WWU MÜNSTER

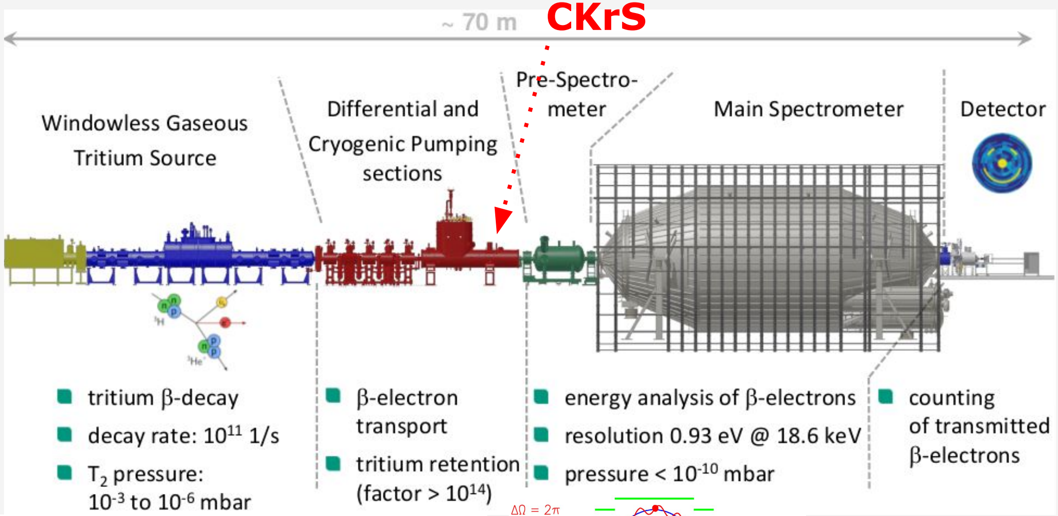
The Condensed Krypton Source as a Calibration Tool for KATRIN

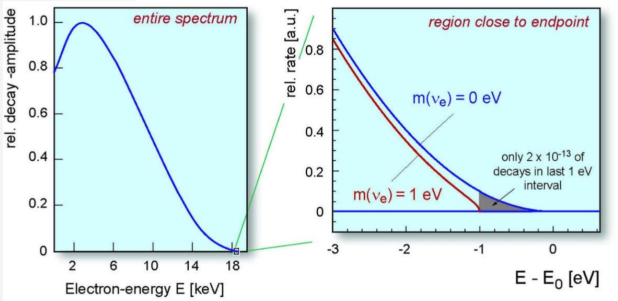
- ➔ The KATRIN Experiment
- ➔ Condensed Krypton Source Setup
- ➔ Commissioning
- ➔ Preliminary results on the stability

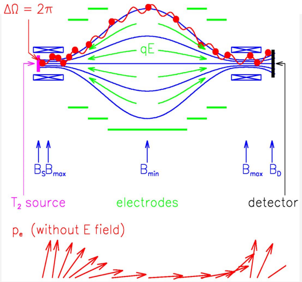
Alexander Fulst
alexanderfulst@wwu.de

The KArlsruhe TRItium Neutrino (KATRIN) Experiment

- Goal: Measure neutrino mass with 0.2 eV/c^2 sensitivity (90% C.L.)
- Kinematic measurement of electrons near the endpoint of tritium beta decay
  - High intensity windowless source
  - Pumping section with tritium retention > 10^{14}
  - Spectrometer with high energy resolution (0.93 eV @ 18.6 keV) and good acceptance (up to 2π)
  - Focal plane detector with 148 pixels for spatial resolution
- Condensed Krypton Source (CKrS) located right before the two spectrometers
  - Calibration source for the spectrometer
- Inauguration 11th June 2018





