Application of CLTD`s for Precise Stopping Power Measurements of Heavy Ions in Matter

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I. Introduction

II. CLTD`s for High Resolution Detection of Heavy Ions
- Design and Performance

III. The TOF – CLTD Spectrometer
- A new Experimental Technique for dE/dx Measurements

IV. Results on Stopping Powers for ^{131}Xe Ions in C, Ni and Au

V. High Resolution In-Flight Mass Identification of Heavy Ions

VI. Summary and Conclusions

I. Introduction

- the success of experimental physics and the quality of the results generally depends on the quality of the available detection systems

- needed for heavy ion physics:

  ⇒ energy sensitive detectors for x-rays, γ-rays

  ⇒ energy sensitive detectors for particles (heavy ions)

- as compared to most other applications of LTD`s:

  ⇒ substantially different energy range:

  E_γ = 10 – 1000 keV

  E_{HI} = 10 – 1000 MeV

I. Introduction

- the concept of LTD`s provides substantial advantage over conventional detection schemes with respect to basic detector properties:
  - ⇒ energy resolution
  - ⇒ energy linearity
  - ⇒ detection threshold
  - ⇒ dynamic range
  - ⇒ radiation hardness

- LTD`s have a large potential for various applications in basic and applied Heavy Ion Research:
  - ⇒ Nuclear Structure and Astrophysics
  - ⇒ Atomic Physics
  - ⇒ Symmetries and Basic Interaction
  - ⇒ Interaction of Radiation with Matter

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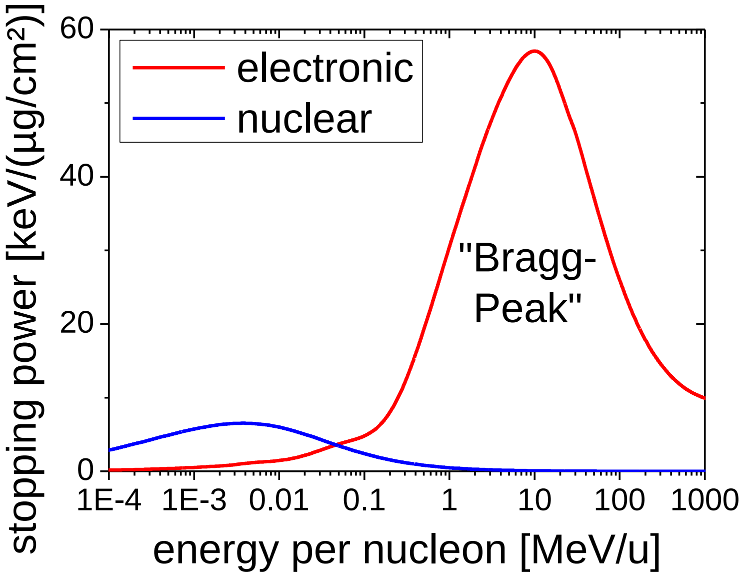
- LTD`s have a large potential for various applications in basic and applied Heavy Ion Research:
  - ⇒ Nuclear Structure and Astrophysics ⇒ in-flight mass determination
  - ⇒ Atomic Physics ⇒ test of QED (talk by Saskia Kraft-Bermuth)
  - ⇒ Symmetries and Basic Interaction
  - ⇒ Interaction of Radiation with Matter ⇒ specific energy loss

Motivation for Stopping Power Measurements



example: stopping power of ^{238}U-ions in gold (SRIM-prediction)

energy loss processes:

- electronic stopping power
  = ionization of target atoms
- nuclear stopping power
  = elastic scattering on target nuclei

important: theoretical understanding

- basic science:
  - interaction of energetic particles with matter
- applied science:
  - material science
  - investigation of radiation damage
  - medicine → tumor therapy
  - …

problem:

accuracy of theoretical models unsatisfactory

⇒ predictions by semi-empirical computer codes

- use best fits on experimental data (example: SRIM)

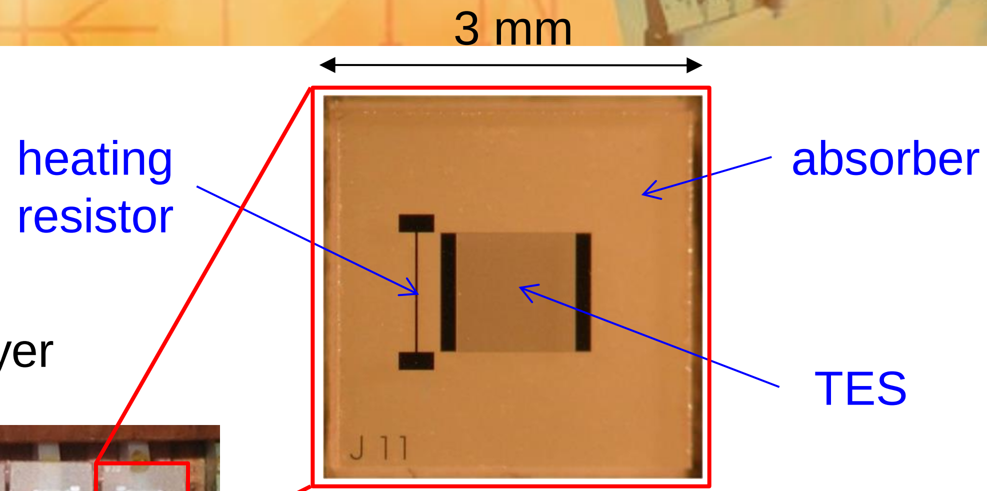
⇒ lots of data needed for different kind of

- targets, projectiles, energies

in particular:

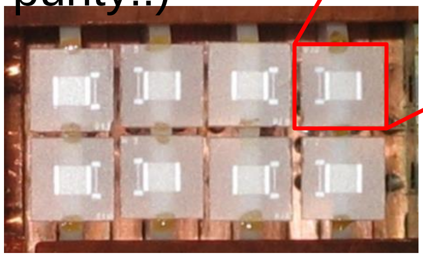
data for very slow and very heavy ions are still scarce

II. CLTD`s for High Resolution Detection of Heavy Ions - Design and Performance

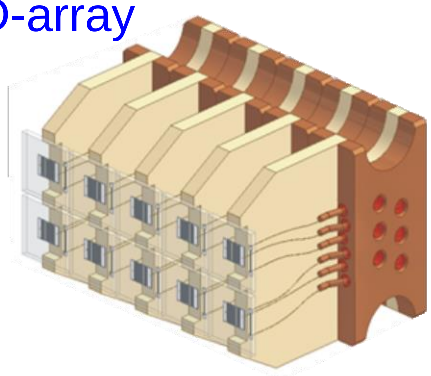


detector:

- absorber:
  3 x 3 x 0.43 mm^3 sapphire (Al_2O_3)
- thermometer:
  Transition Edge Sensor (TES)
  10 nm thick meander shaped Al-layer
  ⇒ photolithography (high purity!!)
- heating resistor:
  Au/Cr strip
- operation temperature:
  T_c = 1.5 – 1.6 K



CLTD-array



current array:

- 8 pixels with individual temperature stabilization in operation
- active area: 12 mm x 6 mm
- windowless coupling of cryostat to beam line

cryostat

CLTD`s for High Resolution Detection of Heavy Ions -Design and Performance

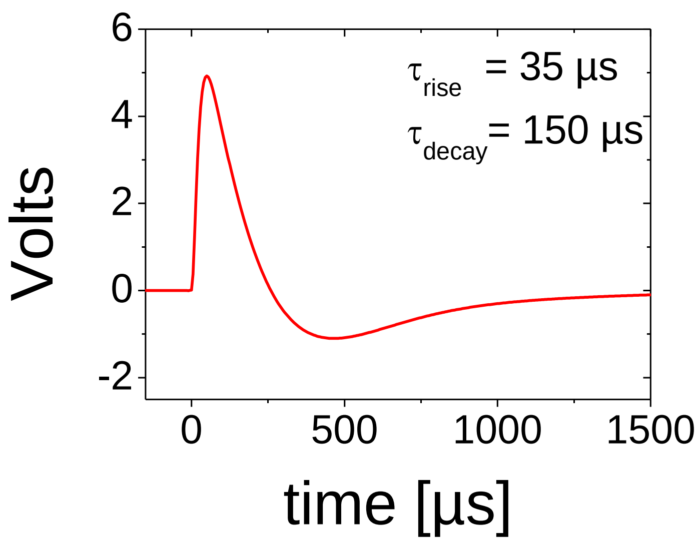
detector performance: response to ^{32}S ions @ 100 MeV

