation based on the experimental setup: Angular resolutions versus track length in horizontal and vertical for the helium mixture and the isobutane.

451 In order to minimize these angular straggling effects, a second set of
 452 simulations were performed with the Si positioned closer to the source. In
 453 this case, we did not analyse only a small portion of a longer trace, but
 454 instead fitted the entire trace length obtained with a reduced source-to-Si
 455 distance that was varied for every simulation at the different distances shown
 456 in Fig. 9. To ensure that the results of this simulation were consistent with
 457 the previous ones, we had to account for the geometrical difference between
 458 the two configurations as placing the slit closer to the source increases the
 459 overall range of emission angles for α particles that can reach the detector. As
 460 shown in Fig. 9, the angular resolution results obtained from this second set of
 461 simulations (triangles) are significantly better than the previous values due to
 462 the decrease in lateral straggling along these much shorter trajectories. This
 463 analysis provides further confirmation for the dominance of lateral straggling
 464 in the angular resolution that can be achieved. Moreover, it confirms that
 465 the energy resolution is not the main contribution to angular resolution in
 466 our measurements (as long as the gain is high enough, see figure 4.d).

467 The same simulations were performed using a 4 mm pad size for the
468 digitization and the results are represented by circles in Fig. 9. The angular
469 resolution obtained is a factor two larger compared to the 2 mm pad. In
470 addition, with the lower transverse multiplicity for a bigger pad size, the
471 fitting algorithm cannot always converged in the track reconstruction for
472 traces shorter than 28 mm.

473 *6.3. range simulation results*

474 The simulation was also used for the study of the range of the α -particles
475 in the detector. The method for the determination of the range is the same
476 as was used with the experimental data: the projected range is calculated
477 from the Bragg curve and then corrected by the horizontal and vertical an-
478 gles obtained from the fits of the charge distribution on the pad plane and
479 the drift times, respectively. Figure 10 shows the distribution of the ranges
480 of the α -particles for the different energies. The left panel corresponds to the
481 distribution obtained selecting forward angles ($\pm 5^\circ$ and $\pm 10^\circ$ in horizontal
482 and vertical, respectively). The mean values obtained for the reconstructed
483 ranges for closed angles are 35.9 ± 0.4 mm, 39.3 ± 0.4 mm and 42.8 ± 0.5 mm
484 for 5.15 MeV, 5.48 MeV and 5.8 MeV, respectively. The range resolution on
485 the stopping point is then 2.5% FWHM. The mean values obtained are in
486 very good agreement with SRIM range calculations as well as the experimen-
487 tal results. The simulated range resolution is also in good agreement with
488 the one obtained experimentally. The right panel of Fig. 10, represents the
489 range distribution for a wider angular range ($\pm 30^\circ$ in horizontal and $\pm 50^\circ$ in
490 vertical). We observe that the range resolution is still good enough to resolve
491 the three peaks of the alpha source with resolutions of 4.2% (35.6 ± 0.6 mm),
492 4.2% (39.0 ± 0.7 mm) and 3.4% (42.4 ± 0.6 mm).

493 **7. Conclusion**

494 Several tests were performed using Micromegas and ThGEM detectors
495 coupled to a 2×2 mm² pad plane in a TPC. The angular resolutions and
496 the accuracy of the stopping point reconstructions were investigated as part
497 of a preliminary study into the possible use of these detectors for low-energy
498 nuclear physics applications. Angular resolutions better than 1° FWHM (in
499 both the horizontal and vertical directions) were obtained in different gases
500 and at various pressures with both detector types. The influence of the gain
501 was investigated and it was shown that the best angular resolutions were

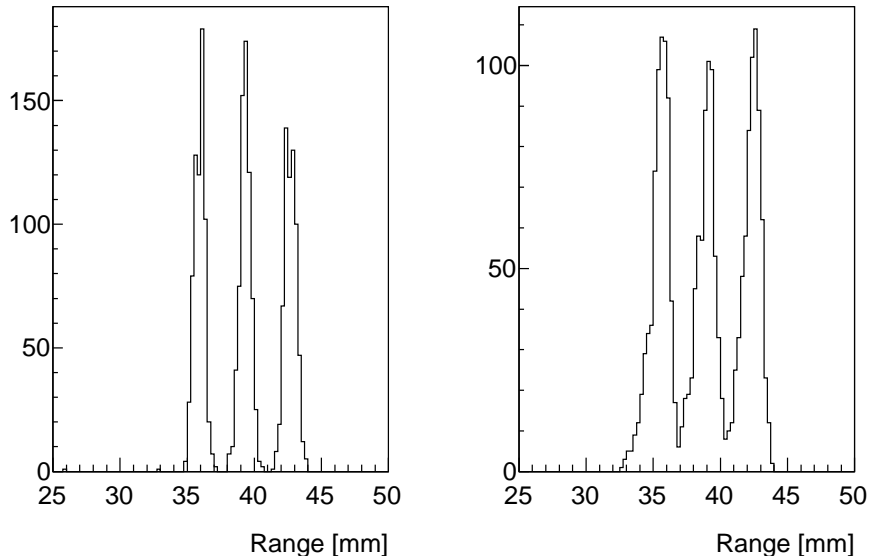


Figure 10: Range distribution calculated from the simulation: closed angle (left) and open angle (right).

502 obtained when the energy resolution is optimized, generally at intermedi-
 503 ate gains. An energy resolution of 5% FWHM for 5.8 MeV α -particles was
 504 measured from the charge profile and, using the range measurements, can
 505 be improved to 4% FWHM. All of these experimental results have been de-
 506 scribed with a Geant4 simulation and it has been shown that care must be
 507 taken before determining any quantitative conclusions from such simulations
 508 since their description of the angular and energy straggling processes appear
 509 to be under and over-estimated, respectively. The experimental results pre-
 510 sented in this work are better than present detectors such as MAYA and
 511 they validate the use of Micromegas and ThGEMs for active-target applica-
 512 tions in nuclear physics where high density pad planes are required. These
 513 results also validate the use of a high granularity pad plane ($2 \times 2 \text{ mm}^2$)
 514 with MPGDs since the transverse diffusion in the drift gap ensures a good
 515 transverse multiplicity between 3 and 4 pads.

516 A demonstrator Micromegas version of the ACTAR TPC detection sys-
 517 tem with 2048 pixels is presently under construction and will be used to
 518 test a new set of electronics for TPCs (GET: General Electronics for TPCs

519 funded by France ANR-09-BLAN60203-01) that are being developed for such
520 high-density applications. The demonstrator will provide an opportunity to
521 address other challenges that can arise with big chambers such as the drift
522 field homogeneity, and the mechanical integration and the robustness of the
523 connections.

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