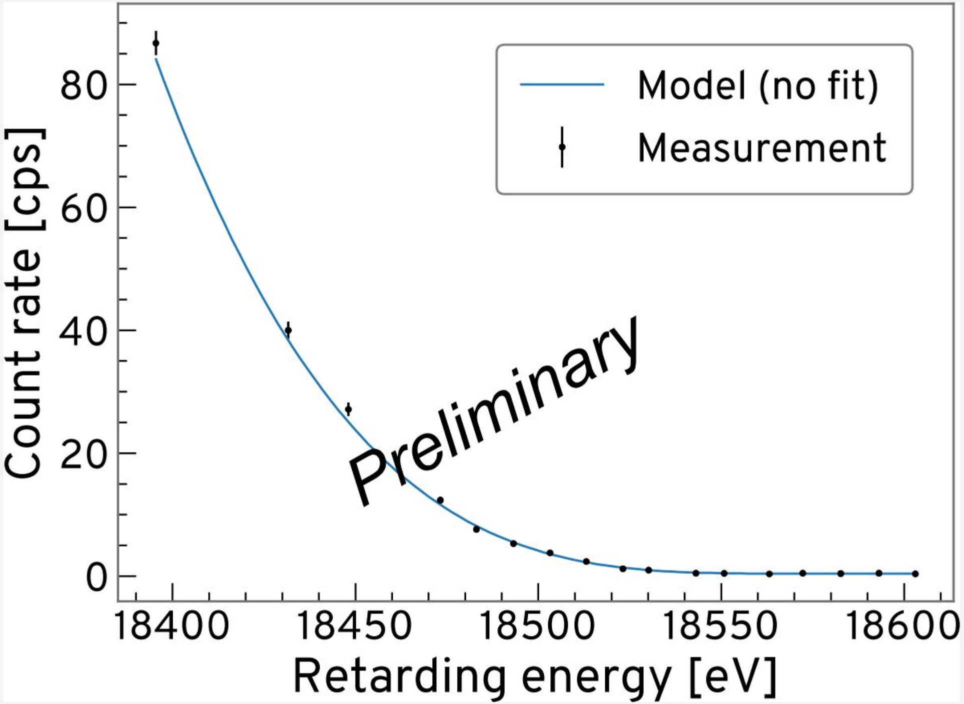


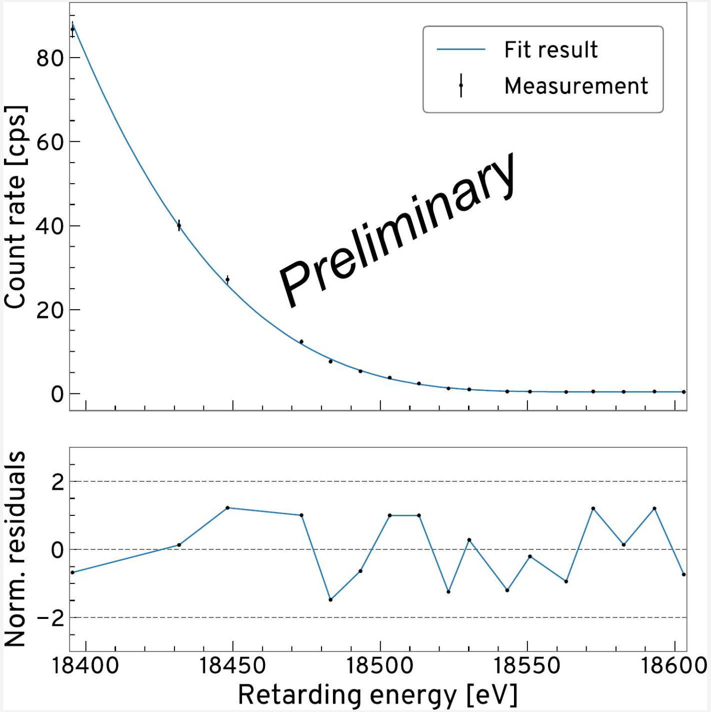
$$\frac{d\Gamma}{dE} = Cp\,(E+m_e)\,(E_0-E)\,\sqrt{(E_0-E)^2-m_{\nu e}^2}\,F\,(Z+1,E)\,\Theta\,(E_0-E-m_{\nu_e})\,S(E)$$

$$C = \frac{G_F^2}{2\pi^3}\cos^2\theta_C\,|M|^2 \qquad m_{\nu e}^2 = \sum_{i=1}^{3}|U_{ei}|^2\,m_i^2$$

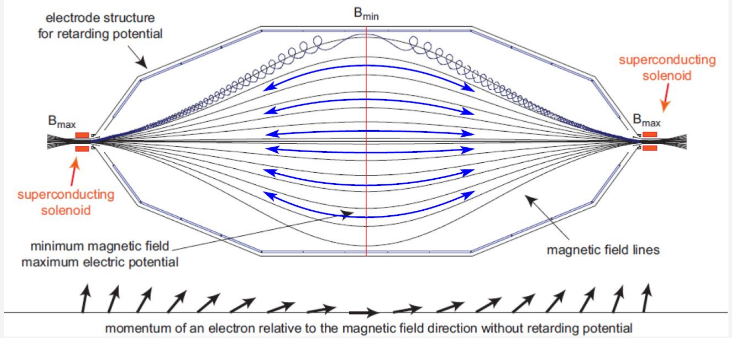
First Tritium Spectrum

- Fit of
  - Total activity
  - Constant Background
  - Endpoint E
- χ^2/d.o.f. = 15.0/14



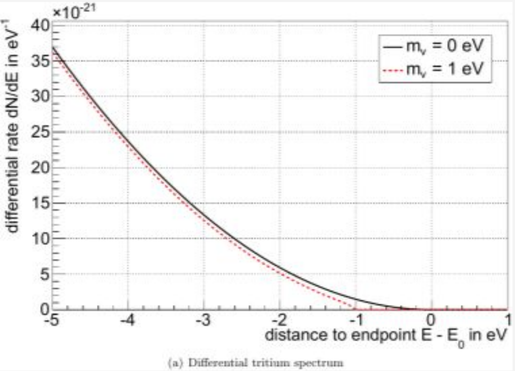


MAC-E Filter Principle

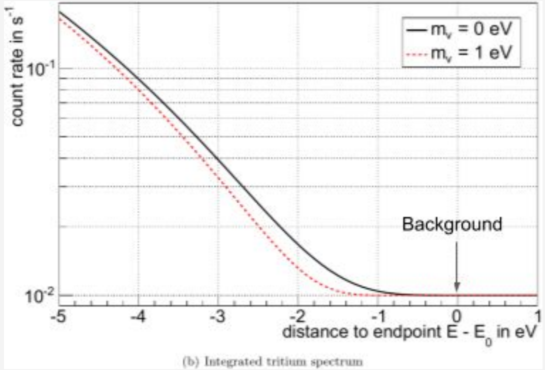


K. A. Hugenberg, *Design of the electrode system for the KATRIN main spectrometer*, 01/2008

- Adiabatic motion: $\left|\frac{1}{B}\frac{\mathrm{d}\mathbf{B}}{\mathrm{d}t}\right| \ll \omega_{cyc} = \frac{eB}{m_e}$
  - Magnetic moment $\mu = \frac{E_\perp}{B}$ is constant
- Energy resolution is given by: $\frac{\Delta E}{E} = \frac{B_{min}}{B_{max}}$
- Electrons either pass the spectrometer or are reflected
  - The MAC-E filter is a high-pass filter, thus KATRIN measures an integrated spectrum.



