Calibration of the energy response of the SWEATERS MICROMEGAS detector with ion beams and X-rays

2nd year admission exam
Statistic
17th December 2024

Andrea Foresi 39th cycle

SWEATERS experiment

Detector for atom detection in a space environment

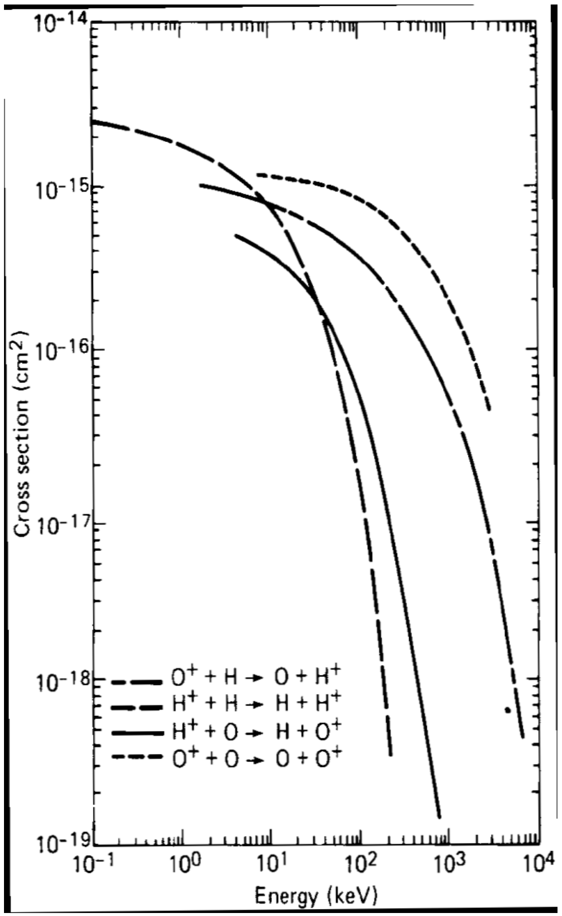
Detector based on MICROMEGAS techonolgy

The Ion Beam Facility built in the INFN Pisa laboratory

Energetic Neutral Atom (ENA)

- ENA detection in space is powerful technique for Space Weather research
- ENA can be created by charge exchange processes between ions of the solar wind and atoms of the magnetosphere
- The cross section of this creation process defines the ENA energy range [1-100] keV
- The SWEATERS Project goal is to develop a detector that provides precise **energy measurement** and direction reconstruction of the incoming ENA

$$I_1^{\cdot} + A_2 \rightarrow A_1 + I_2^{\cdot}$$



Doi: 265:251–288, 2000.

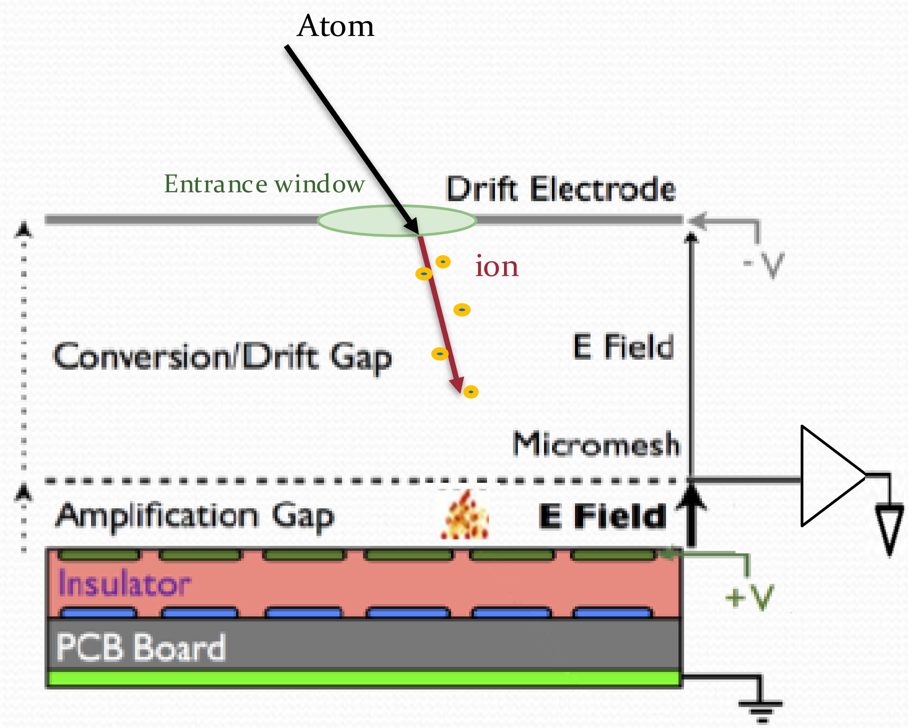
A MICROMEGAS (MM) for atoms detection in space

- A MM detector kept at low pressure can meet the requirements

- Ultrathin (2D) materials (thickness of o(nm)) can be used as gas-tight entrance window and to induce ENAs ionization as they enter the detector

- An ion of few keV of energy releases all its energy into the sensitive medium

- A proper read-out chain connected to the mesh electrode is used to measure the energy https://doi.org/10.1016/j.nima.2022.167915



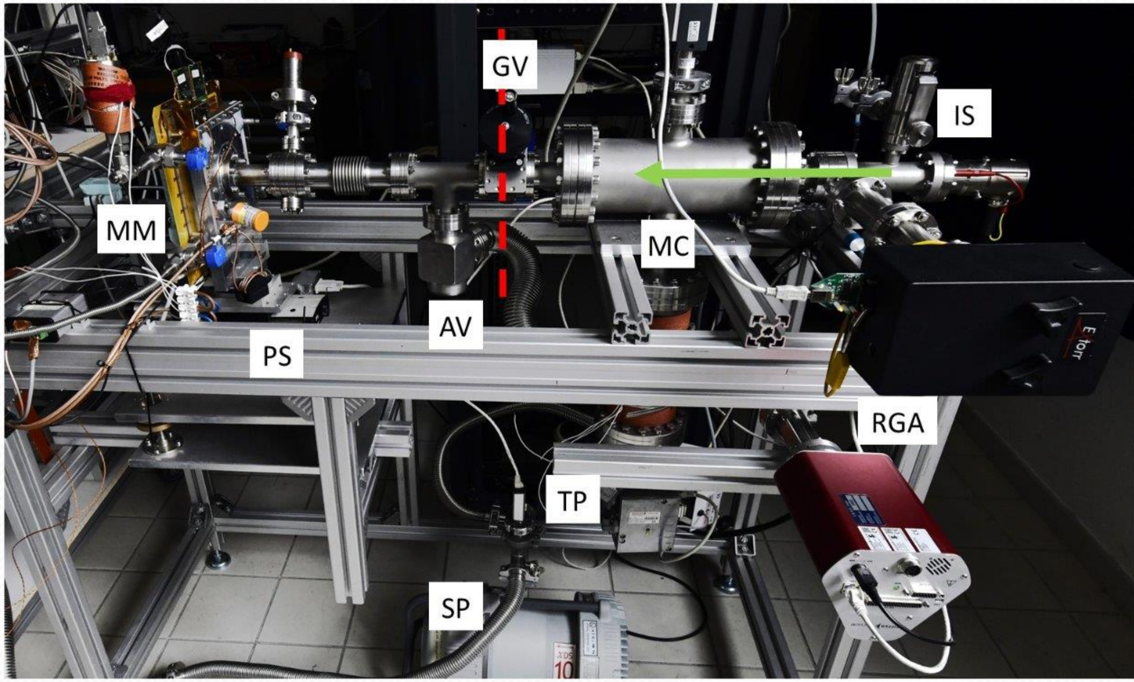
To guarantee the integrity of the entrance window and to increase the atom track:

gas pressure must be lower than 100mbar

Ion Beam Facility (IBF)

