Westfälische Wilhelms-Universität Münster
Graduiertenkolleg 2149 Research Training Group

Determination of the tritium Q-value at the KATRIN experiment

KATRIN Karlsruhe Tritium Neutrino Experiment
Bundesministerium für Bildung und Forschung
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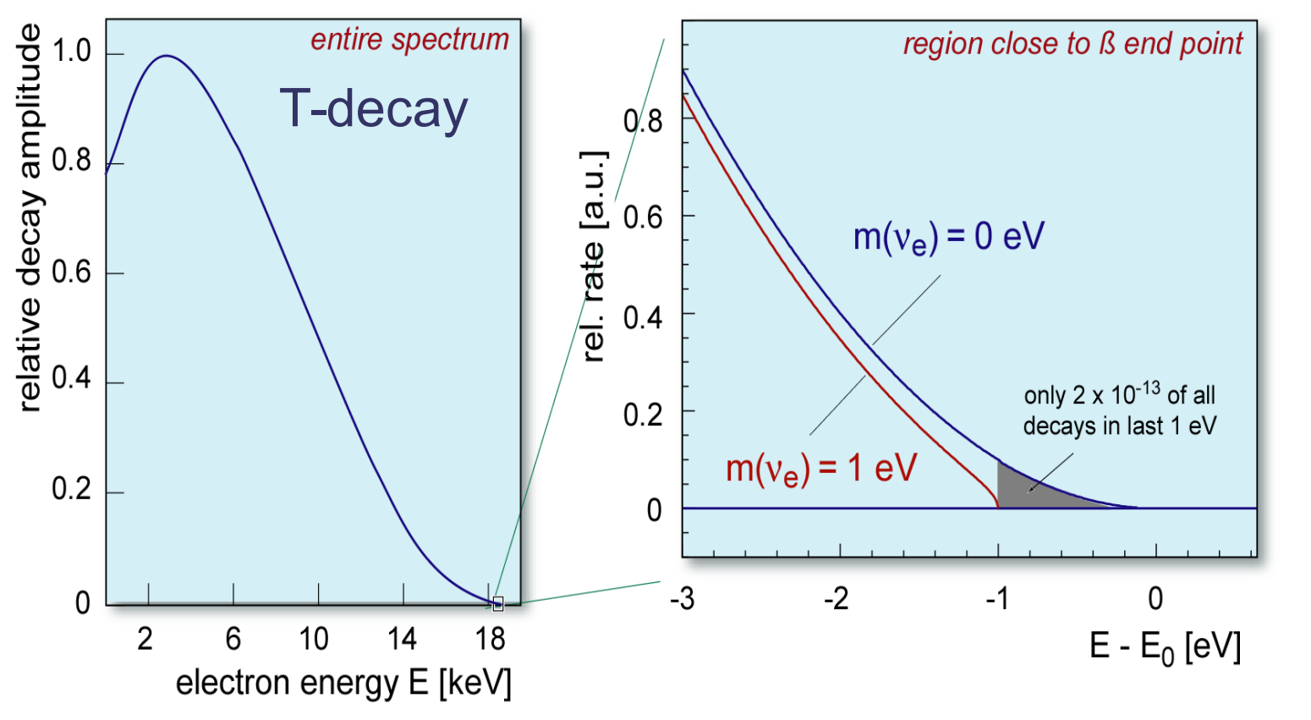
Kinematic determination of m(ν_e)

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

$$C = \frac{G_F^2}{2\pi^3}\cos^2\theta_C |M|^2$$

$$m_{\nu_e} = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

(modified by final states, recoil corrections, radiative corrections, ...)



Requirements

low endpoint energy
high source luminosity
high energy resolution
very low background
stability of experimental parameters on the ppm level