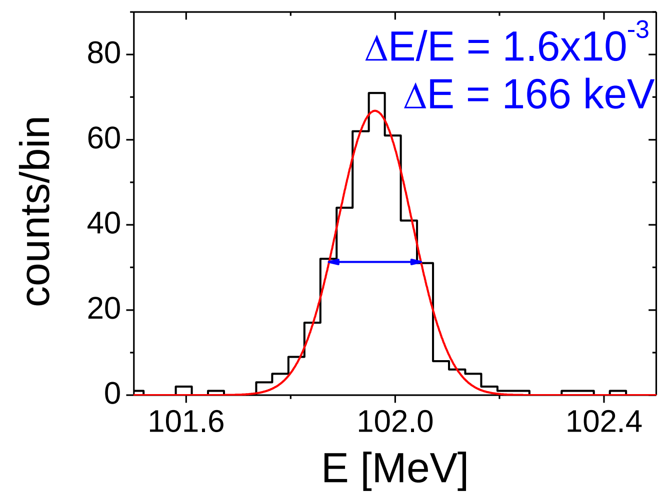
rate capability:

≥ 200 sec^{-1}

resolution:

$\Delta E/E = 1.6 \times 10^{-3}$





systematical investigation of energy resolution:

with UNILAC-beam:	for ^{209}Bi, E = 11.6 MeV/u ⇒ $\Delta E/E = 1.8 \times 10^{-3}$
with ESR-beam:	for ^{238}U, E = 360 MeV/u ⇒ $\Delta E/E = 1.1 \times 10^{-3}$
with Tandem-beam:	for ^{152}Sm, E = 3.6 MeV/u ⇒ $\Delta E/E = 1.6 \times 10^{-3}$

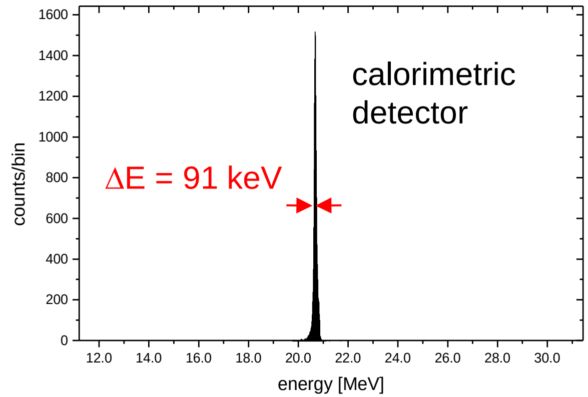
⇒ for heavy ions: ≥ 20 x improvement over conventional Si detectors

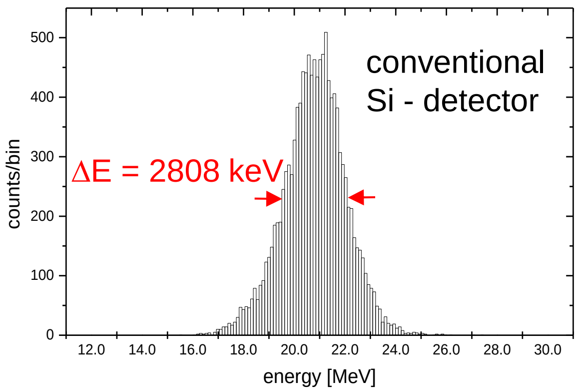
Comparison of Detector Performance: CLTD – Conventional Si Detector

energy resolution:

example:

^{238}U @ 20.7 MeV)

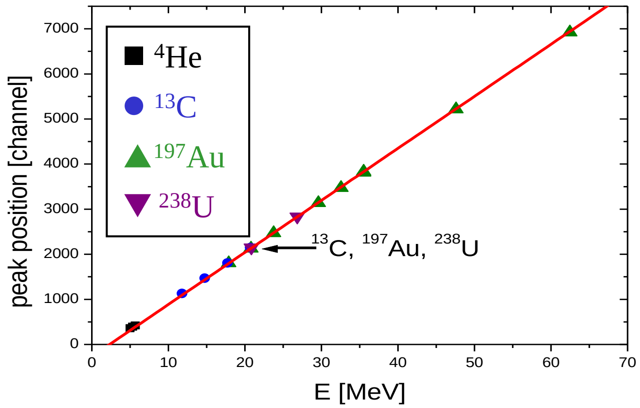


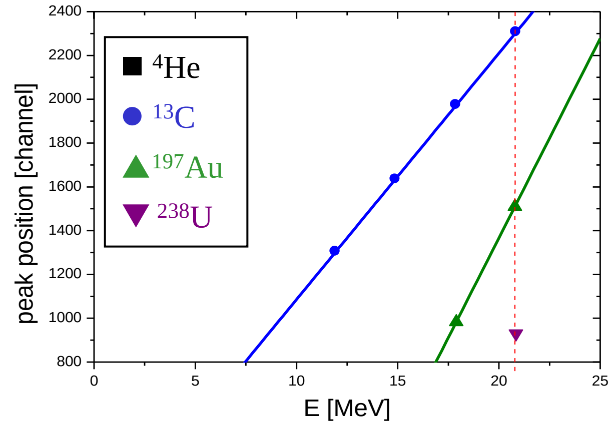


energy linearity:

example:

^{13}C, ^{197}Au, ^{238}U





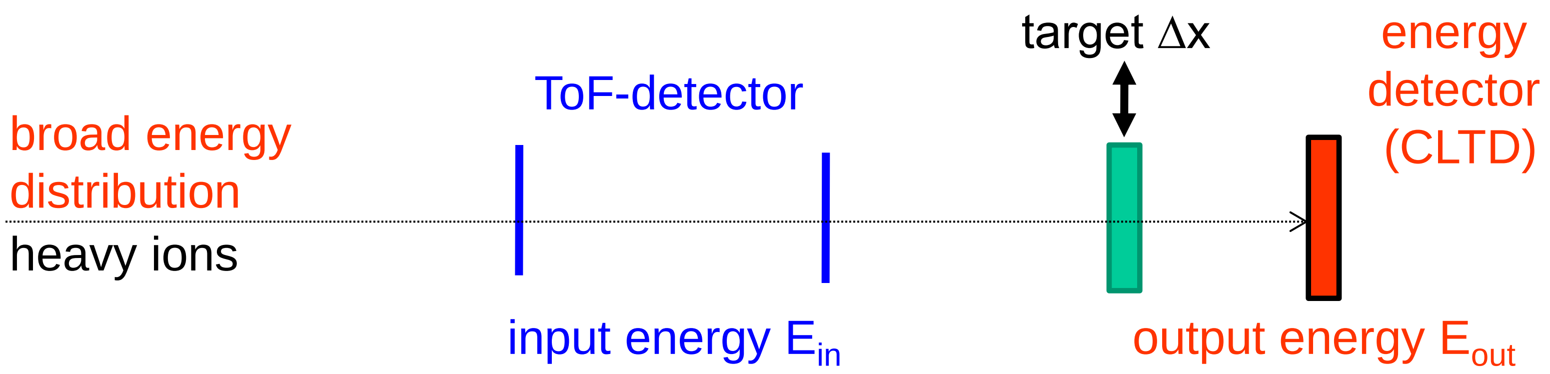
for conventional ionization detector:

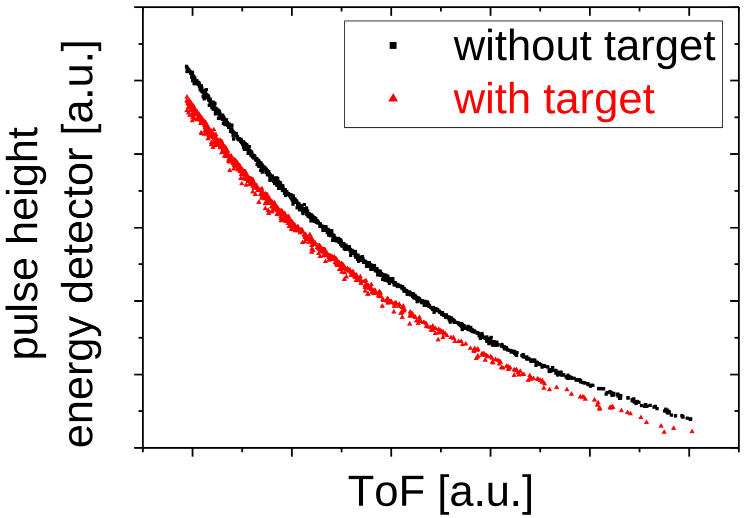
high ionization density leads to charge recombination