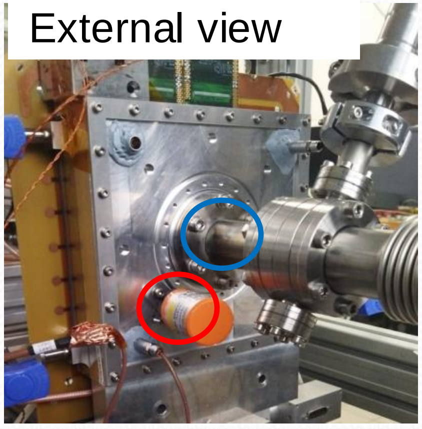
https://doi.org/10.1016/j.nima.2024.169918

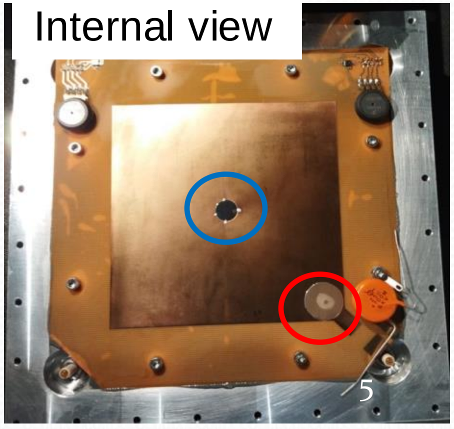
- The IBF consists of:
  - main chamber (MC)
  - commercial ion source (IS), energy range 0.2-5 keV
  - residual gas analyzer (RGA)
  - scroll pump (SP) and turbo pump (TP)
  - positioning system (PS)
  - valves to separate the IBF sections (AV, GV)
  - A gas distribution system to fill the MM with the $ArCO_2$ gas mixture
- For online detector calibration, the MM top cover is equipped with two entrance windows:
  - 5um diameter pin-hole (CW)
  - 2x50um thickness PEEK layer (LW)



CW

LW





Spectra analysis

Three results are needed from the analysis of these spectra:

- an estimate of the peak position, that is, the energy released in the ionization processes
- the uncertainties of the estimated parameters
- a goodness of fit test for a deeper understanding of the process that occur into SWEATERS project apparatus

Maximum Likelihood Esimator

- For the point estimation it is used the Maximum Likelihood Estimator (MLE)
- The MLE is an implicit estimator derived from the knowledge that the expectation value of the fisher score must be equal to zero if calculated with the exact value of the unknown parameters

$$k_n(\vec{x},\theta) = \frac{1}{n}\sum S_{x_i}(\theta) = \frac{1}{n}\sum \frac{d\log L_{x_i}(\theta)}{d\theta} = \frac{1}{n}\frac{d\log L_{tot}(\theta)}{d\theta}$$

$$\frac{d\log L_{tot}(\theta)}{d\theta}\Big|_{\theta=\hat{\theta}} = 0$$

- Every bin of the reconstructed spectra can be considered as a single variable distributed like a Poissonian
- Differently from the Least square estimator, a bin with low number or zero entries still give information to the MLE
- To perform a point estimation with the MLE the ROOT libraries are used. The fits were performed over TH1F histograms using the option "L"
- The uncertainties of the parameters estimated with the option "L" were obtained by calculating the second derivative of the Likelihood respect the parameters.
- These estimations are performed by the minuit algorithms by applying approximation and numerical calculations around the maximum calculated by the MLE

Likelihood ratio goodness of fit

•doi: 10.1214/aoms/1177732360
•Nuc.Inst. Met. 221 (1984) 437-442

- For the goodness of fit test a X^2 distribution is needed
- The Wilks theorem state that asymptotically the distribution of the likelihood ratio is distributed like X^2

$$\lambda = L(y;n)/L(m;n).$$

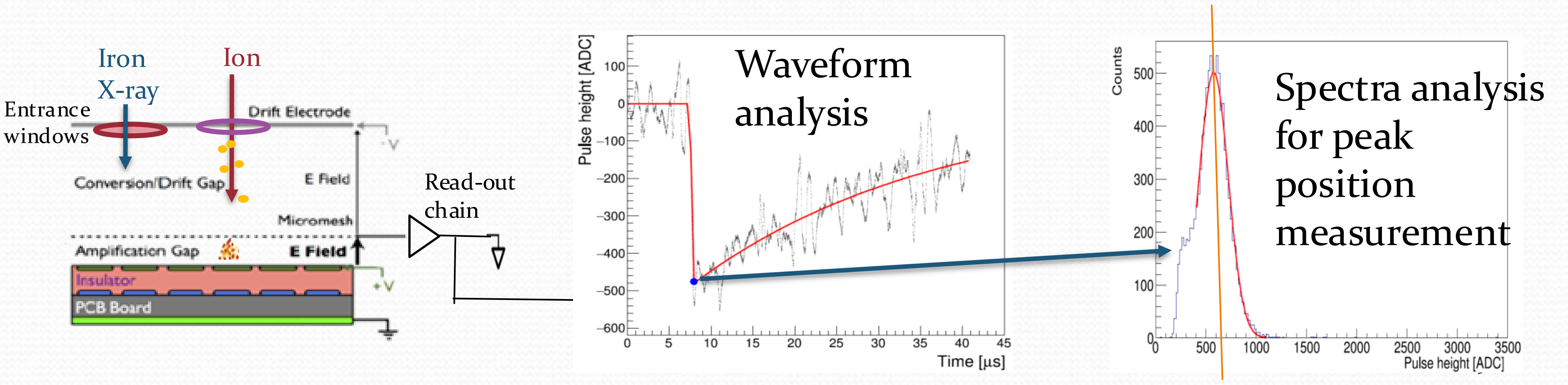
$$\chi^2_\lambda = -2 \ln \lambda = -2 \ln L(y;n) + 2 \ln L(m;n),$$

- Using the same option "L" for the TH1 fit, ROOT calculate the value of the X^2 and the correspondent p-value for the goodness of fit test

- To apply these three methods the computation of a proper Probability Density Function (PDF) is required
- Next slides will show the application of these statistical methods to some spectra reconstructed with the SWEATERS MICROMEGAS detector by irradiating it with different sources

Detector characterization procedure

- Before connecting the MM to the Ion Beam Facility (IBF), the MM was characterized with an X-ray ^{55}Fe source placed in front of the MM central window
- At the IBF in our laboratory, the MM was irradiated with He and H_2 ion beams accelerated at energies between 2.5 keV and 5 keV, which pass through the central window on the top cover of the MM
- The collected data were analyzed to study interaction of low energy light ions and X-rays with the gas at low pressure
- The characterization was performed analyzing the spectra reconstructed from the analysis of the signals induced on the mesh electrode