(a) Differential tritium spectrum

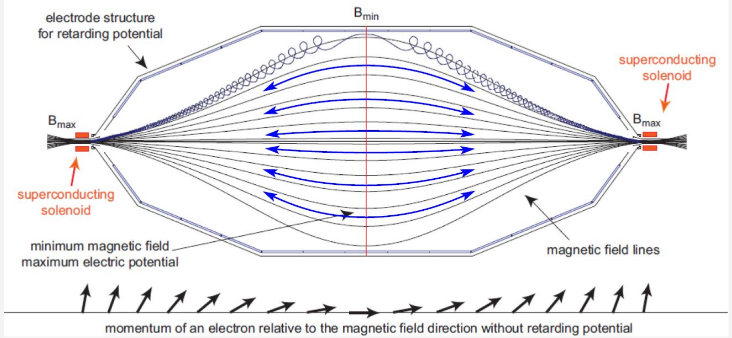


(b) Integrated tritium spectrum

S. Groh, Modelling of the response function and measurement of transmission properties of the KATRIN experiment, 2015

$$E_{\parallel}^{ana} - qU = E_0 - E_{\perp}^{ana} - q$$
$$= E_0 - E_0 \cdot \sin^2\theta \cdot \frac{B_{ana}}{B_{source}} - qU > 0$$

MAC-E Filter Principle

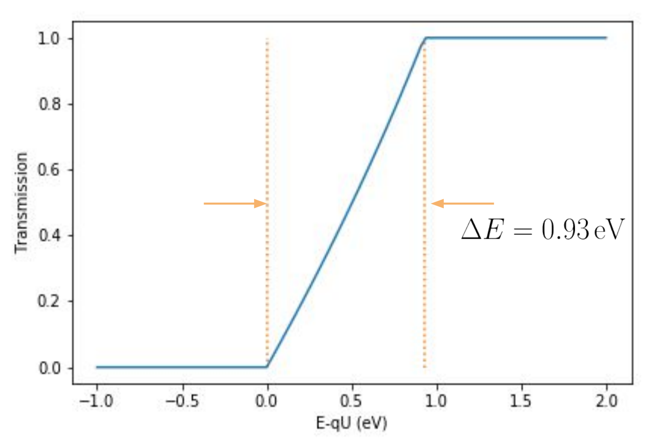


K. A. Hugenberg, *Design of the electrode system for the KATRIN main spectrometer*, 01/2008

- Adiabatic motion: $\left|\frac{1}{B}\frac{\mathrm{d}\mathbf{B}}{\mathrm{d}t}\right| \ll \omega_{cyc} = \frac{eB}{m_e}$
  - Magnetic moment $\mu = \frac{E_\perp}{B}$ is constant
- Energy resolution is given by: $\frac{\Delta E}{E} = \frac{B_{min}}{B_{max}}$
- Electrons either pass the spectrometer or are reflected
  - The MAC-E filter is a high-pass filter, thus KATRIN measures an integrated spectrum.

- Transmission function for KATRIN

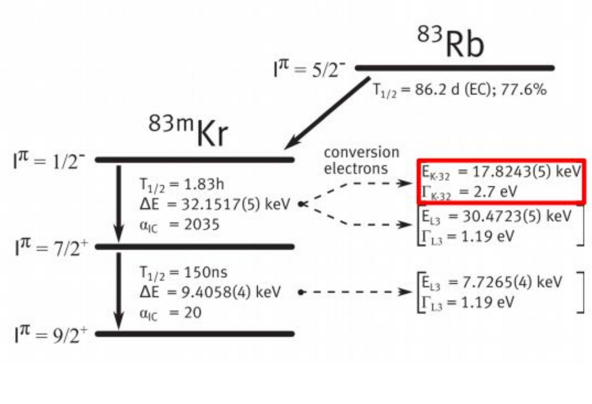
$$T(E, qU) = \begin{cases} 0, & \text{for } E < qU \\ 1 - \sqrt{1 - \frac{E-qU}{E}\frac{B_{source}}{B_{ana}}}, & \text{for } qU < E < qU + \Delta E \\ 1 - \sqrt{1 - \frac{B_{source}}{B_{max}}}, & \text{for } qU + \Delta E \end{cases}$$