→ **MAC-E filter concept**

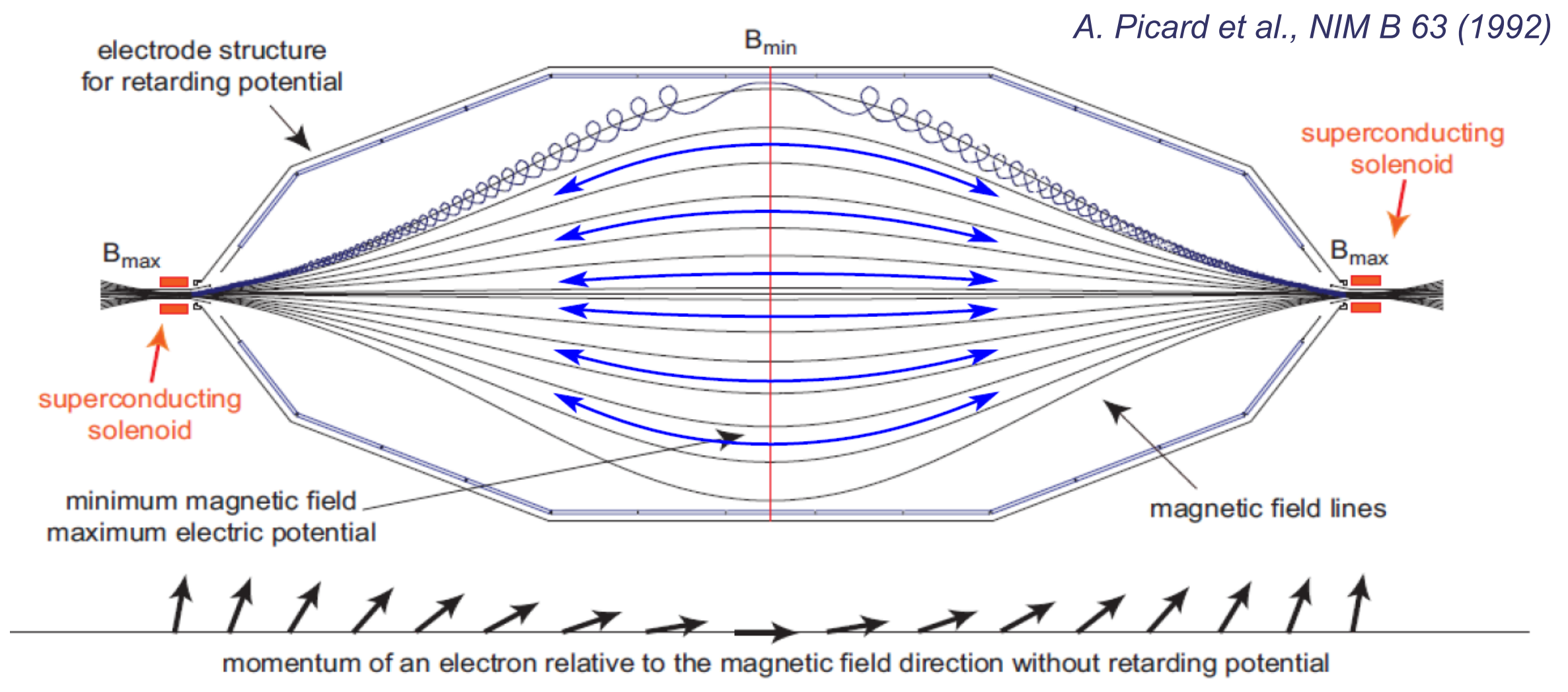
Tritium

E_0 ≈ 18.6 keV, $T_{1/2}$ = 12.3 a
S(E) = 1 (super-allowed)

MAC-E filter concept

Magnetic Adiabatic Collimation with Electrostatic Filter

A. Picard et al., NIM B 63 (1992)



Adiabatic transport → $\mu = E_\perp / B$ = const.

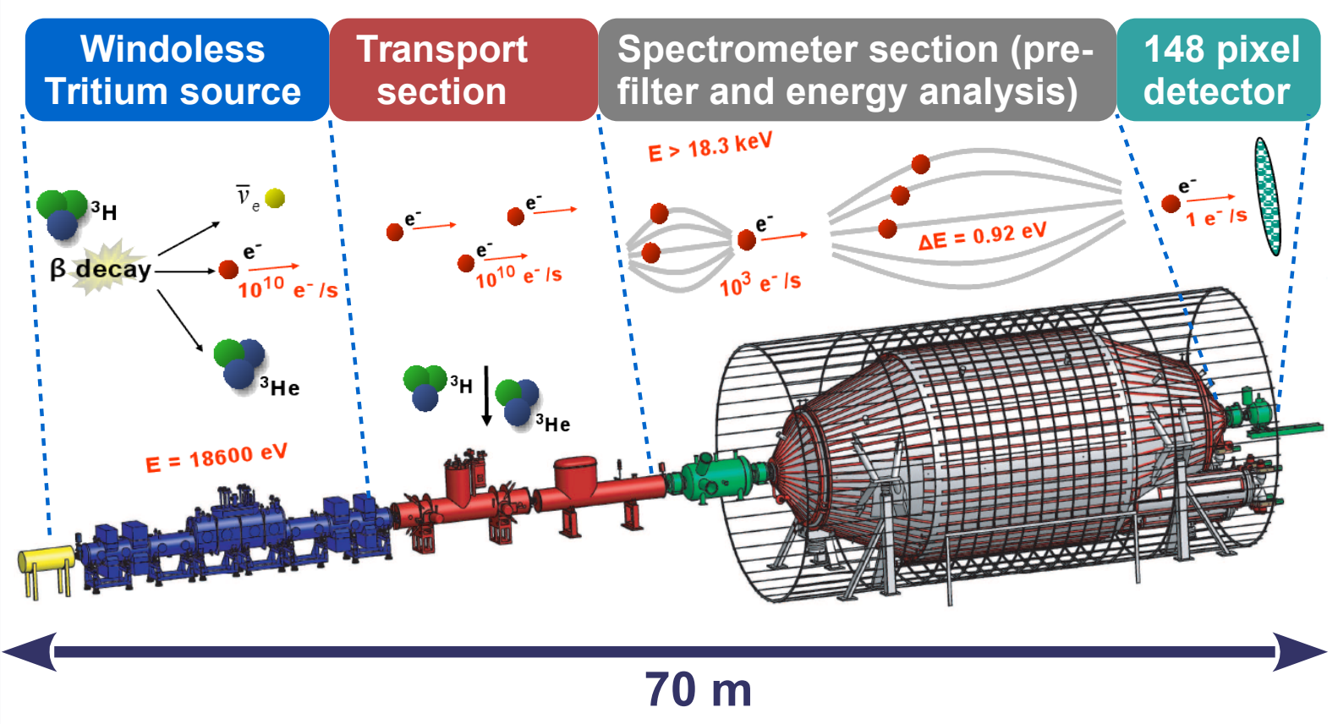
B drops by $2\cdot10^4$ from solenoid to analyzing plane → $E_\perp \to E_{||}$