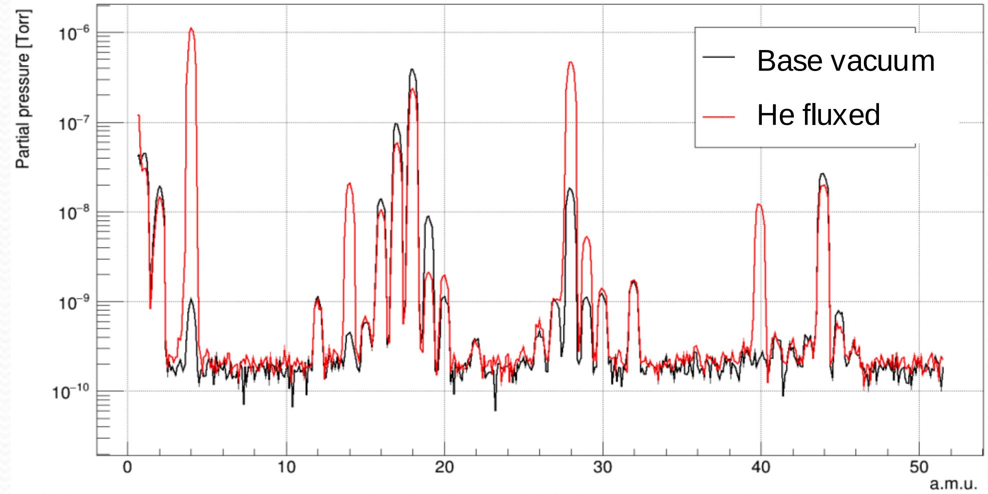


Ion spectra

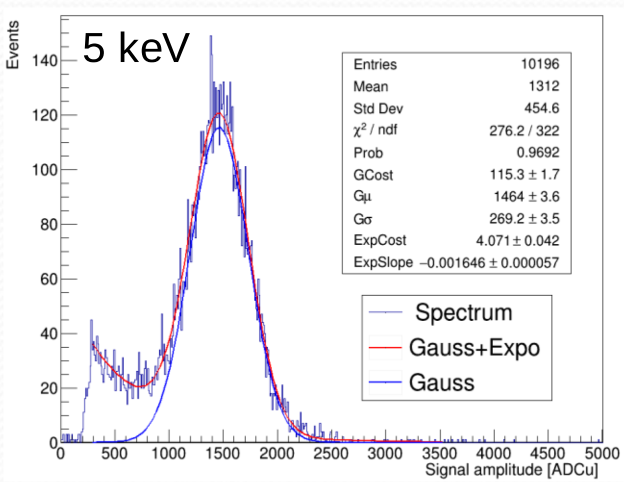
The MM was irradiatated with He and H_2 beams with energy between 3-5 keV keeping the gas pressure at 150mbar

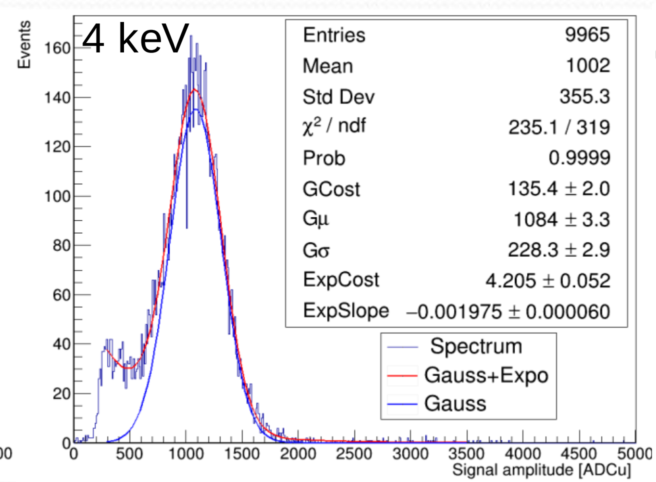
He spectra

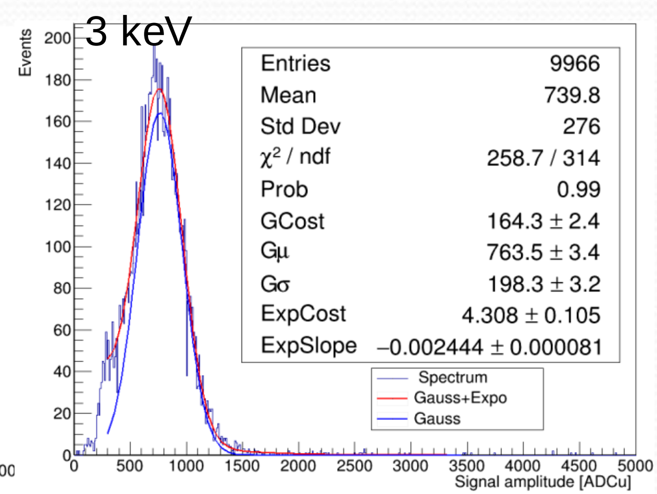
- The manufacturer states that the IS provide a monochromatic beam with an uncertainty of tens of eV
- Fluxing the He into the IS some contaminants gases were accelerated
- The contaminants are heavier than the helium and once they enter within the detector they release less energy than the main projectiles
- The effect of the contaminants appear like an exponential tail



$$\mathrm{PDF} = \frac{\mathrm{GCost}}{\sqrt{2\pi}\mathrm{G}\sigma} e^{-0.5\left(\frac{\mathrm{x - G}\mu}{\mathrm{G}\sigma}\right)^2} + e^{(\mathrm{ExpCost} + x \cdot \mathrm{ExpSlope})}$$