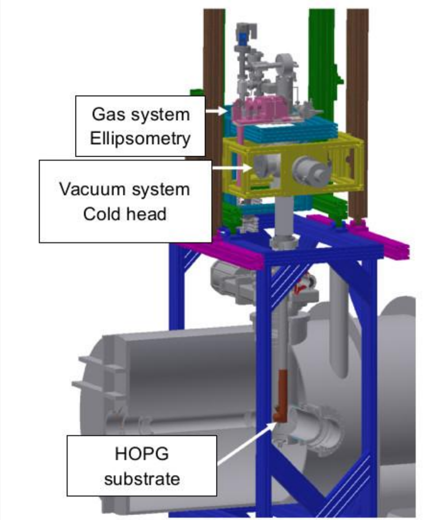


The Condensed Krypton Source

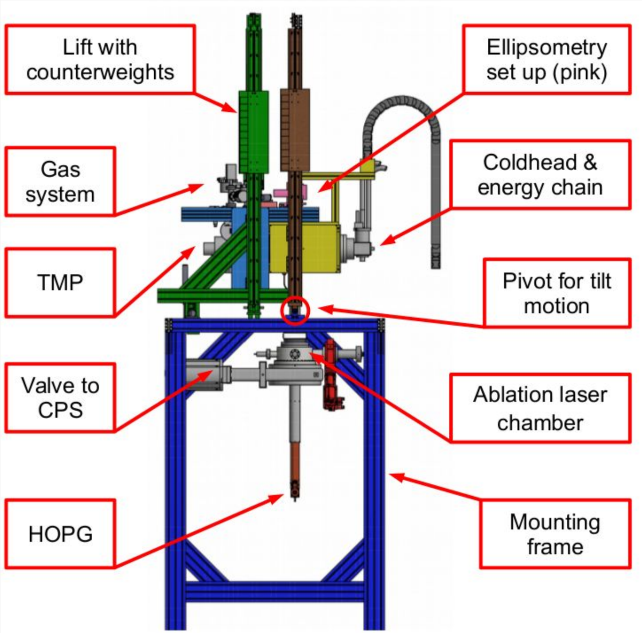
Motivation

- Inhomogeneities in the electric and magnetic fields in the analyzing plane need to be known precisely
  - Per-pixel transmission function measurements with an isotropically emitting source can be used to determine field values
- Utilize a nuclear standard for energy calibration
- ^{83m}Kr:
  - Highly converted transitions with several nearly monoenergetic lines with different widths (one close to ^{3}H endpoint)
  - Short half-life (1.83 h) prevents contamination of spectrometers
- Energy stability of conversion lines in the ppm range demonstrated at former Mainz Neutrino Experiment



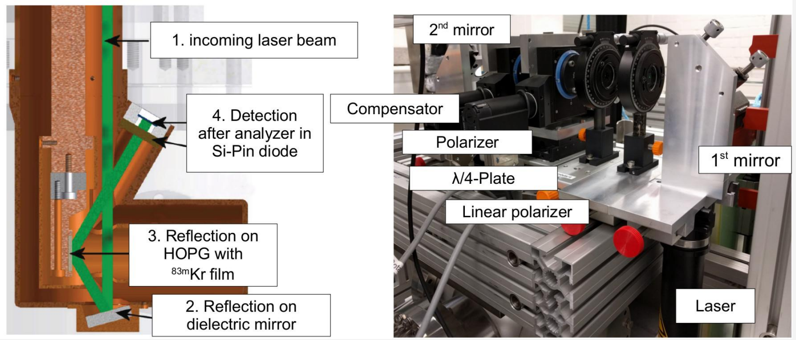


The Condensed Krypton Source



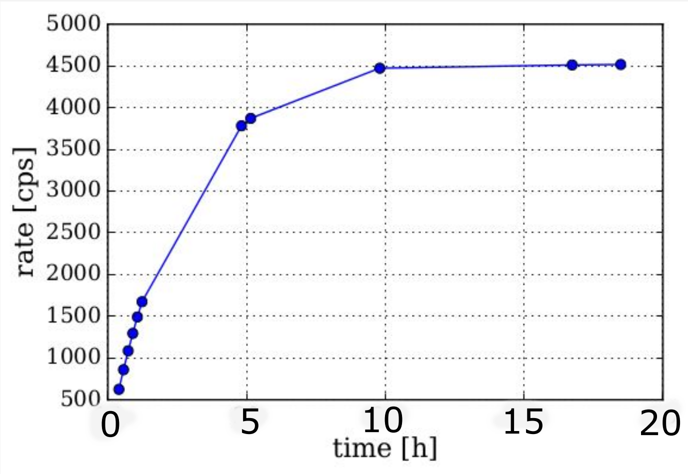
Key Features

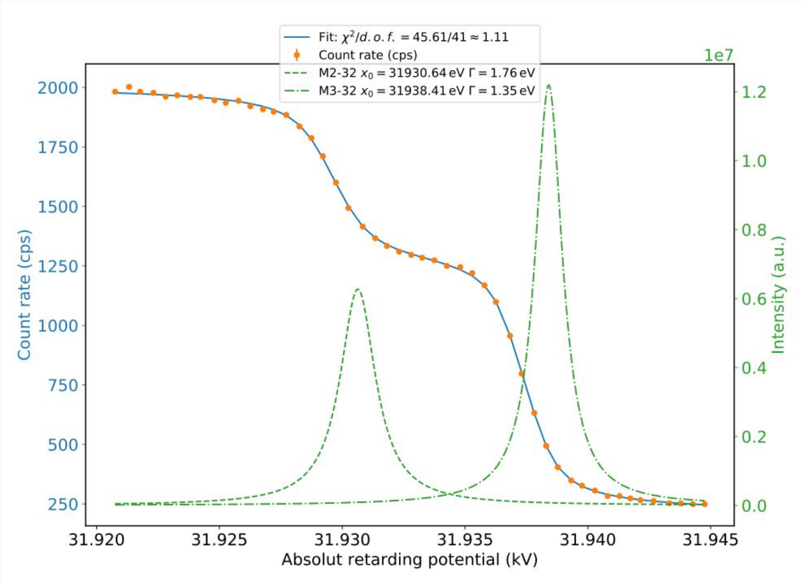
- Continuous condensation of ^{83m}Kr onto Highly Oriented Pyrolytic Graphite (HOPG) allows for steady operation
- Motion system allows for pixel selective calibration measurements
- Ellipsometry can be used to monitor the condensed film *in-situ* and represents an ultra-high-precision vacuum gauge
- Laser ablation system for reproducible clean substrate surface
- Vacuum- and cryo-system to reach 10^{-10} mbar and 26 K
- Isolated for up to 1 kV to shift the K-32 electrons to ^{3}H endpoint