Only electrons with $E_{||} > eU_0$ can pass the retardation potential

Energy resolution $\Delta E = E_{\perp,\max,\text{start}} \cdot B_{\min} / B_{\max} \approx 1$ eV

Characterization of potential inhomogeneities using electrons of well defined energy and angle from a suitable calibration source
→ e-gun development

KATRIN experiment at KIT



4 fit parameters
$m^2(\nu)$, endpoint E_0, amplitude, background

KATRIN design sensitivity: 5 year measurement (eff. 3 y of data)	statistical uncertainty σ_{stat} ≈ 0.018 eV² systematic uncertainty $\sigma_{sys,tot}$ ≈ 0.017 eV² → sensitivity for upper limit 0.2 eV/c² (90% C.L.) → observable with 5σ: $m(\nu_e)$ = 0.35 eV

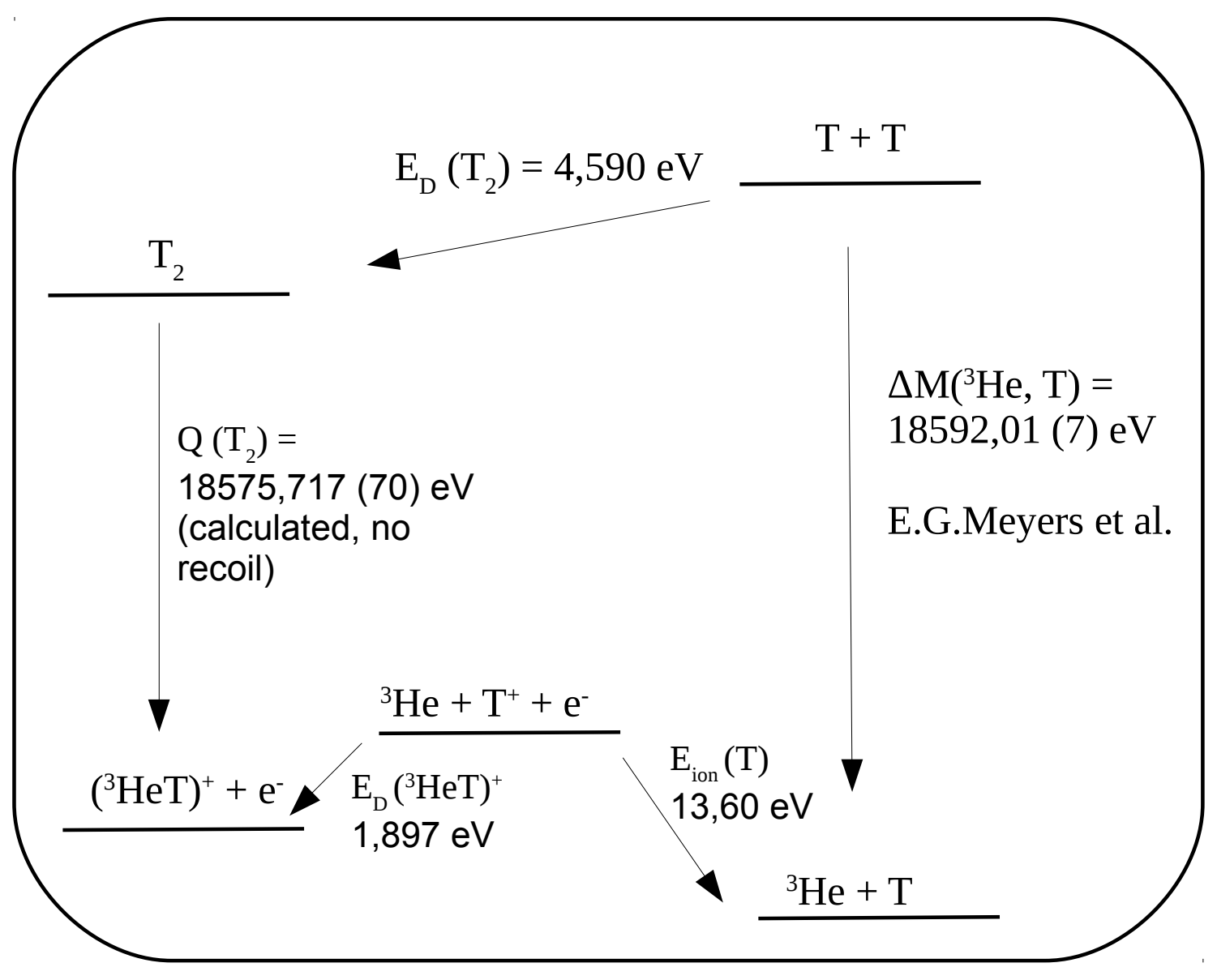
Endpoint and Q-value of T_2

The endpoint E_0 of the spectrum is the maximum possible Energy a beta electron can get from the decay of one of the tritium atoms in a T_2 molecule assuming zero neutrino mass.

The mass difference between ^{3}He and T is known from a penning trap measurement by E.G. Meyers with 70 meV precision.

From this we can deduce the Q-value of molecular tritium if we know the molecular binding energies.

We obtain the Endpoint E_0 of the spectrum by subtracting the recoil Energy of a T_2 molecule.