$\Rightarrow$ pronounced pulse height defects $\Rightarrow$ nonlinear energy response

$\Rightarrow$ fluctuation of energy loss processes $\Rightarrow$ limited energy resolution

III. The TOF – CLTD Spectrometer
- A New Experimental Method for dE/dx Measurements





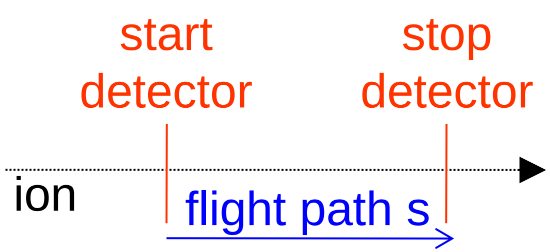
as compared to previous measurements with conventional energy detector (for example: Trzaska et al., Zhang et al.):

⇒ by use of CLTD's as energy detector:

- improved energy resolution
  → higher sensitivity
- improved energy linearity (no pulse height defect)
  → reduced energy calibration errors

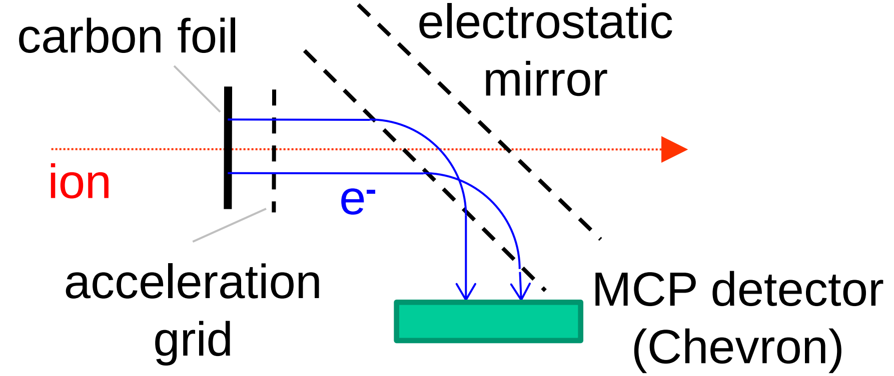
Detectors for the Time of Flight (TOF) Measurement

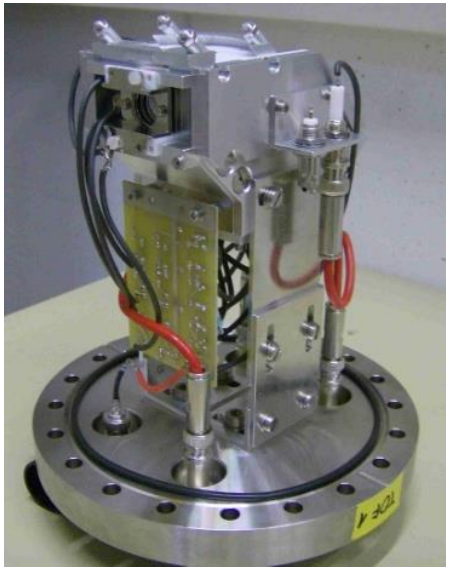
<u>time-of-flight (ToF) measurement:</u>

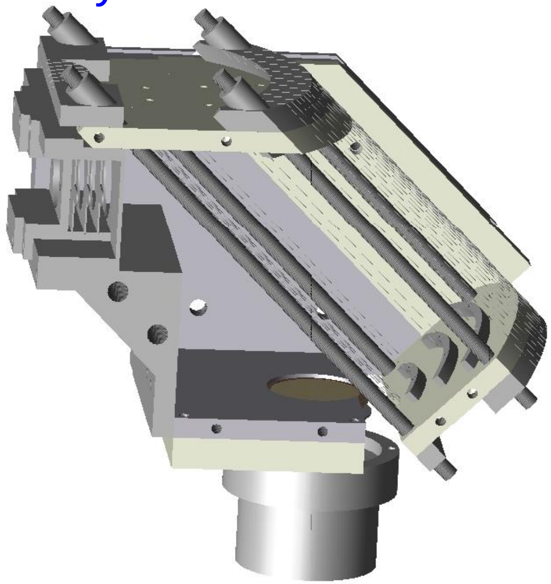


s,ToF ⇒ velocity

<u>detection scheme:</u>







original design: Wastyn et al., GSI Annual Report (1978) p.80

detection of secondary electrons
→ non-destructive time-pickoff of heavy ion passage

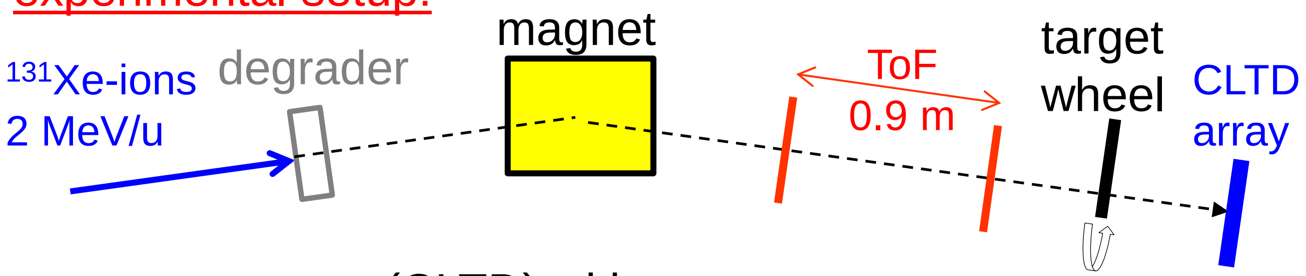
carbon foil affects ion energy
→ very thin foils needed (few μg/cm²)

time resolution for
^{131}Xe and ^{238}U-ions:
Δt (FWHM) = 140 - 220 ps

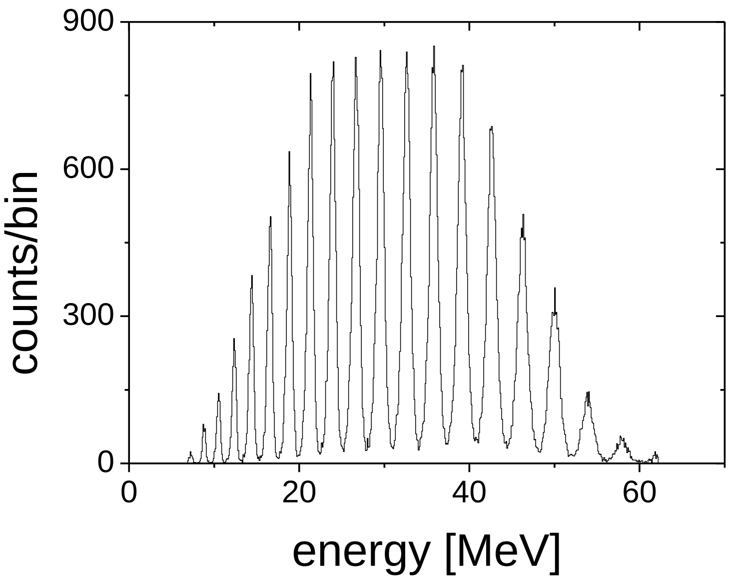
IV. Results on Stopping Powers for ^{131}Xe-Ions in C, Ni and Au

measurements at K-130 cyclotron at JYFL Jyväskylä

experimental setup:



energy spectrum (CLTD) without target

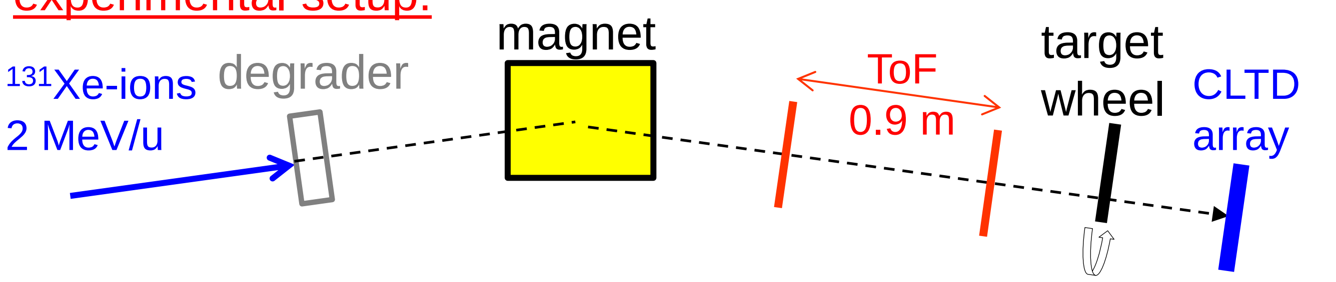


structure in energy distribution due to charge state selection in the magnet

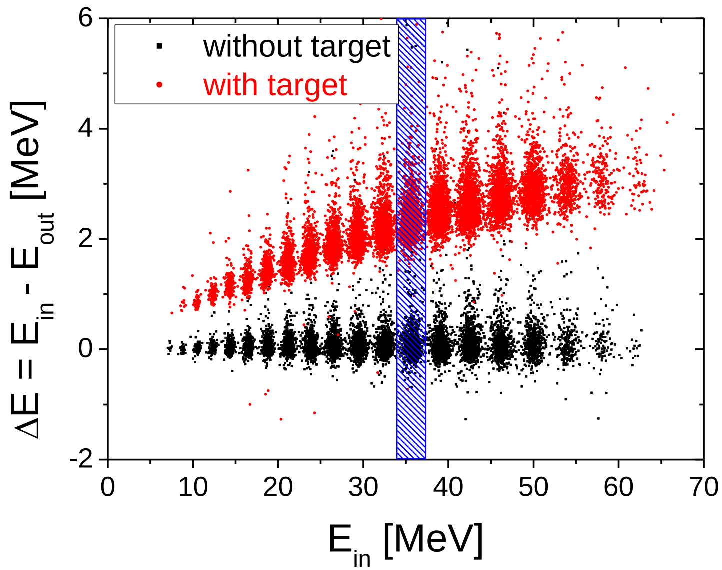
IV. Results on Stopping Powers for ^{131}Xe-Ions in C, Ni and Au

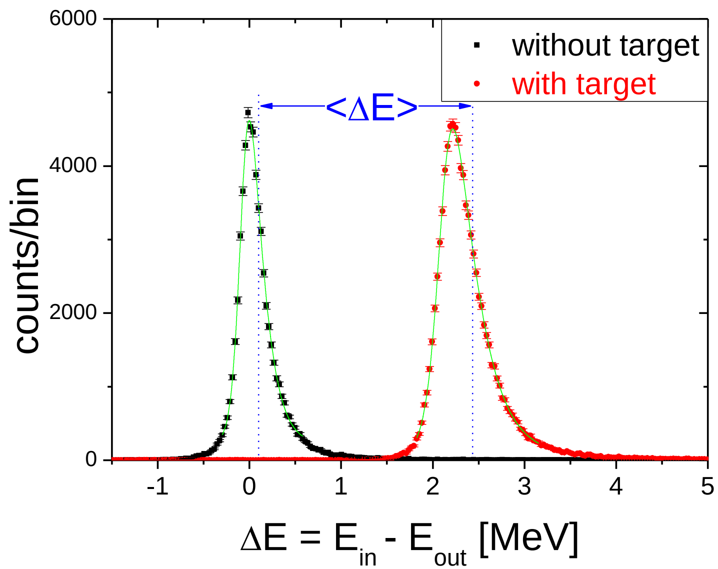
measurements at K-130 cyclotron at JYFL Jyväskylä

experimental setup:



target thickness Δx determined by weighting + energy loss of α-particles
→ high accuracy



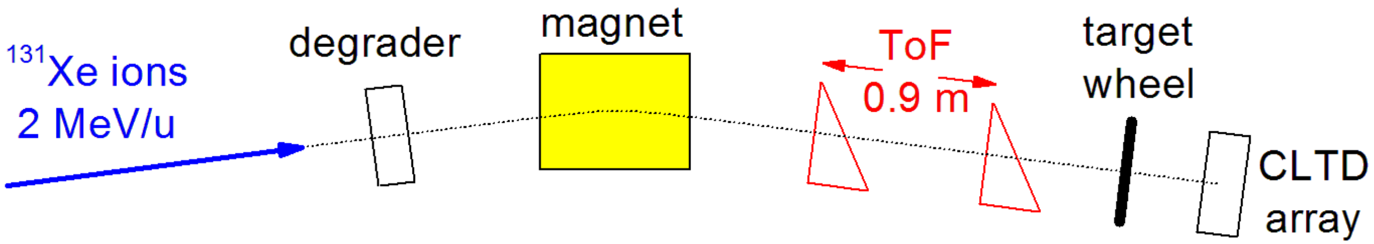


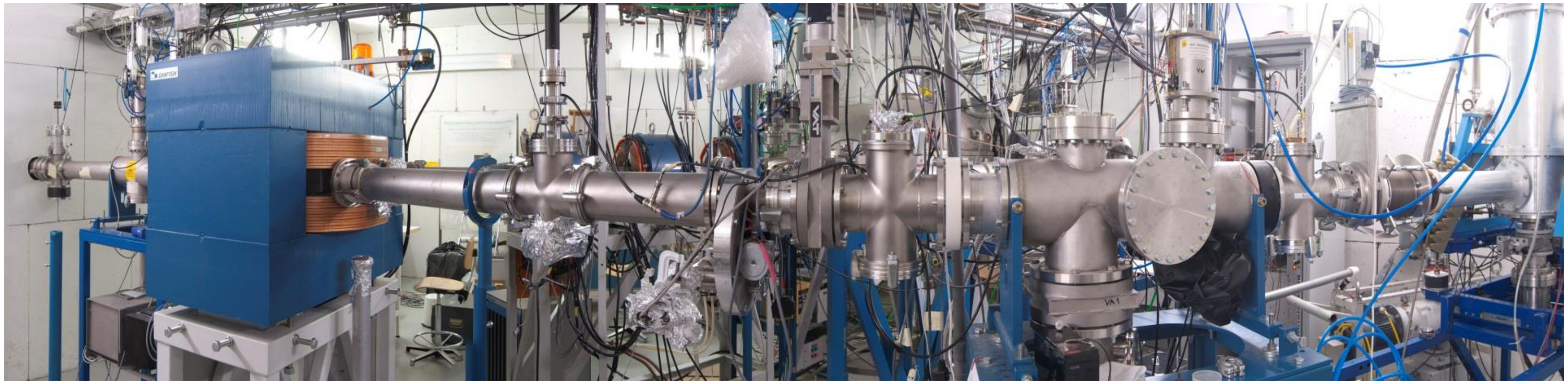
example: ^{131}Xe in 53 µg/cm² carbon

Results on Stopping Powers for ^{131}Xe-Ions in C, Ni and Au

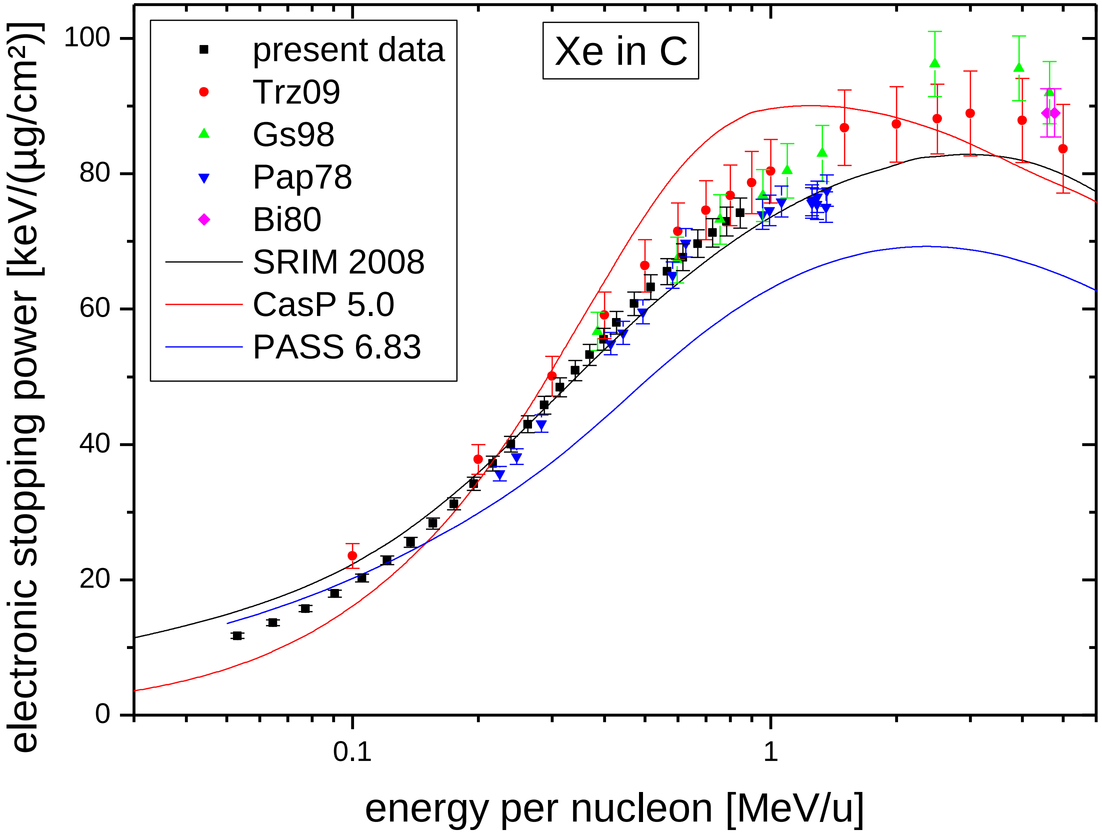
joint experiment with the Jyväskylä group at the Jyväskylä facility

experimental setup:





Results on Stopping Powers: 0.05 – 1.0 MeV/u ^{131}Xe-Ions in C



reference data taken from online database of H. Paul:
http://www.exphys.jku.at/stopping/

experimental uncertainties:

- detectorcal.: <1 %
- target foils: 3 %
- statistics: <0.5 %
  (lowest energies: <2 %)
- **total: 3 – 4 %**

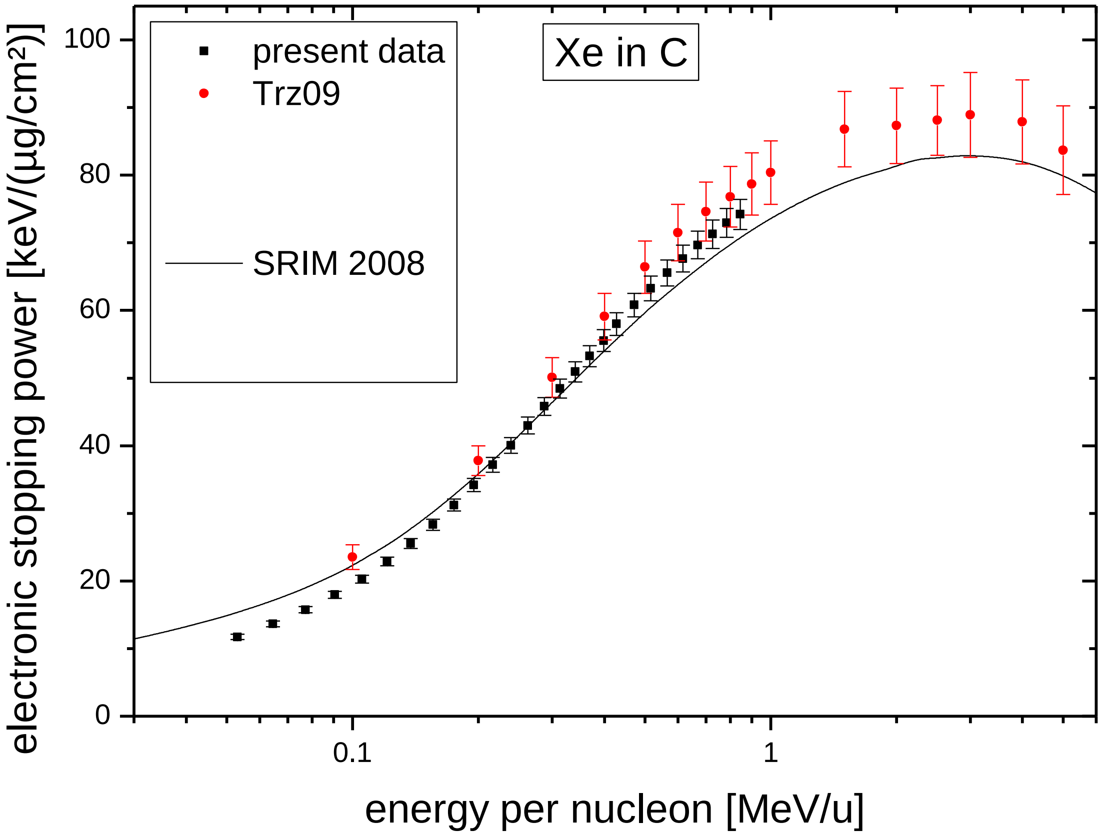
➢ substantial deviations from SRIM-predictions (semiempirical calculations)

➢ data extended to lower energies

➢ agreement with Geissel et al.

➢ deviations from data from Trzaska et al. and Pape et al.

Results on Stopping Powers: 0.05 – 1.0 MeV/u ^{131}Xe-Ions in C



reference data:
W.H. Trzaska et al., Nucl. Instr. Meth. B 267 (2009) 3403

experimental uncertainties:

- detectorcal.: <1 %
- target foils: 3 %
- statistics: <0.5 %
  (lowest energies: <2 %)
- **total: 3 – 4 %**

compare to uncertainties of Trzaska et al:

same setup with conv. Si-det.

- detectorcal.: 2 – 3 %
- target foils: 2 %
- statistics: 2 – 7 %
- **total: 6 – 8 %**

due to use of CLTD:

→ reduction of calibration errors and statistical errors

→ access to lower energies (higher sensitivity)

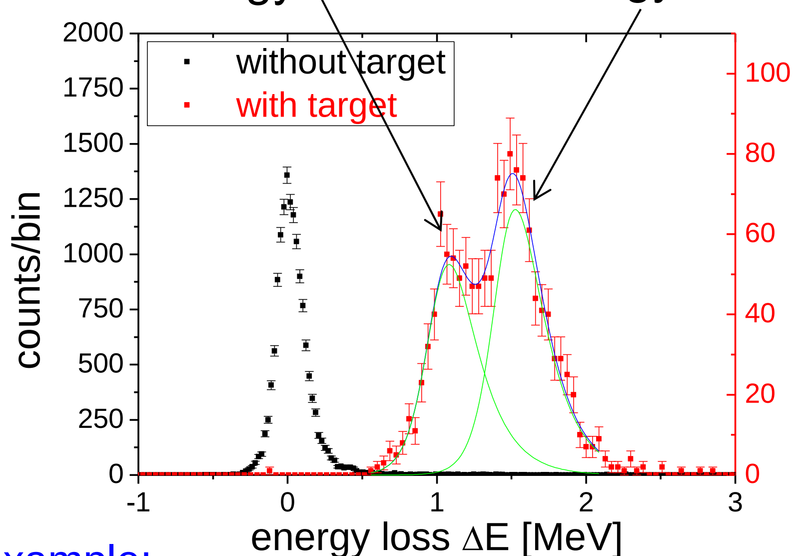
Stopping Power Measurements – Effect of Channeling

for thin Ni- and Au-targets:

→ double-peak structure in measured energy loss

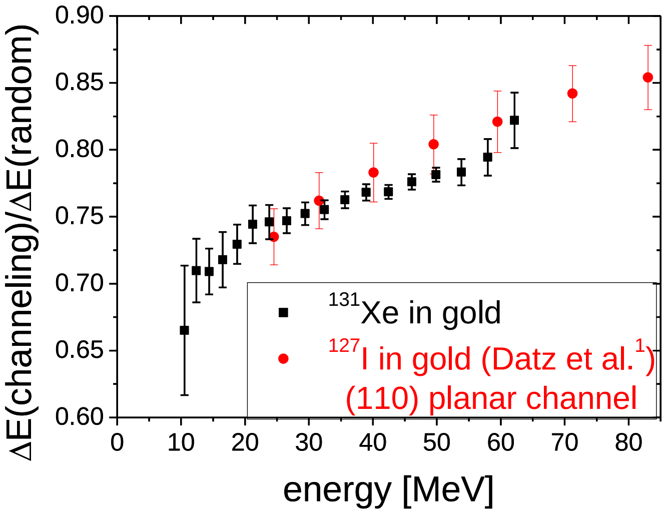
explanation:

"channeling energy loss" "random energy loss"



example:

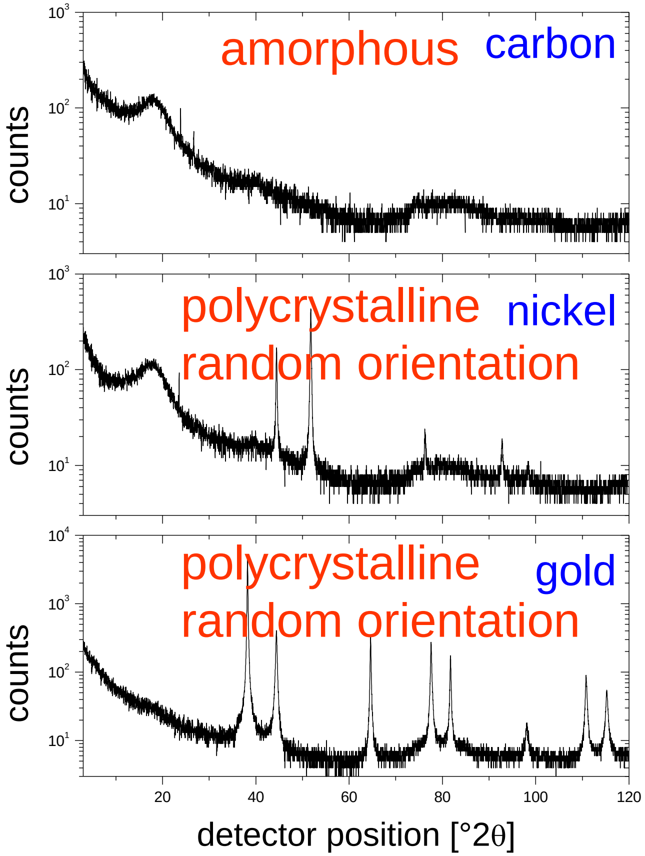
Xe (13 – 15 MeV) in Au (363 µg/cm²)



1) Datz et al., Nucl. Inst. Meth., 38 (1965) 221

X-Ray Diffraction Analysis of the Absorber Foils

Is the interpretation of the data correct? channeling appears only in crystalline absorbers!
problem: targets not grown as single crystals

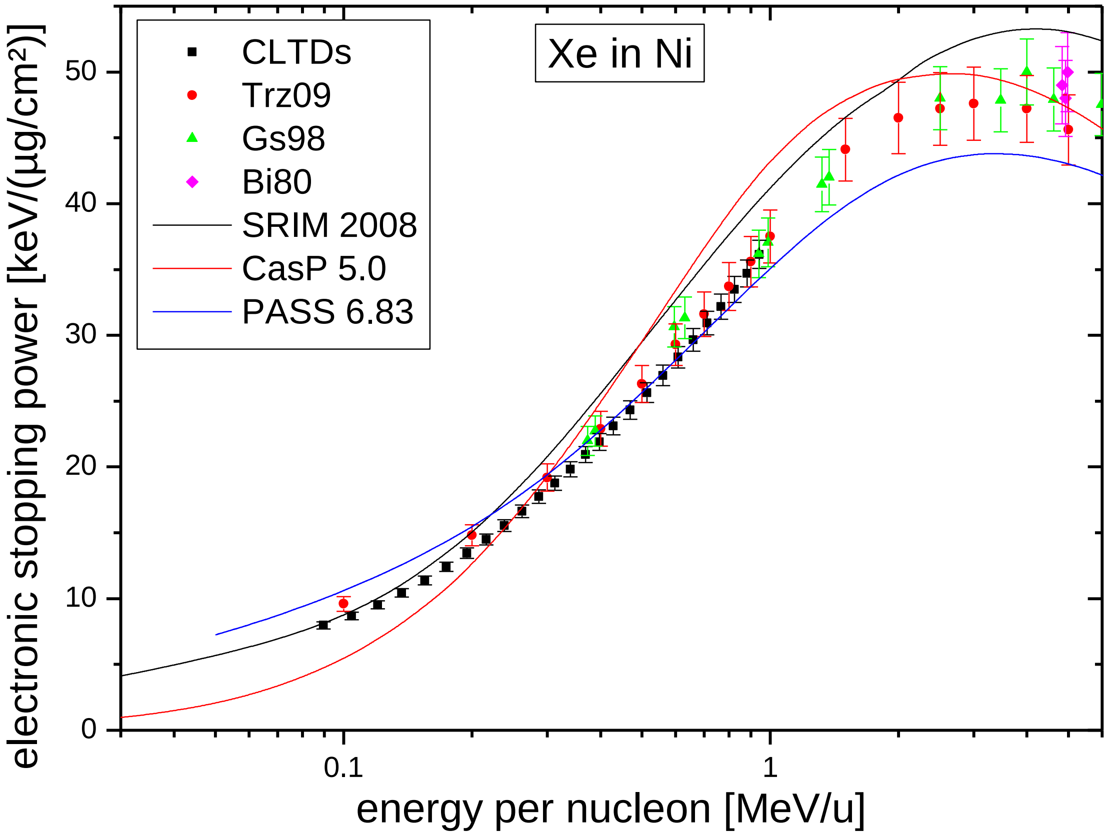


XRD-measurements performed by
Manu Lahtinen, University of Jyväskylä

the X-ray analysis confirms polycrystalline structure in Ni and Au foils

the channeling effect is enhanced due to much stronger multiple scattering for random energy loss

Results on Stopping Powers: 0.09 – 1.0 MeV/u ^{131}Xe-Ions in Ni (only Random Energy Loss)



experimental uncertainties:

- detectorcal.: <1 %
- target foils: 3 %
- statistics: <1 %
  (lowest energies: <2 %)
- total: 3 – 4 %

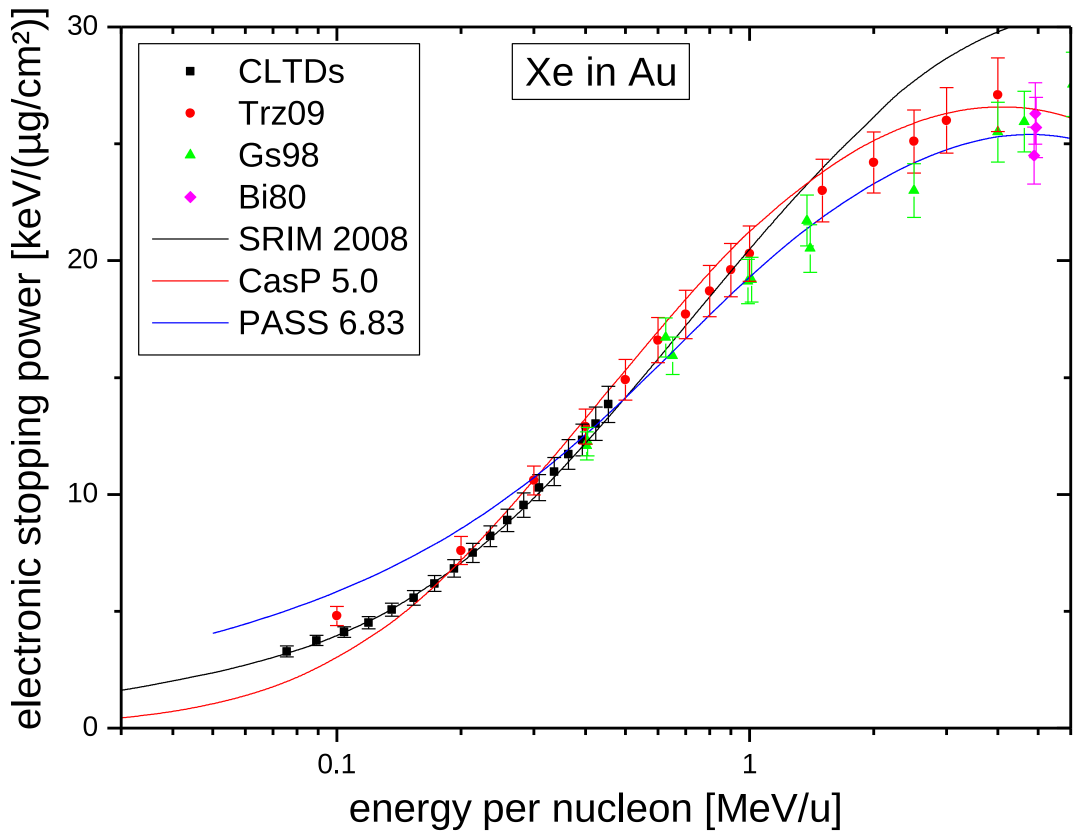
➢ substantial deviations from SRIM-predictions

➢ agreement with Geissel et al.