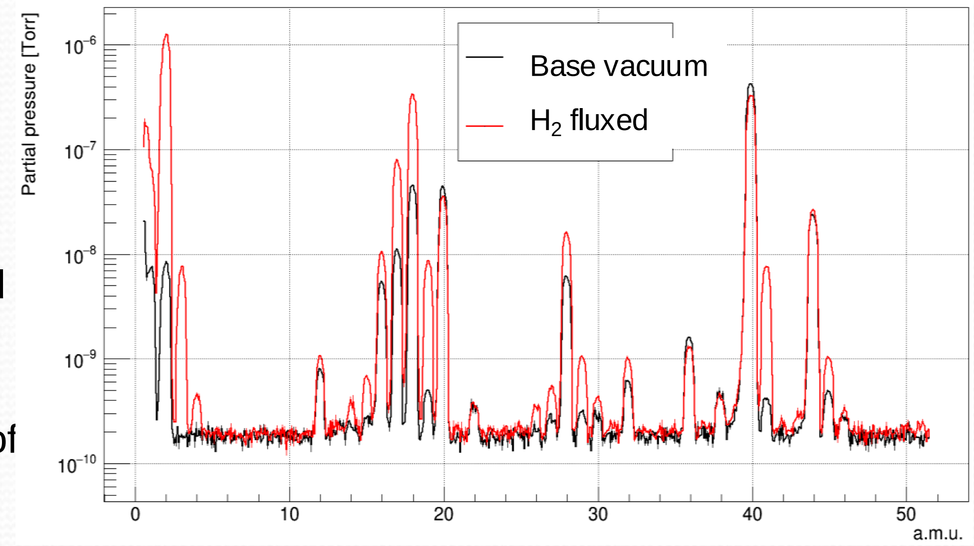




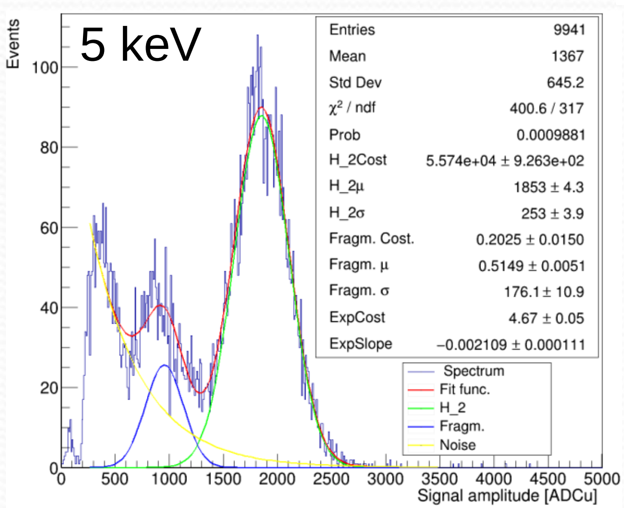


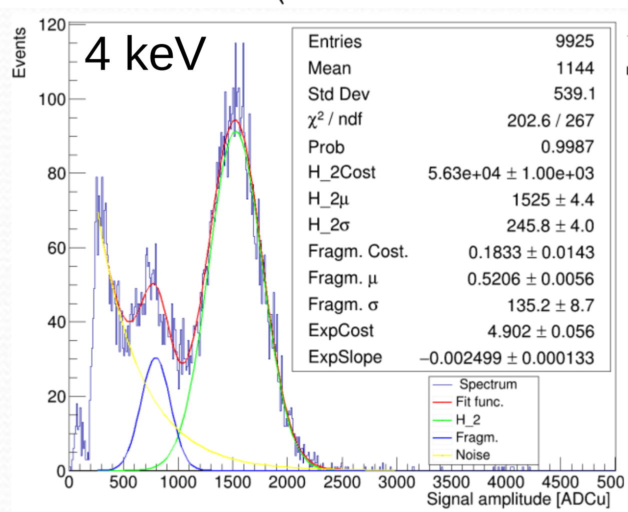
H_2 spectra

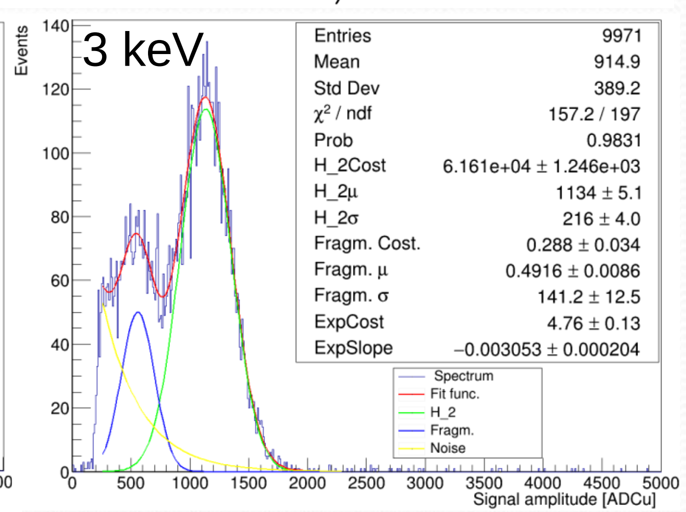
- While fluxing the H_2 the contaminants increase
- Due to the creation process of the H_2 also vapor contaminants were accelerated and fragmenteted even into light ions
- Preliminary studies on the interaction of H2 ion with the entrance windows shown the possibility of these ions to pass through the pin hole
- The H_2 spectra show a second peak at half the energy of the main peak



$$\mathrm{PDF} = \mathrm{H\_2Cost}\left(\frac{e^{-0.5\left(\frac{\mathrm{x - G\mu}}{\mathrm{G\sigma}}\right)^2}}{\sqrt{2\pi}\mathrm{G\sigma}} + \frac{\mathrm{Fragm.Cost.}}{\sqrt{2\pi}\mathrm{Fragm.\sigma}} e^{-0.5\left(\frac{\mathrm{x - G\mu \cdot Fragm.\mu}}{\mathrm{Fragm.\sigma}}\right)^2}\right) + e^{(\mathrm{ExpCost}+x\cdot\mathrm{ExpSlope})}$$





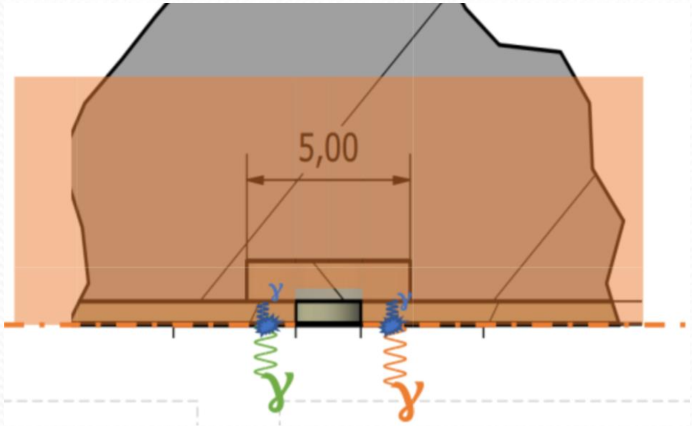


X-ray spectra

Analysis of the spectra of ^{109}Cd and ^{55}Fe sources varying the MM pressure

^{109}Cd spectra explanation

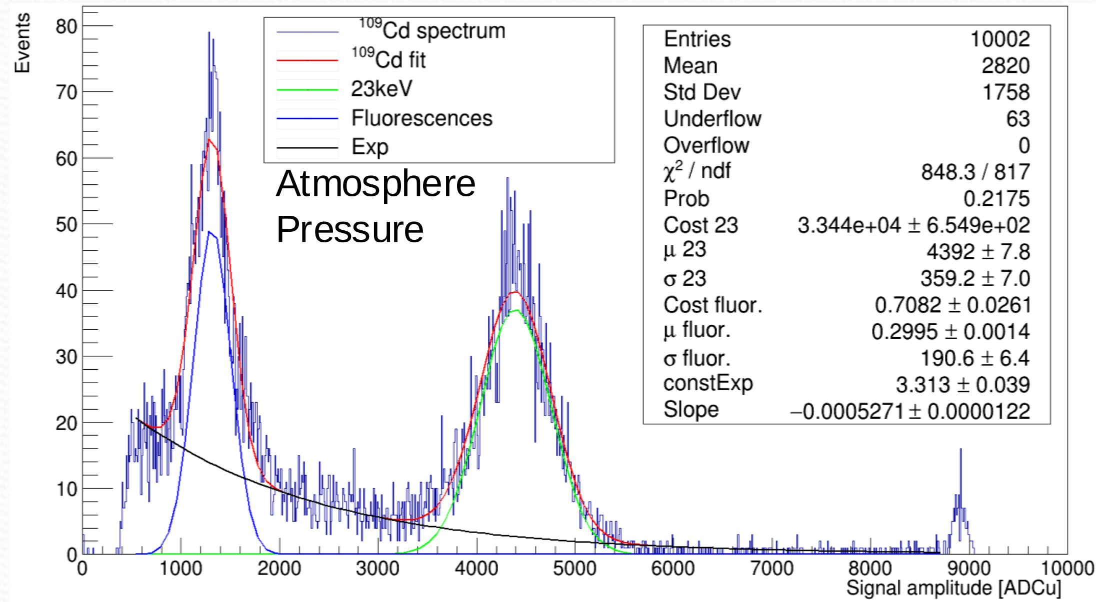
- Radiative sources have many spectral emission lines which become indistinguishable with a MM detector.
- The average of the energies of the main X-ray emissions by the ^{109}Cd source is 23.1 keV. https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html
- Photon with this energies can interact with the surrounding materials causing fluorescence emissions:
    - X-rays of 6.4 keV of energy from the interaction with the entrance window (stainlees stell, Molibdenum)
    - X-rays of 8.0 keV of energy from the interaction with the cathode (copper)