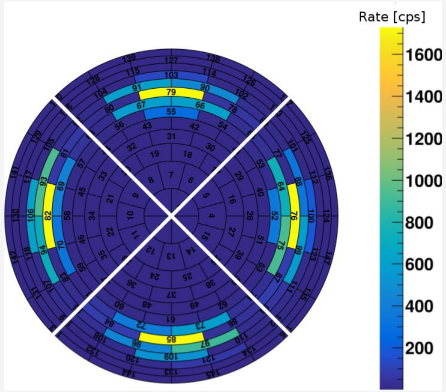
Very First Measurements

- ^{83m}Kr is condensed onto the substrate, rate stabilizes after 10 h
- Electrons reach the detector at selected pixel
- Scans of 18 different lines from 7.48 keV to 32.14 keV
- Reproduced for 3 different films



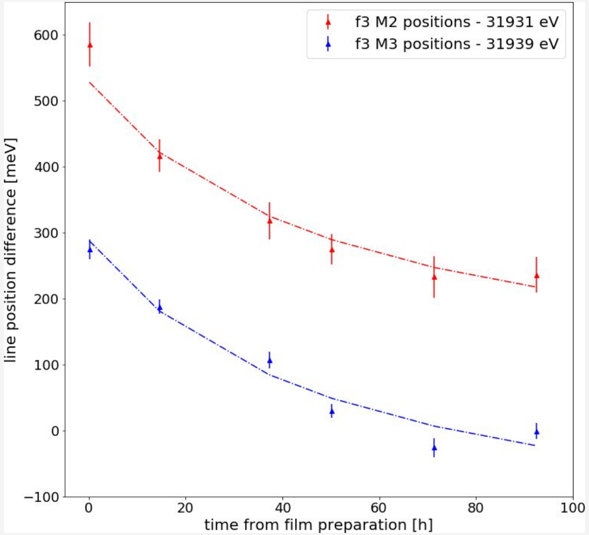


- Measured spectrum is a Lorentzian convoluted with the transmission function of the main spectrometer
- Fit gives the parameters of the underlying Lorentzian, here shown for the M2 and M3 lines of the 32 keV transition

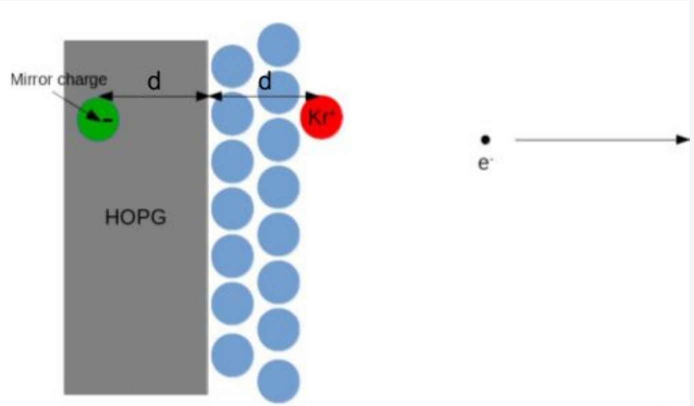


Stability I

- Fitted position of Lorentzian over time shows a drift that seems to stabilize
- Detected electrons come from Kr condensed onto HOPG so one has to consider surface effects
- Explained by image charge effect



- After the decay, a positively charged Kr ion is left behind
- A negative mirror charge is induced in the substrate
- This system is bound and it’s binding energy can be given to the electron as additional kinetic energy
- As the film grows, this additional energy is reduced

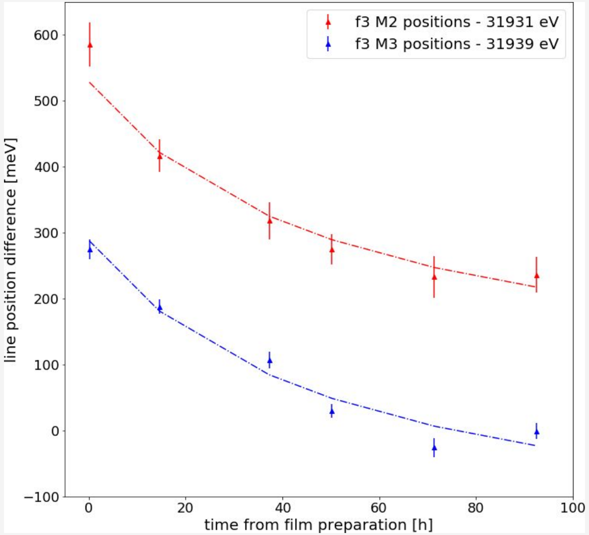


$$V(t) = \frac{1}{2} \cdot \frac{1}{4\pi\epsilon_0} \cdot \frac{q \cdot q}{2(a \cdot t + b) \cdot a_{Kr}} + c$$