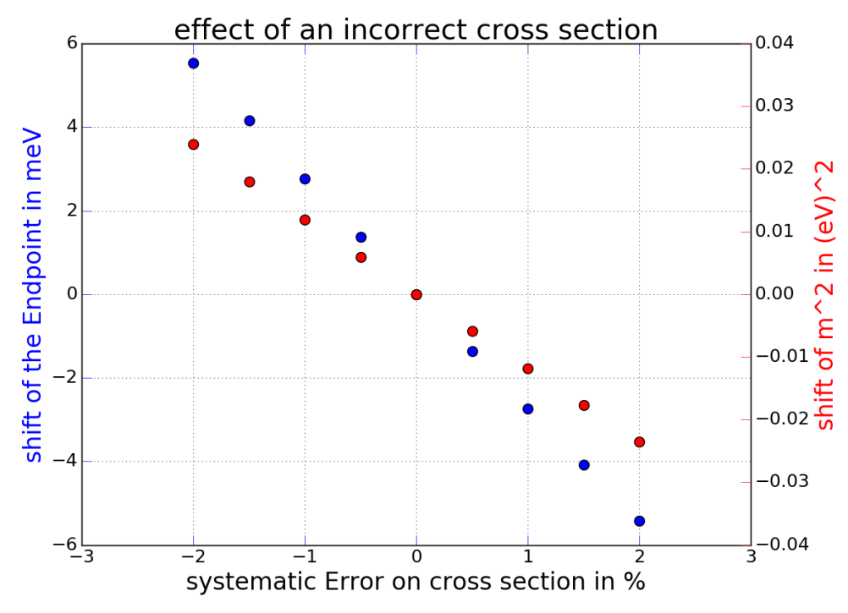


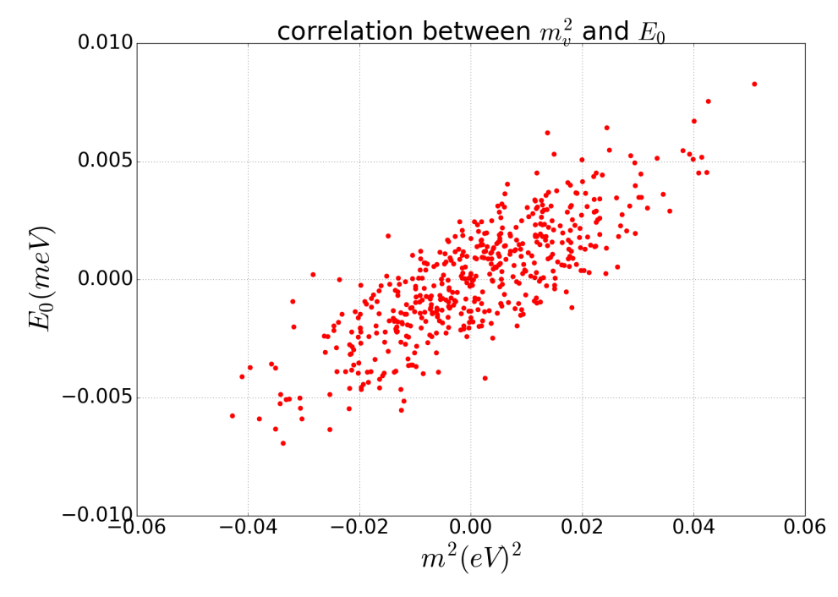
E_{recoil} = 1,72 eV
$Q(T_2)$ = 18575,717 (70) eV
$\boxed{E_0 = Q(T_2) - E_{recoil} = 18573{,}997\ (70)\ \text{eV}}$

How a measurement of the endpoint E_0 can help the KATRIN experiment

Realistic:
A measurement of the Endpoint E_0 at KATRIN and a comparison to an external experimental value allows us to check if we understand our systematics.
Some of our systematics influence E_0 directly and others influence E_0 indirectly because our fit parameters E_0, amplitude and $m^2(\nu_e)$ are correlated in the fit of the electron energy spectrum.

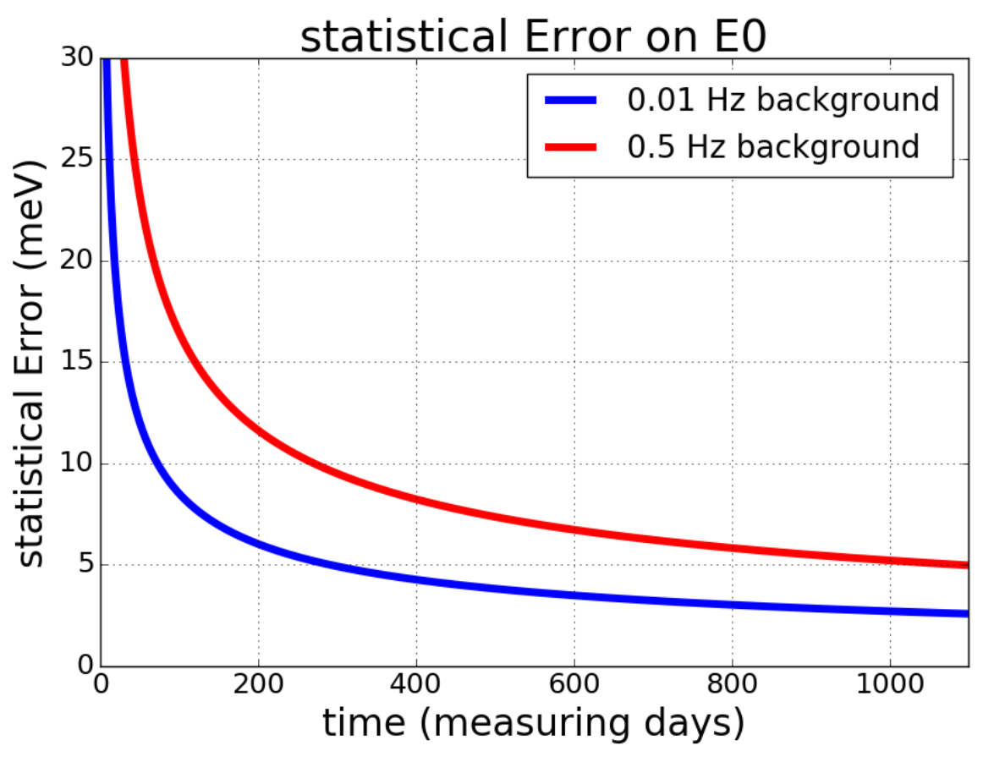
Hypothetical:
If we would know the endpoint E_0 exactly we would reach the same statistical sensitivity in 1 year of measurement time which we do in 3 years.
At the moment an improvement of the statistical Error is not realistic because the required uncertainty of < 5 meV of an external value and our systematics (e.g. the retarding voltage) combined is out of reach.