➢ deviations from data of Trzaska et al. for low energies

reference data taken from online database of H. Paul: http://www.exphys.jku.at/stopping/

Results on Stopping Powers: 0.07 – 0.5 MeV/u ^{131}Xe-Ions in Au (only Random Energy Loss)



experimental uncertainties:

- detectorcal.: <1 %
- target foils: 5 %
- statistics: <2 %
  (lowest energies: <5 %)
- total: 5 – 7 %

- agreement with SRIM-prediction
- agreement with Geissel et al.
- deviations from data of Trzaska et al. for low energies
- data extended to lower energies

reference data taken from online database of H. Paul: http://www.exphys.jku.at/stopping/

V. High Resolution In-Flight Mass Identification of Heavy Ions

important for many applications: isotope mass identification

standard method:

B • ρ ⇒ p
TOF ⇒ v

$$m = \frac{p}{v}$$

disadvantage:

- needs big magnet spectrometer
- small solid angle
- charge state ambiguity because of B • ρ = p/Q (especially for slow heavy ions!)
- small dynamic range

alternative method:

energy ⇒ E
TOF ⇒ v

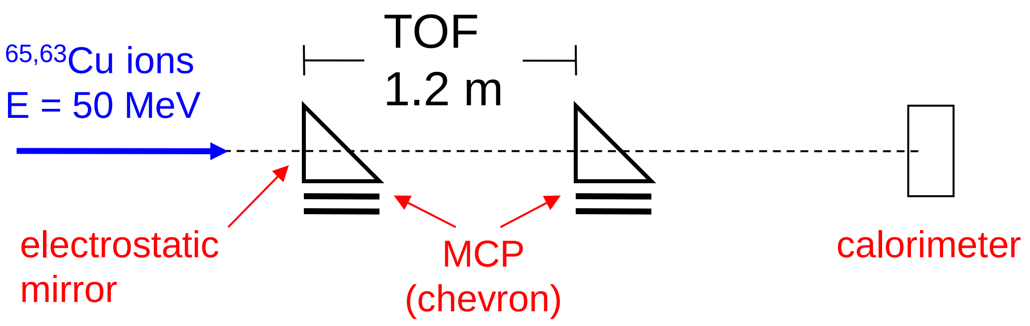
$$m = \frac{2E}{v^2}$$

$$\left(\frac{\Delta m}{m}\right)^2 = \left(\frac{\Delta E}{E}\right)^2 + \left(2\frac{\Delta t}{t}\right)^2$$

for conventional setups: mass resolution is limited by energy resolution!
⇒ calorimetric detectors

High Resolution In-Flight Mass Identification: Results for ^{63,65}Cu-Ions

measured at Tandem accelerator at MPI in Heidelberg

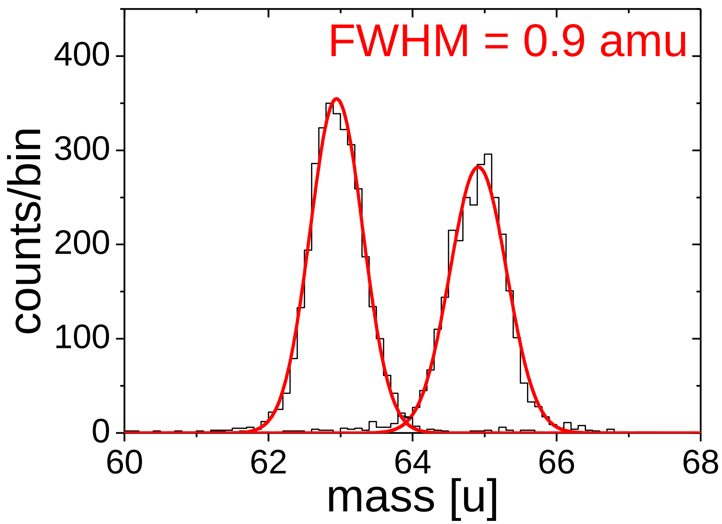


energy $\Rightarrow$ E
TOF $\Rightarrow$ v

$$m = \frac{2E}{v^2}$$

$$\left(\frac{\Delta m}{m}\right)^2 = \left(\frac{\Delta E}{E}\right)^2 + \left(2\frac{\Delta t}{t}\right)^2$$

^{63,65}Cu ions @ 50 MeV



$\Delta t = 680$ ps

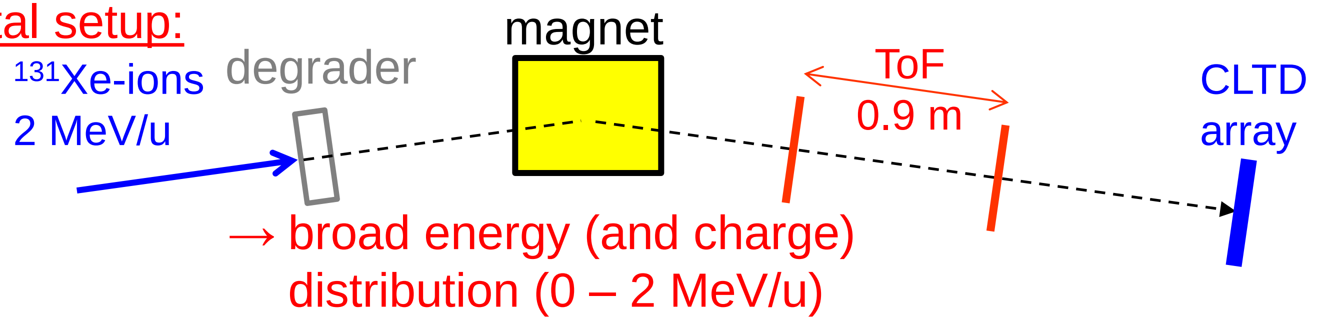
$\Delta E = 330$ keV

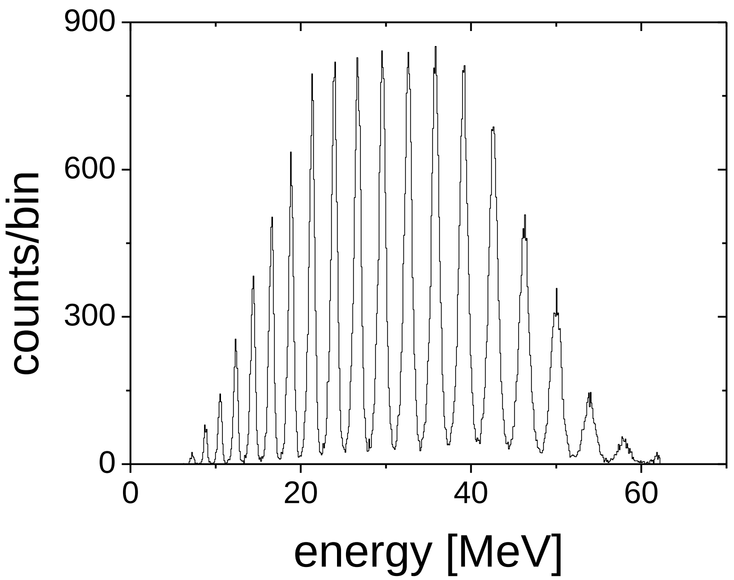
limitation: TOF measurement !

High Resolution In-Flight Mass Identification: Results for ^{131}Xe-Ions

low energetic ^{131}Xe ions @ K-130 cyclotron at JYFL Jyväskylä

experimental setup:

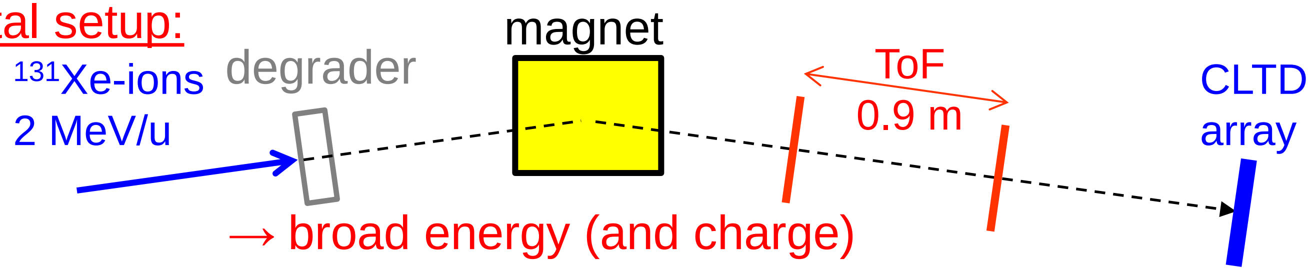




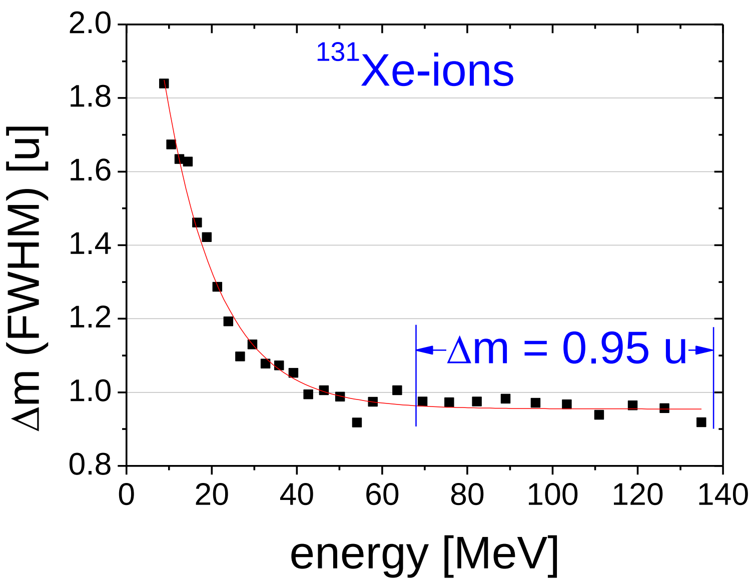
High Resolution In-Flight Mass Identification: Results for ^{131}Xe-Ions