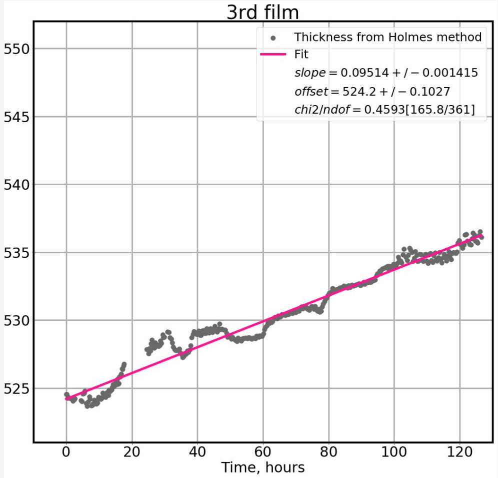
- For a simple model assume a linear growth with time (backed by ellipsometry data)
- Shown on the left: fit with a=(0.025 ± 0.007) monolayers/h Krypton equivalent

Stability I

- Fitted position of Lorentzian over time shows a drift that seems to stabilize
- Detected electrons come from Kr condensed onto HOPG so one has to consider surface effects
- Explained by image charge effect



- After the decay, a positively charged Kr ion is left behind
- A negative mirror charge is induced in the substrate
- This system is bound and it's binding energy can be given to the electron as additional kinetic energy
- As the film grows, this additional energy is reduced

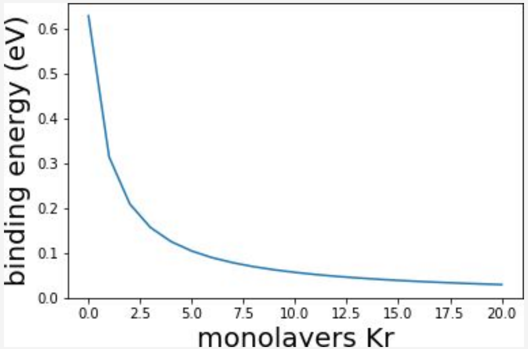


$$V(t) = \frac{1}{2} \cdot \frac{1}{4\pi\epsilon_0} \cdot \frac{q \cdot q}{2(a \cdot t + b) \cdot a_{Kr}} + c$$

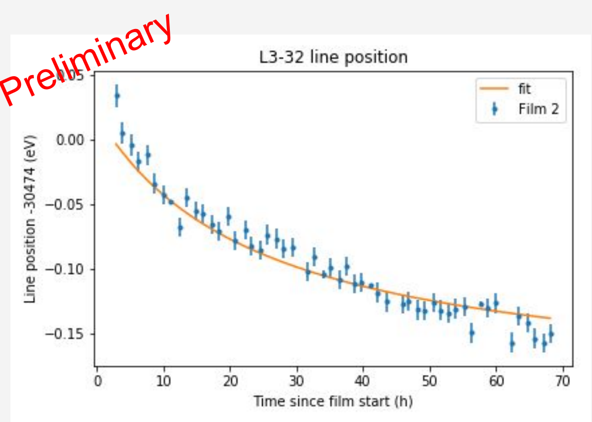
- For a simple model assume a linear growth with time (backed by ellipsometry data)
- Shown on the left: fit with a=(0.025 ± 0.007) monolayers/h Krypton equivalent

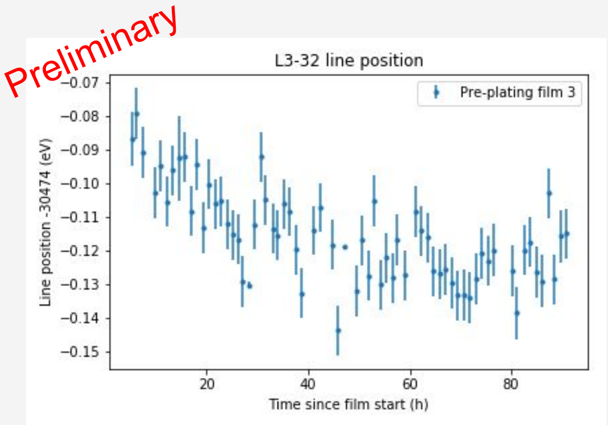
Stability II

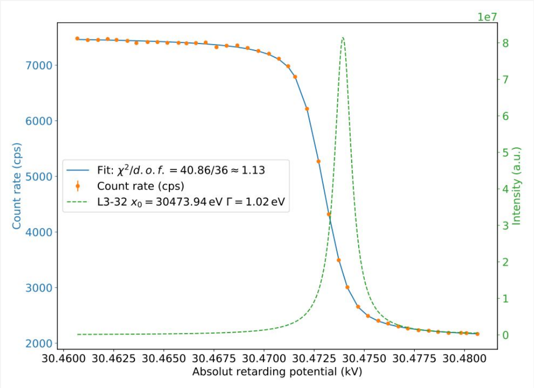
- Possible improvements for energy stability:
  - Better vacuum with bake-out → slower film growth
  - Pre-plating → increase initial distance, smaller slope
- Results can be seen in new measurements of L3-32 line
- Stability of ~ 50 meV in 100 h with pre-plating



$$V(t) = \frac{1}{2} \cdot \frac{1}{4\pi\epsilon_0} \cdot \frac{q \cdot q}{2(a \cdot t + b) \cdot a_{Kr}} + c$$