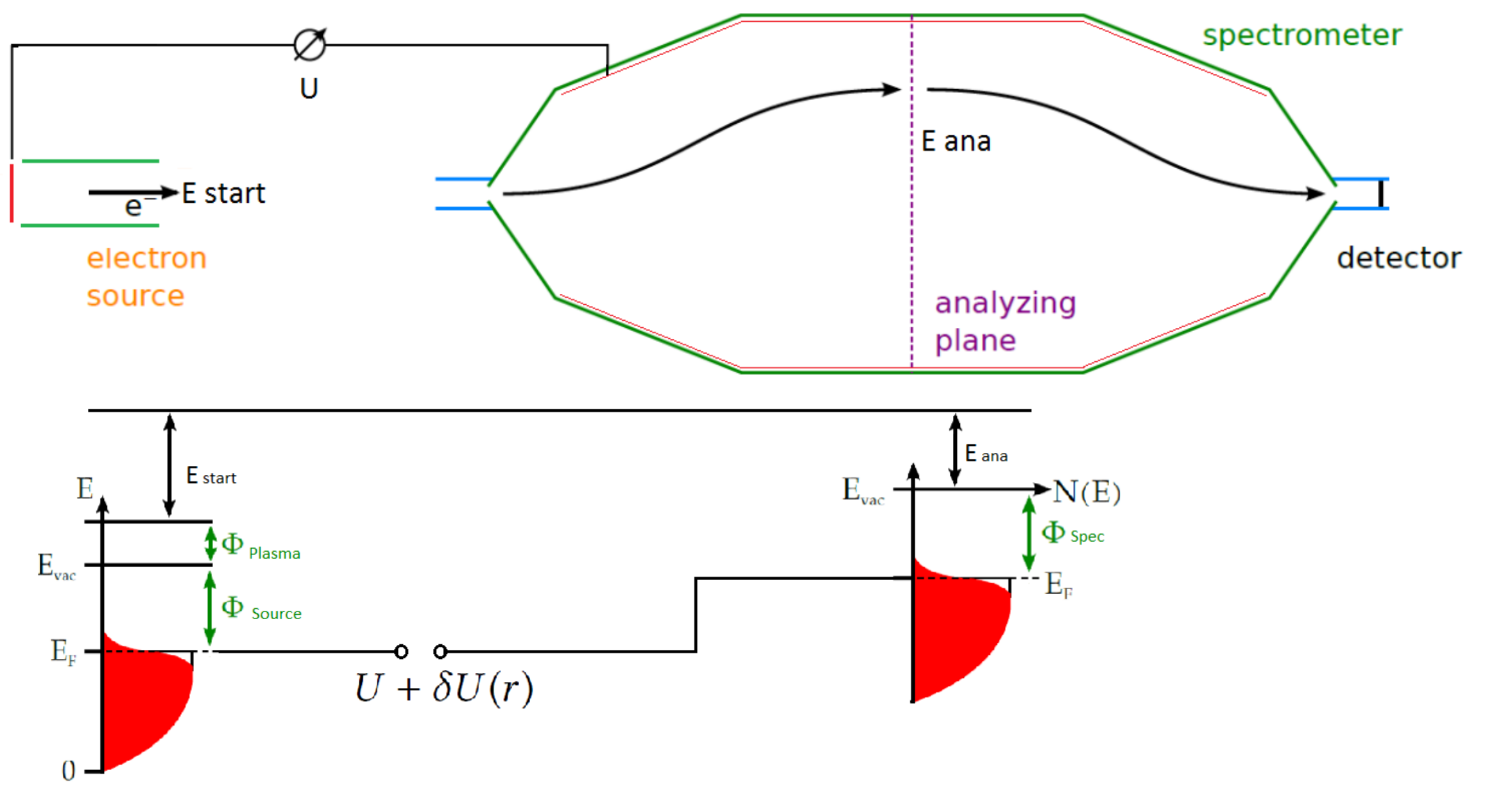


Statistical uncertainty on E_0 at KATRIN

The statistical uncertainty on E_0 at the KATRIN experiment will be only 2-3 meV with 3 years of data, below 17 meV after 1 month of data taking, and below 100 meV after just 1 day. These numbers are true for the design sensitivity of KATRIN.
If we assume a much higher background of 0.5 Hz, the uncertainty will increase to 5 meV after 3 years of measurement time.