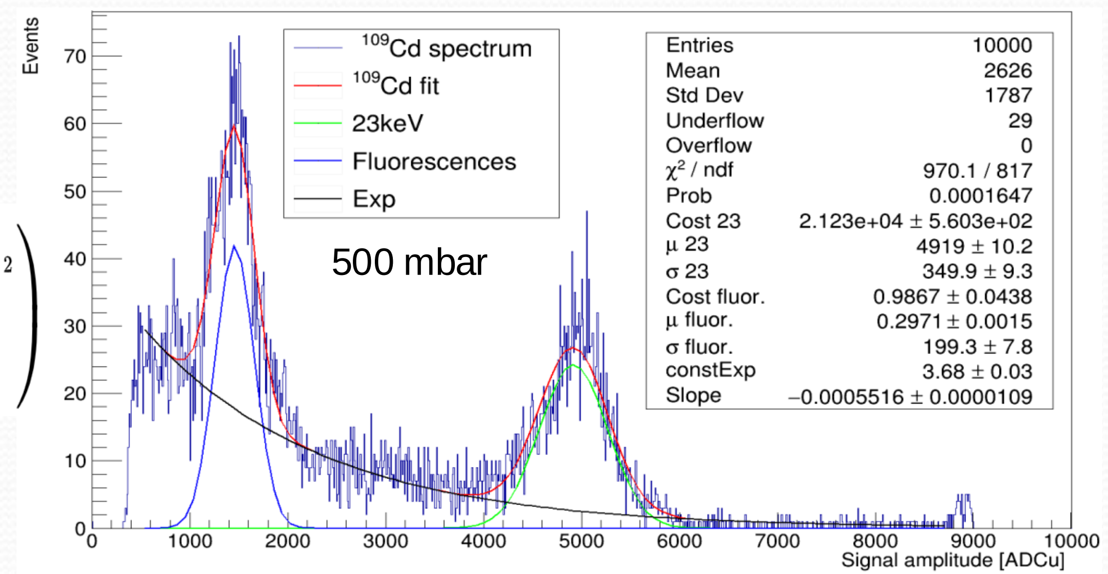


^{109}Cd spectra

- The Interaction probability of an X-ray emitted from the ^{109}Cd is too low
- The trigger rate was about 20-30Hz causing the triggering of noise events
- The exponential curve must be added on the PDF
- The noise contribution increase lowering the MM gas pressure

$$\mathrm{PDF} = \mathrm{Cost23}\left(\frac{e^{-0.5\left(\frac{x-\mu 23}{\sigma 23}\right)^2}}{\sqrt{2\pi}\,\sigma 23} + \frac{\mathrm{Cost\ fluor.}}{\sqrt{2\pi}\,\sigma\mathrm{fluor}} e^{-0.5\left(\frac{x-\mu 23\cdot\mu\mathrm{fluor}}{\sigma\mathrm{fluor}}\right)^2}\right) + e^{(\mathrm{costExp}+x\cdot\mathrm{Slope})}$$

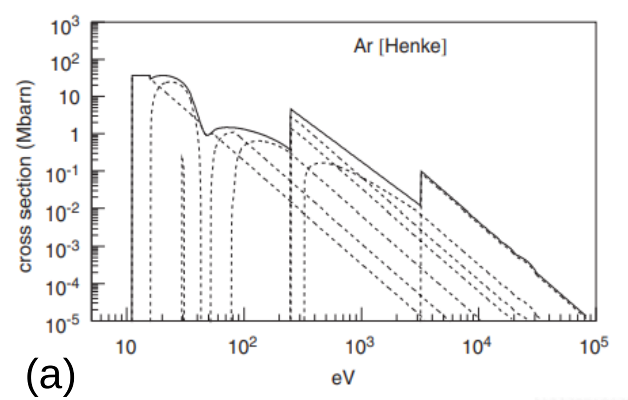




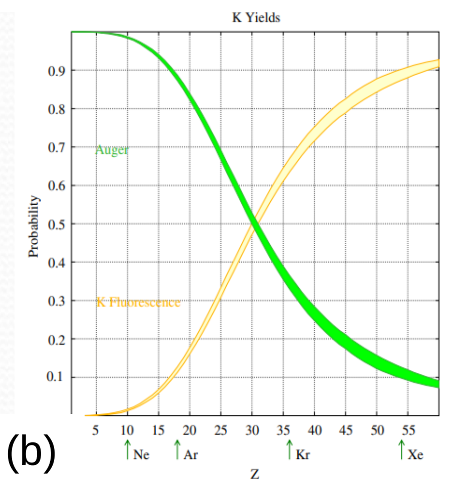
^{55}Fe, Argon escape peak

- When an ^{55}Fe X-ray interat with an Argon atom it make mostly photoelectric effect with the K-shell of the target (a)
- After the relaxation of the excited Argon there is a probability to emit a fluorescence photon of energy of

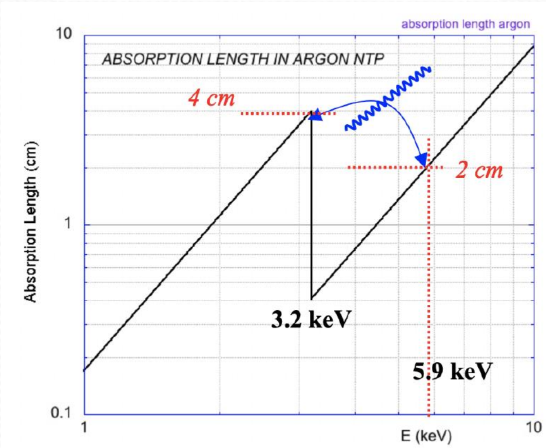
  (X-ray energy) – (Argon boundary energy) (b)
- Only for the ^{55}Fe X-rays the interaction probability of the reemitted photon is lower than for the parent photon © and can't interact with the medium causing a loss of energy measured
- This effect is also simulated using a combination of Geant4, Degrad and Garfield softwares



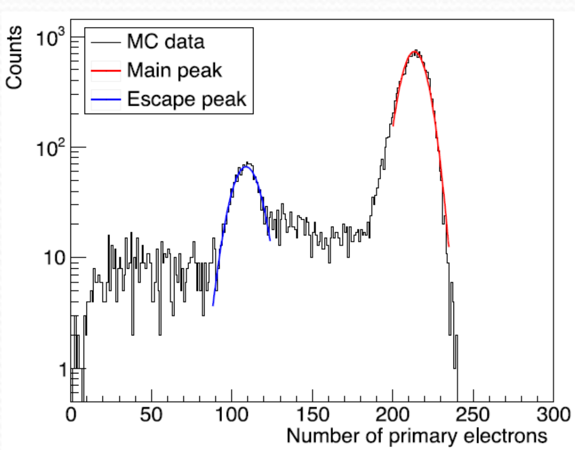
(a)



(b)



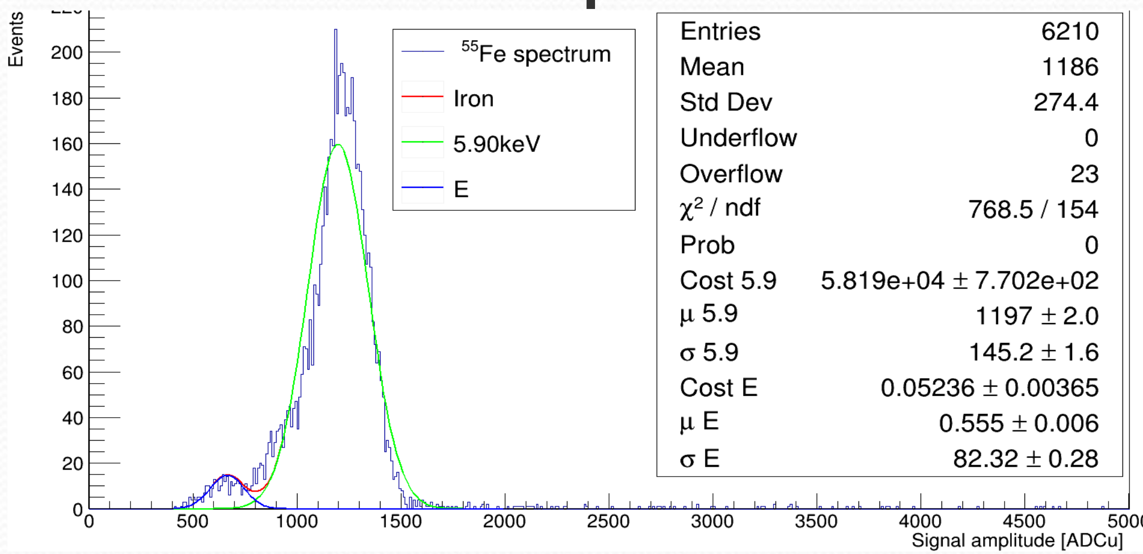
(c)