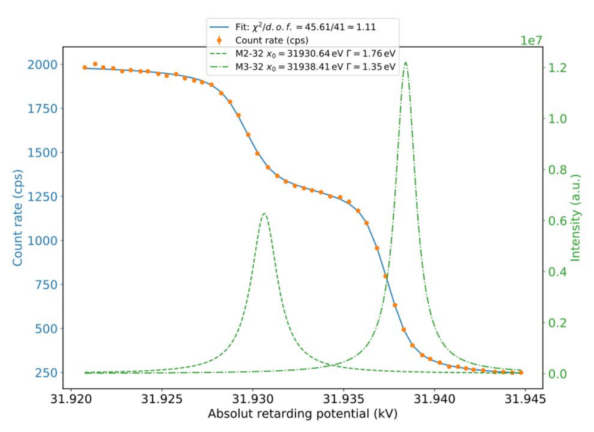


Summary and Upcoming investigations

- Condensed Krypton Source commissioned and working, conversion electrons can be analyzed
- Surface effects matter!
    - Image charge model predictions have been used to improve the energy stability
    - More investigations needed (e.g. line broadening through polarization)
- Flux tube scan for inhomogeneities, per-pixel analysis and comparison with simulated fields
    - Care for magnetron drift
- Checks for reproducibility of line position for different films
- Improve ellipsometry analysis
    - Found an offset in the calibration
    - Hardware fixes needed for the diode