Energy of an electron in the analyzing plane



$$E_{ana} = E_{start} + \Phi_{plasma} + \Phi_{source} - q(U + \delta U(r)) - \Phi_{spec}$$

Only electrons with $E_{ana} > 0$ make it to the detector.
To determine the Q-value we measure the spectrum (E_{start}) and we also need to know all the other parameters of this equation.

Determination of δU and $\Phi_{spectrometer}$ with an e-gun (1)

First we need to determine the work function of the photoelectron gun.
This can be done by measuring the intensity of the egun at different wavelength and fitting the fowler function to it.

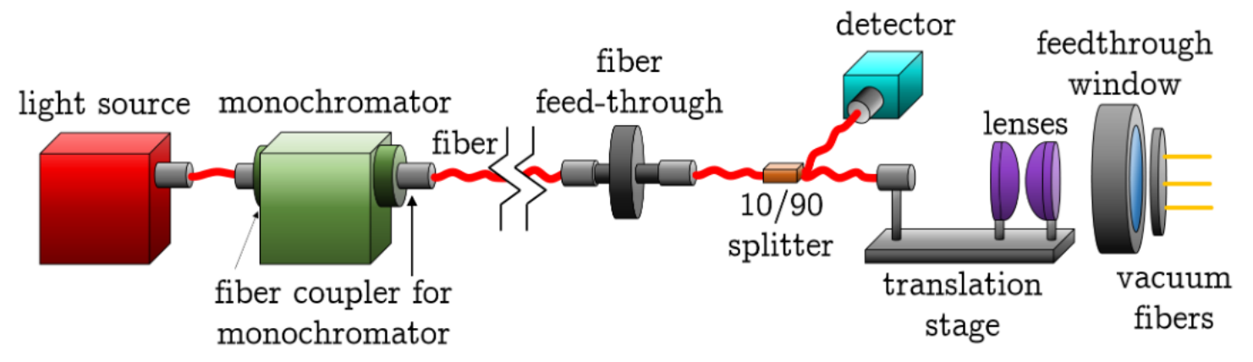
$$\frac{I}{T^2} = A \cdot f(\mu)$$

$$f(\mu) = \left[e^{\mu} - \frac{e^{2\mu}}{2^2} + \frac{e^{3\mu}}{3^2} + \ldots\right] \text{for } \mu \leq 0$$

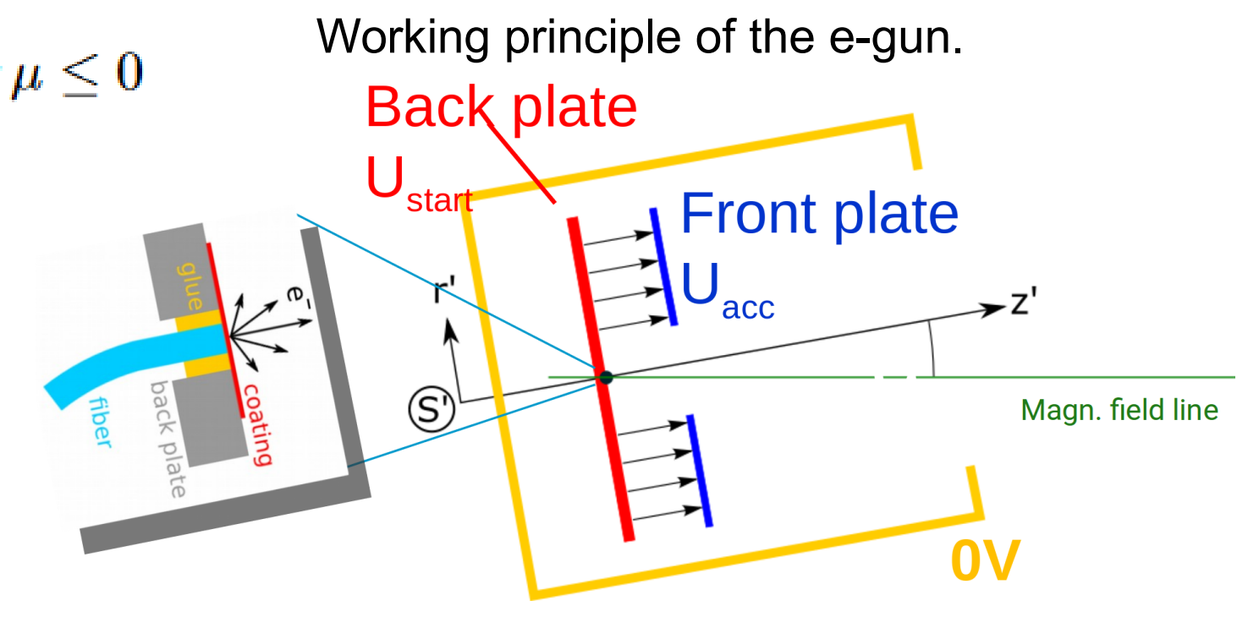
$$\mu = \frac{\hbar\omega - e\Phi}{k_B T}$$

This has already been done by J. Berens with a different egun. The error on the egun workfunction was < 20 mV.

Optical setup of the electron gun.



Working principle of the e-gun.