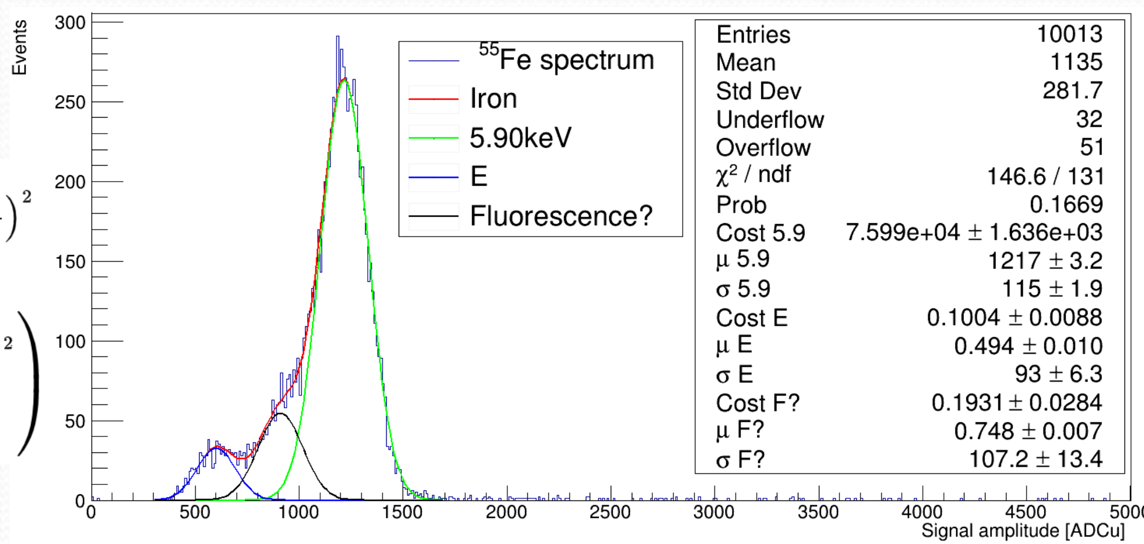


^{55}Fe X-ray spectra at ambient pressure

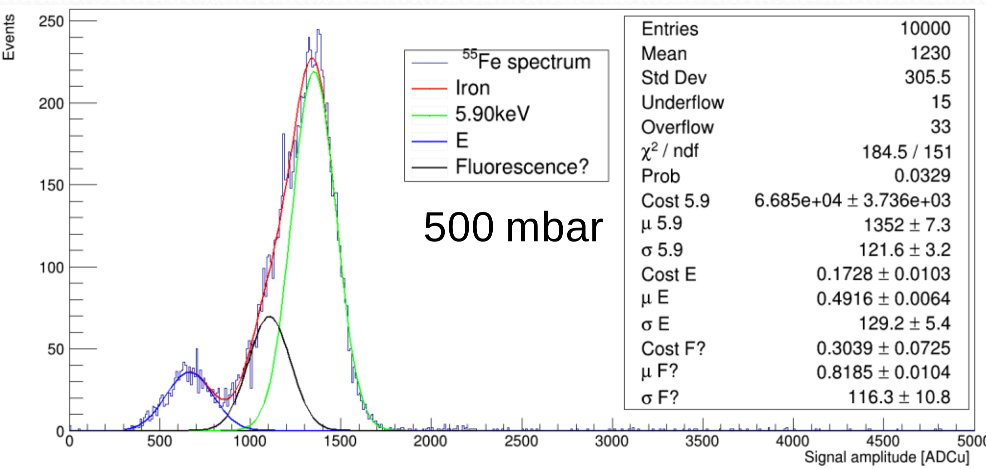
- The models take account of the main peak centered at 5.96 keV and of the escape peak
- By an observation of the spectrum seems that the interaction of the X-ray causes other effects. Fluorescence? Lost of energy?

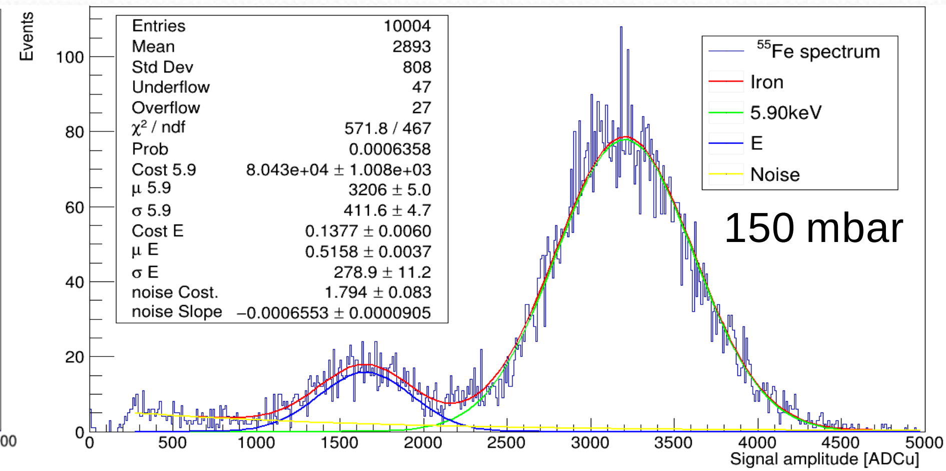
$$\mathrm{PDF} = \mathrm{Cost5.9}\left(\frac{e^{-0.5\left(\frac{x-\mu 5.9}{\sigma 5.9}\right)^2}}{\sqrt{2\pi}\,\sigma 5.9} + \frac{\mathrm{CostE}}{\sqrt{2\pi}\,\sigma \mathrm{E}}e^{-0.5\left(\frac{x-\mu 5.9\cdot\mu \mathrm{E}}{\sigma \mathrm{E}}\right)^2} + \frac{\mathrm{CostF?}}{\sqrt{2\pi}\,\sigma \mathrm{F?}}e^{-0.5\left(\frac{x-\mu 5.9\cdot\mu \mathrm{F?}}{\sigma \mathrm{F?}}\right)^2}\right)$$