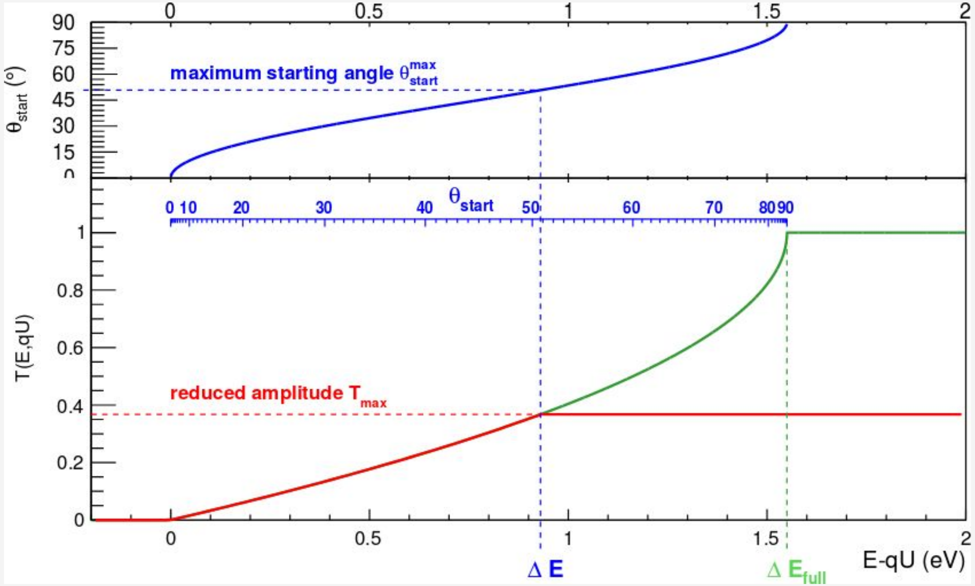
WWU MÜNSTER

Thank you for your attention

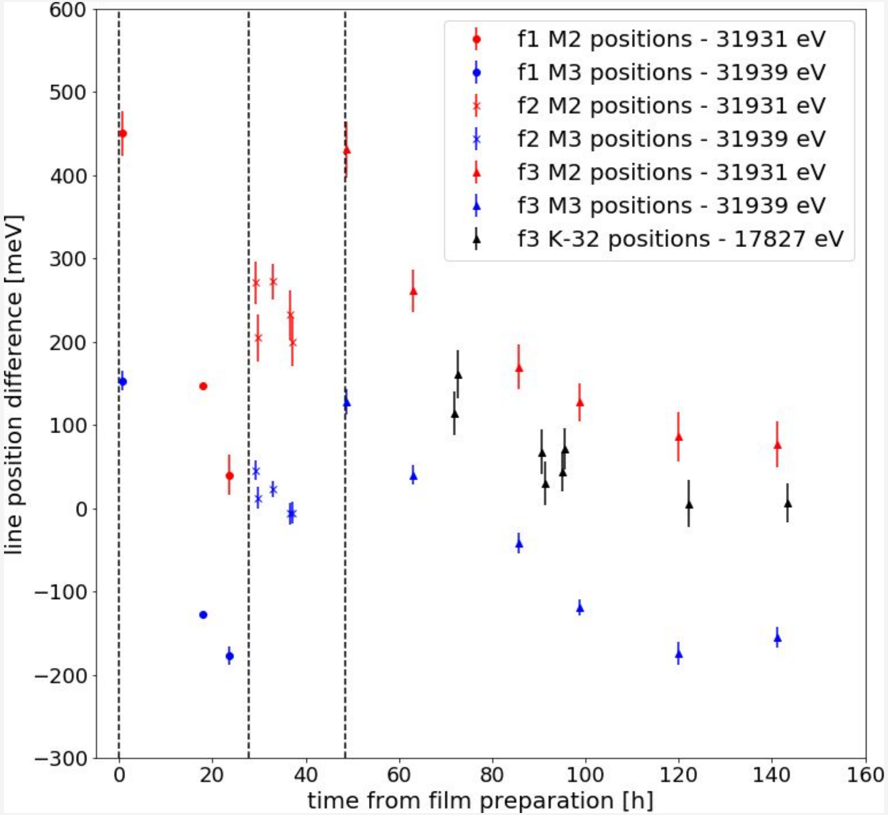


living.knowledge

Backup

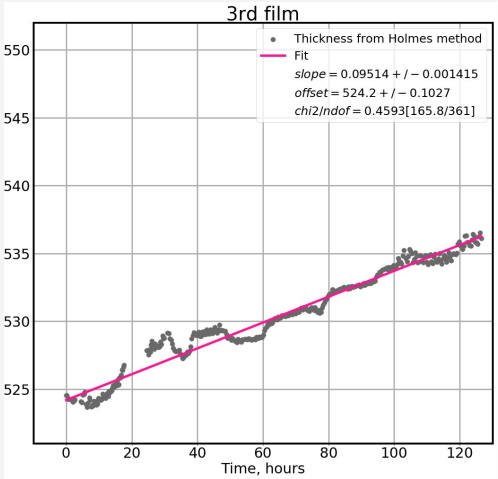


maximum starting angle θ_{start}^{max}
θ_{start} (°)
θ_{start}
reduced amplitude T_{max}
T(E,qU)
E-qU (eV)
Δ E
Δ E_{full}

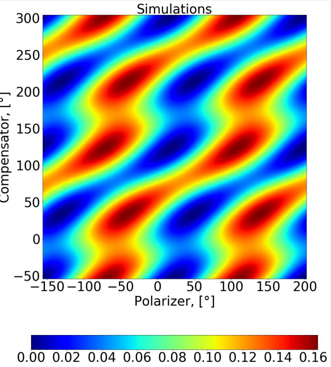

f1 M2 positions - 31931 eV
f1 M3 positions - 31939 eV
f2 M2 positions - 31931 eV
f2 M3 positions - 31939 eV
f3 M2 positions - 31931 eV
f3 M3 positions - 31939 eV
f3 K-32 positions - 17827 eV
line position difference [meV]
time from film preparation [h]
600
500
400
300
200
100
0
−100
−200
−300
0
20
40
60
80
100
120
140
160

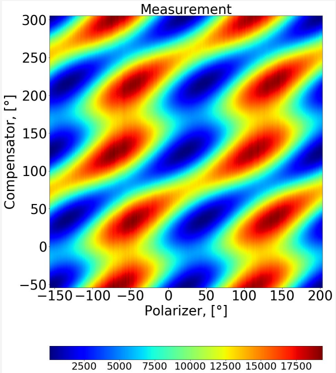
Laser ellipsometry

- Thin film investigations by measuring polarization changes upon reflection
- Null ellipsometry: find polarizer and compensator angle for which the reflected light is minimal, this depends on refractive index and film thickness
- Condensation of radioactive krypton alone should not lead to a shift since the used amount is too low to yield an observable effect
- Ellipsometry can be used to monitor the vacuum conditions very precisely



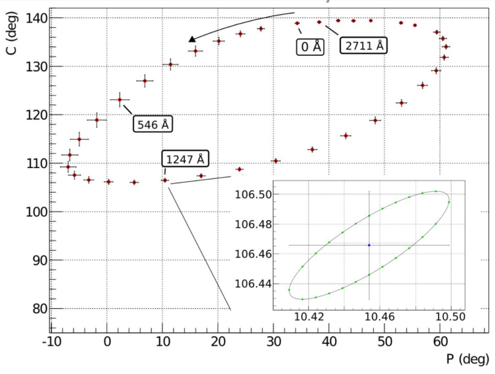
M. Fedkevych





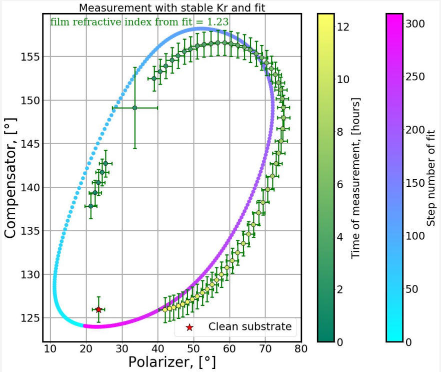
R. Sack, M. Fedkevych

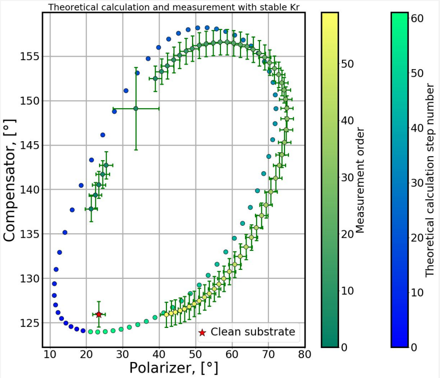
- Good agreement between measurements and simulation for the naked substrate
- Linear film growth observed
- Full “ellipse” can be frozen with stable krypton for calibration of the system



S. Bauer

Measurements with Stable Krypton





Error bars: errors x 20

Figures by M. Fedkevych

"Fit"

n=1.23

speed = 27.15 ml/h

offset = 123.9 ml

"Fit": calculate ellipses for different parameters and find the one with minimal distance to measured data.

Cannot fit measured ellipse well & refractive index from best fit differs from Kr literature value (1.28):

- ➔ residual gases freezing along with Kr
- ➔ gas may also freeze onto the dielectric mirror

"Holmes"

n=1.23

speed = 19.91 ml/h

offset = 172.5 ml

"Holmes method": analytical solution of inverse problem of ellipsometry for 3-phase optical system (ambient-film-substrate). Film parameters are extracted from measured minima position coordinates.