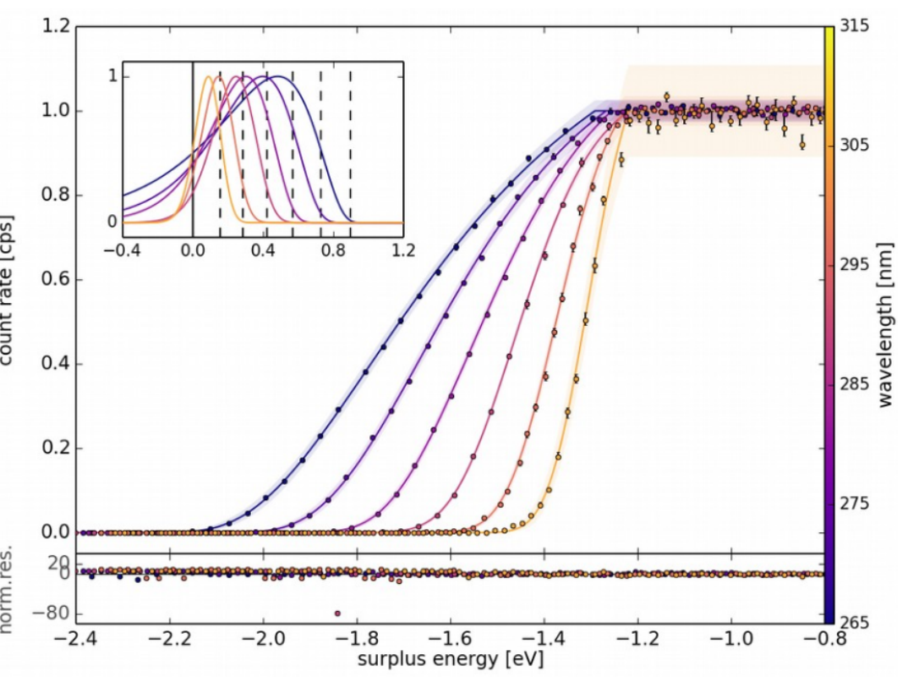


Picture by J. Behrens, P. Ranitzsch

Determination of δU and $\Phi_{spectrometer}$ with an e-gun (2)

Once we know the work function of the e-gun, we can measure the transmission function of the spectrometer at a low e^- energy (at low voltage the energy resolution of the spectrometer is much better). This allows us to determine the effective transmission function, which contains both the voltage inhomogeneity δU and the work function of the spectrometer Φ.

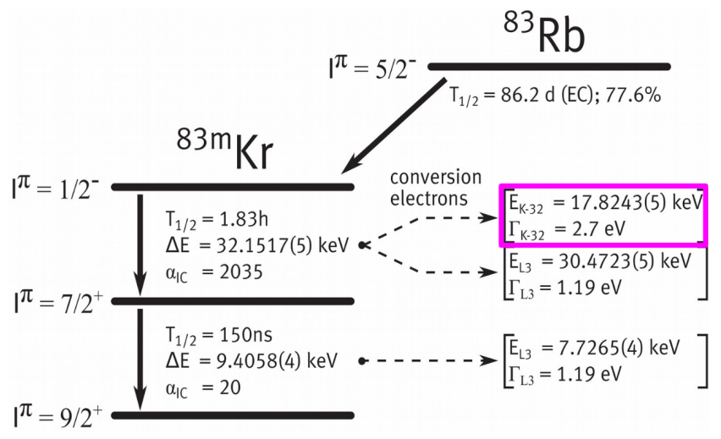
Transmission at different wavelengths corresponding to different surplus energies.

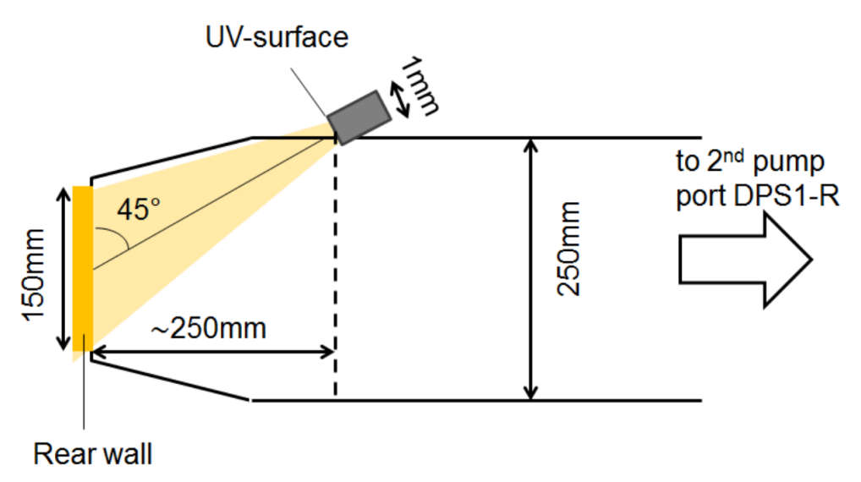


Plot by Jan Behrens

Determination of the Source work function Φ_{source} and the plasma potential Φ_{plasma}.

A measurement mode where ^{83m}Kr is mixed in the source with D_2 or T_2 gas can be used to gain information about the plasma potential Φ_{plasma}.
Unfortunately a measurement with ^{83m}Kr can only be done at a temperature of 110K. At this temperature the plasma potential is higher than at the nominal value of 30K for tritium measurements.
Depending on how well the Kr lines are known these measurements can also be used to determine the effective work function of the source.
At the moment these lines are known only with 300 meV or even 500 meV uncertainty. However there are measurements planed with a condensed Krypton source which might provide a better value.