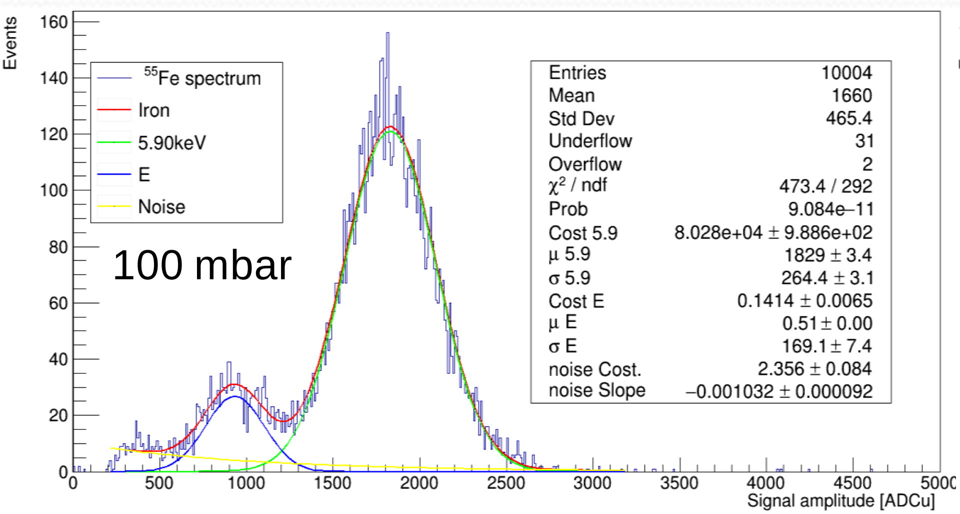


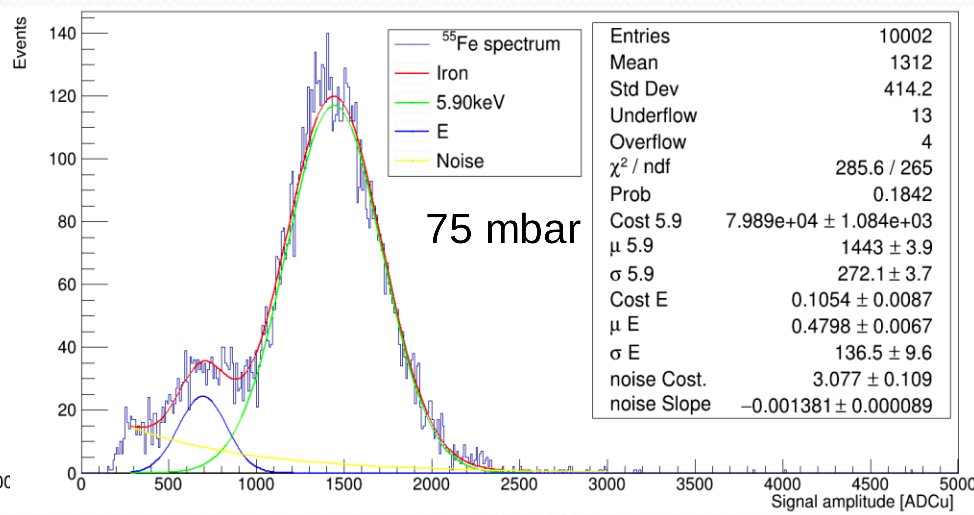


^{55}Fe X-ray spectra at low pressure









Conclusions

- The MLE and Likelihood Ratio statistical methods have been successfully applied to a large number of data sets collected over the 2024

- The goodness-of-fit test results showed that the PDFs developed so far are a good starting point for improving our detector simulations, a critical point for our project studying a field of physics that is still unexplored

- These methods will be applied to the data collected with 2.5 keV and 2 keV ion beams in an attempt to demonstrate a lower sensitivity of our detector to light ions

- For the future, I'm considering the possibility of performing fits on unbinned data using MLE for point estimation and Kolmogorov-Smirnof for goodness of fit

Ion - gas interaction

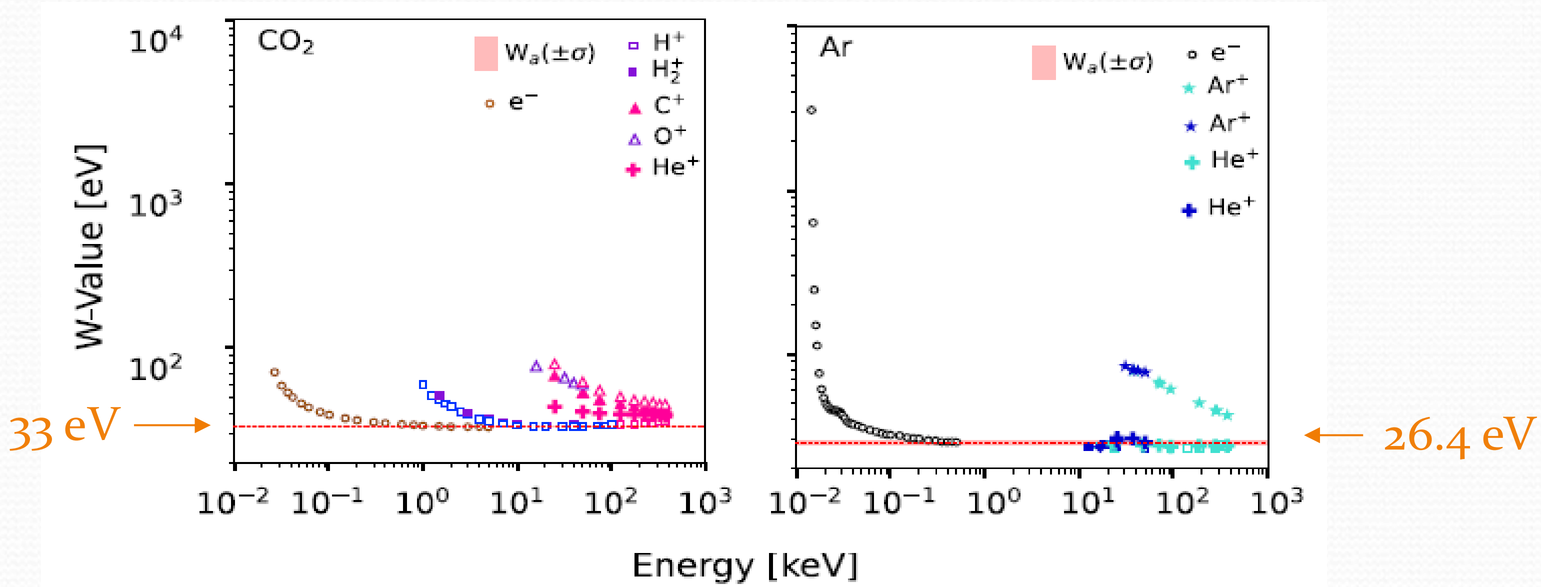
- The interaction of ionizing radiation with kinetic energy *T* of few keV with a gaseous medium depends on the projectile type and its kinetic energy

- The **Ionization Quenching factor (IQF)** is defined as the ratio between the kinetic energy of an electron and that of an ion, resulting in the same "visible" energy in the ionisation detector