low energetic ^{131}Xe ions @ K-130 cyclotron at JYFL Jyväskylä

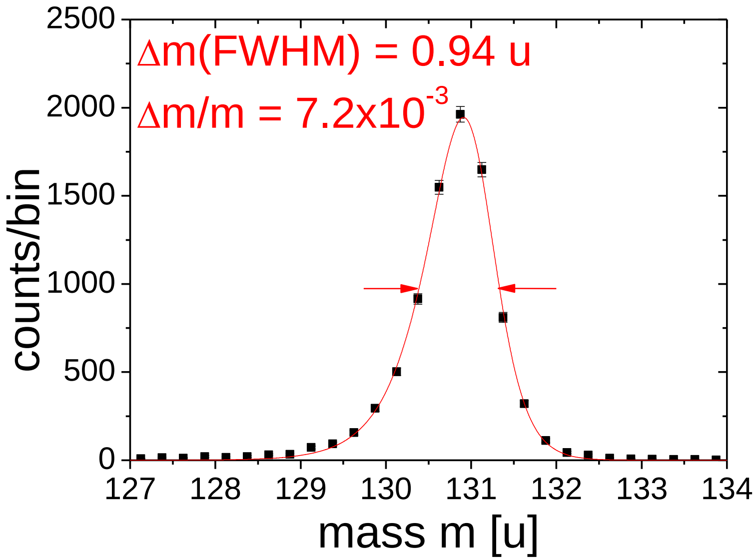
experimental setup:



→ broad energy (and charge) distribution (0 – 2 MeV/u)

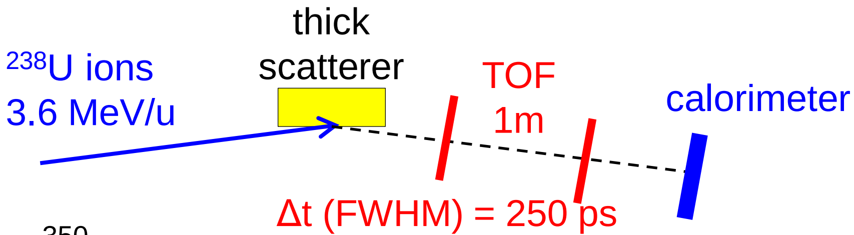


mass spectrum @ 107 – 115 MeV

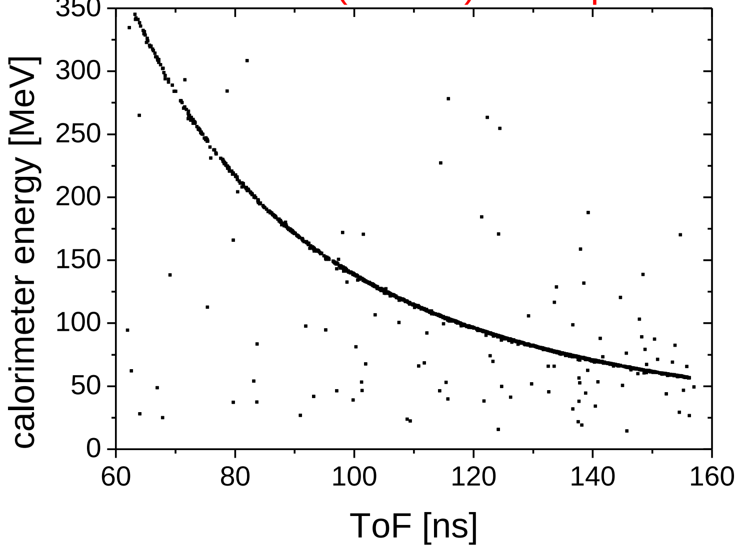


High Resolution In-Flight Mass Identification: Results for ^{238}U-Ions

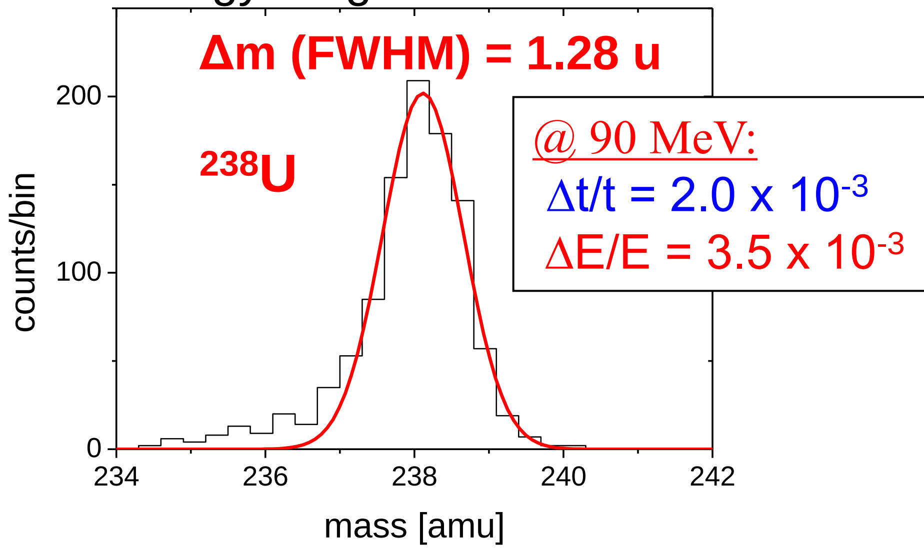
experimental setup: low energetic ^{238}U ions @ UNILAC accelerator at GSI



→ broad energy distribution (0 - 3.6 MeV/u)



energy range: 65 - 150 MeV



- ➢ not reachable with conventional E-ToF system
- ➢ advantage to Bρ-ToF method:
  - ▪ high dynamic range
  - ▪ not affected by charge state ambiguities

Perspectives for Applications

High Resolution Mass Identification for:

- identification of reaction products from reactions with radioactive beams (for slow heavy ions: no charge state ambiguities, high dynamic range)
  ⇒ potential application at FAIR
- identification of isotopes after in-flight gamma spectroscopy
  ⇒ potential application at FAIR
- identification of superheavy elements (for Z ≥ 113: decay chain does not feed a known α chain): Δm ≤ 1 for m = 300 reachable
- identification of rare isotopes in accelerator mass spectrometry
  ⇒ high sensitivity
- identification of fission fragments (replace the COSI FAN TUTTE spectrometer at Grenoble)
  ⇒ investigate structures in the mass distribution

Collaboration

A. Echler[1,2,3], P. Egelhof[1,2], P. Grabitz[1,2],
H. Kettunen[4], S. Kraft-Bermuth[3], K. Müller[3], M. Rossi[4], W.H. Trzaska[4],
A. Virtanen[4]

1 GSI Darmstadt, Germany
2 Univ. Mainz, Germany
3 Univ. Gießen, Germany
4 Univ. Jyväskylä, Finland

VI. Summary and Conclusions

- CLTD`s have substantial advantage over conventional detection systems concerning resolution, linearity, etc.
- CLTD`s were successfully applied for the first time for stopping power measurements ⇒ improvement in sensitivity, systematic uncertainties, and accessible energy range
- CLTD`s allowed the unexpected observation of channeling in polycrystalline absorbers ⇒ potential for further investigations
- CLTD`s allow high resolution in-flight mass determination (not reachable with conventional detectors ⇒ many potential applications
- for perspectives: see poster D 302, presented by Pattrick Grabitz