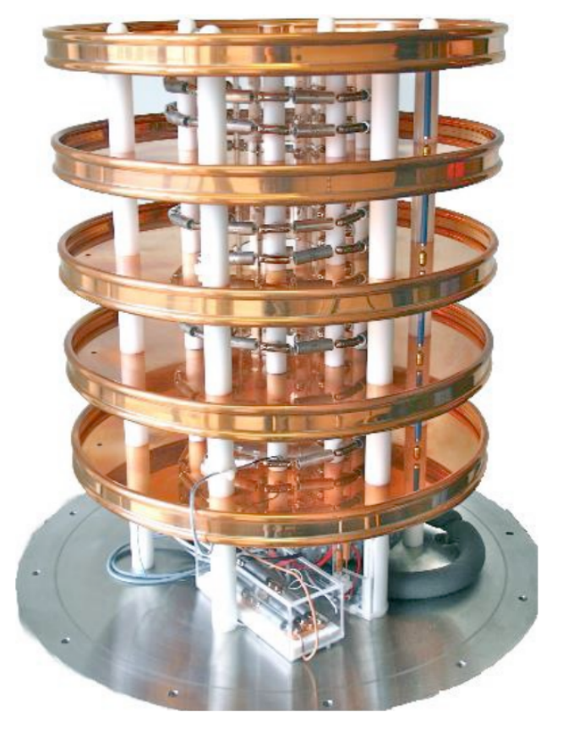




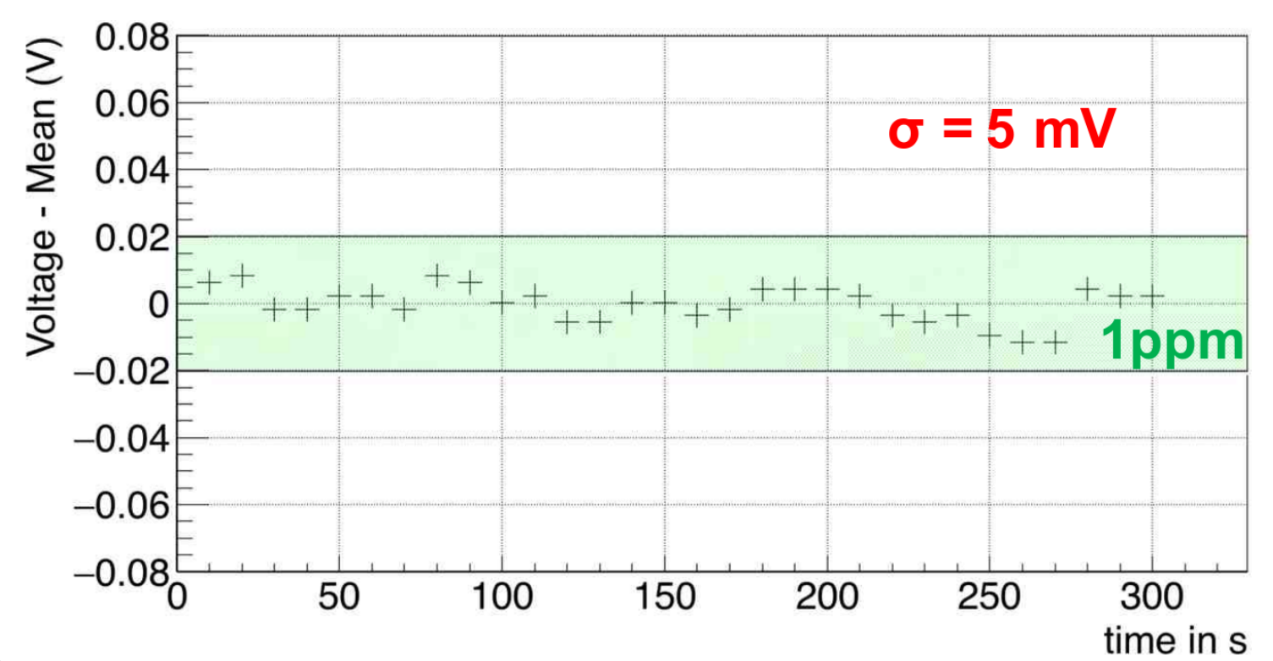
The rear wall (RW) is a gold coated steel plate which will dominantly contribute to the effective source potential. The work function of the RW has been measured with a kelvin probe and it is planned to determine the work function in situ with the fowler method. Setting it to the right electric potential will also lower the plasma potential.

Absolute high voltage U

The Endpoint E_0 can only be determined correctly if the absolute high voltage is known on a ppm level.
Also the neutrino mass measurement at KATRIN requires a high voltage stability on the ppm level.
To fulfill this ambitious goal two high voltage dividers (K35 and K65) have been built.



High voltage divider K-35



Voltage measurement of precision HV supply FuG HCP 70-35000M with K35.

Summary / Outlook

The measurement of the tritium Q-value at KATRIN is dominated by systematical uncertainties.
It is reasonable to assume that we can determine the Q-value with a precision of 70 to 100 meV.

The comparison of the Q-value measured at KATRIN and an external Q-value will be a good check for many of our systematics, i.e. the work functions or the absolute value of the high voltage system.

K. Blaum from MPIK Heidelberg aims to measure the mass difference of T and ^{3}He with <70 meV precision in a penning trap experiment.

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