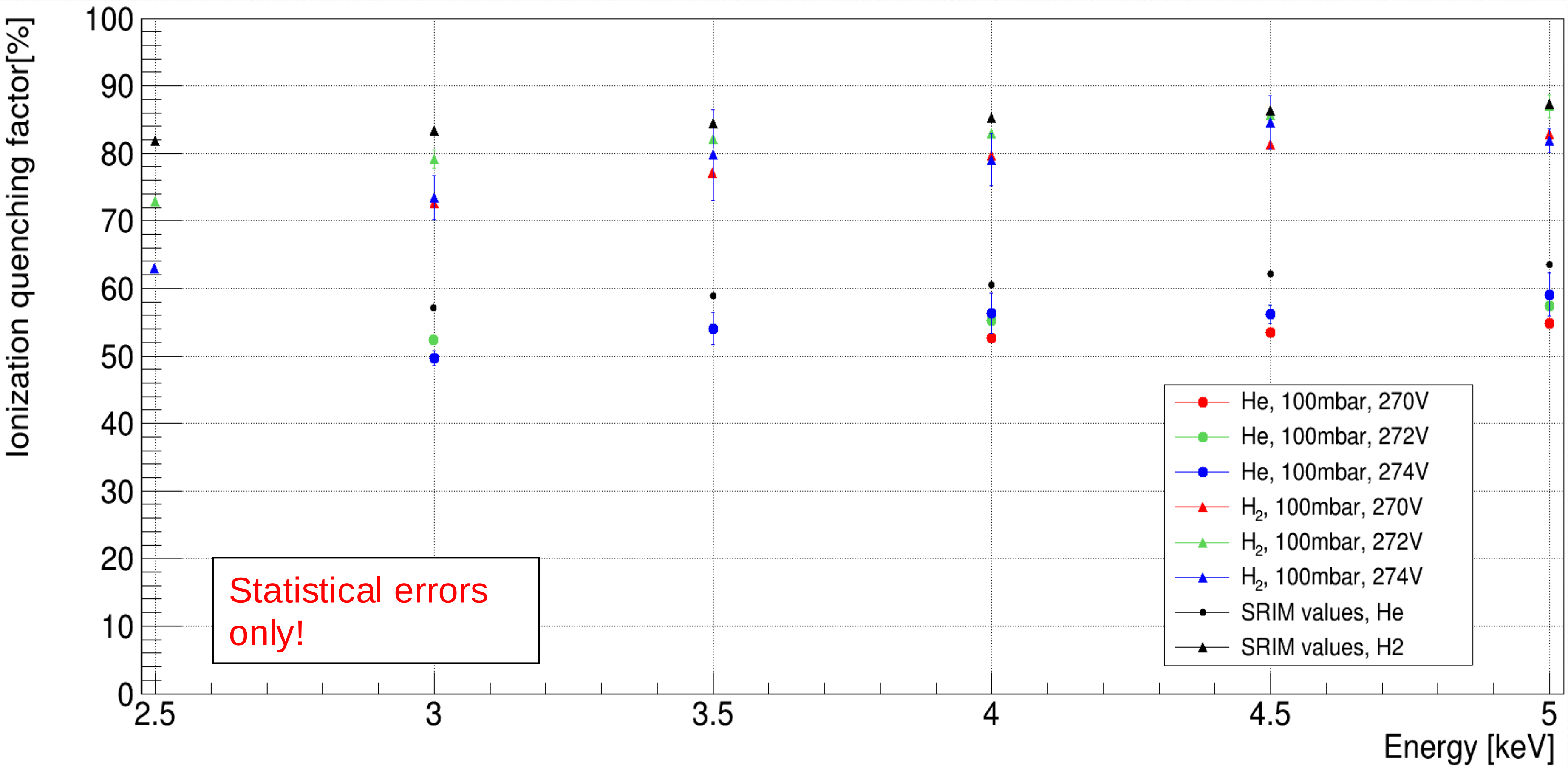
$$\mathrm{IQF} = \frac{T_e}{T_i} = \frac{N_f \cdot W_e(T)}{N_f \cdot W_i(T)} = \frac{W_e(T)}{W_i(T)}$$

where N_f is the number of primary electrons

I. Katsioulas, doi: https://doi.org/10.1016/j.astropartphys.2022.102707

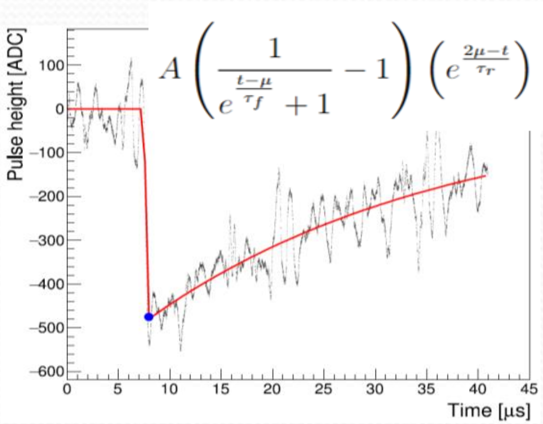


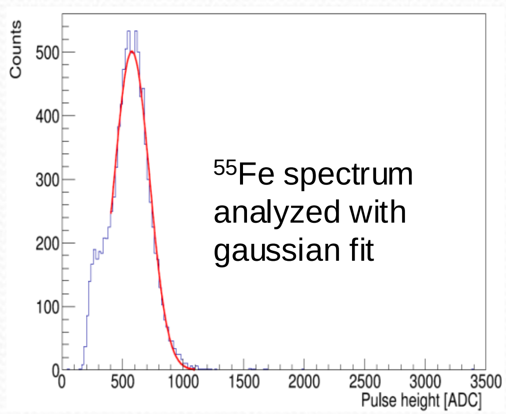
Anodic voltage dependence of the IQF

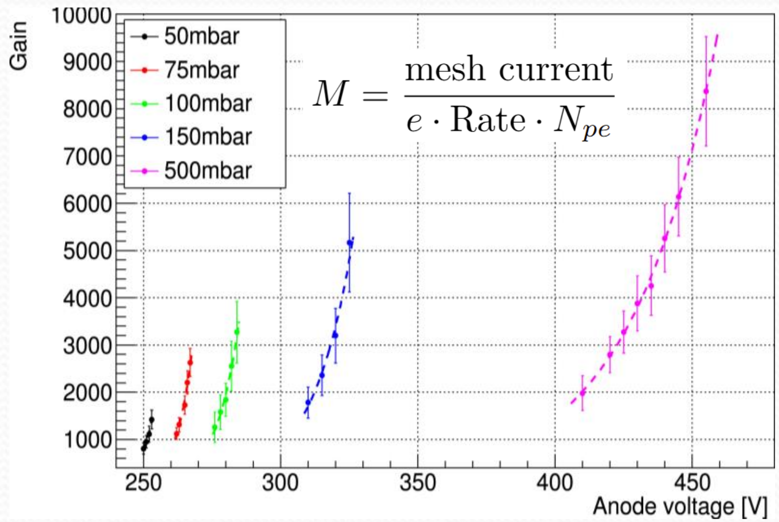


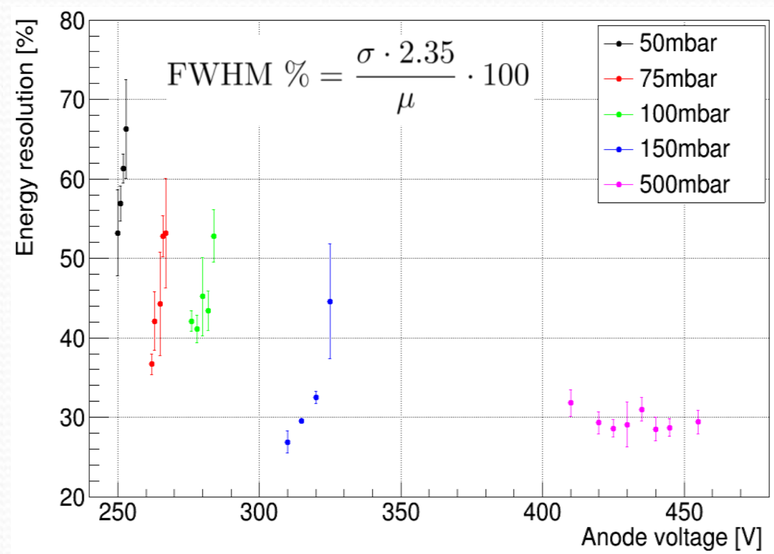
^{55}Fe X-ray characterization

- **GAIN (*M*)** measurament: picoammeter + ratemeter connected to the MM mesh
- **ENERGY RESOLUTION**: mesh signal readout by a custom Charge Sensitive Preamplifier (CSP) + CAEN digitizer an ADC https://doi.org/10.1016/j.nima.2022.167915









- The detector gain and the FWHM energy resolution were studied as a function of the gas pressure and the anodic voltage. https://doi.org/10.1016/j.nima.2024.169494

Our MM detector has demonstrated its ability to work at pressures down to 50mbar