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Electronic interactions of medium-energy ions: Some recent results and their implications for high-resolution depth profiling

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Acknowledgements:

Karim Kantre
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Margareta Linnarsson



ION TECHNOLOGY
CENTRE



Swedish Foundation for
Strategic Research



Swedish Research
Council



Göran Gustafsson
Foundation

Ion Physics in Uppsala



Anders
Ångström

Tandemaccelerator

Ion-Implanter + MEIS

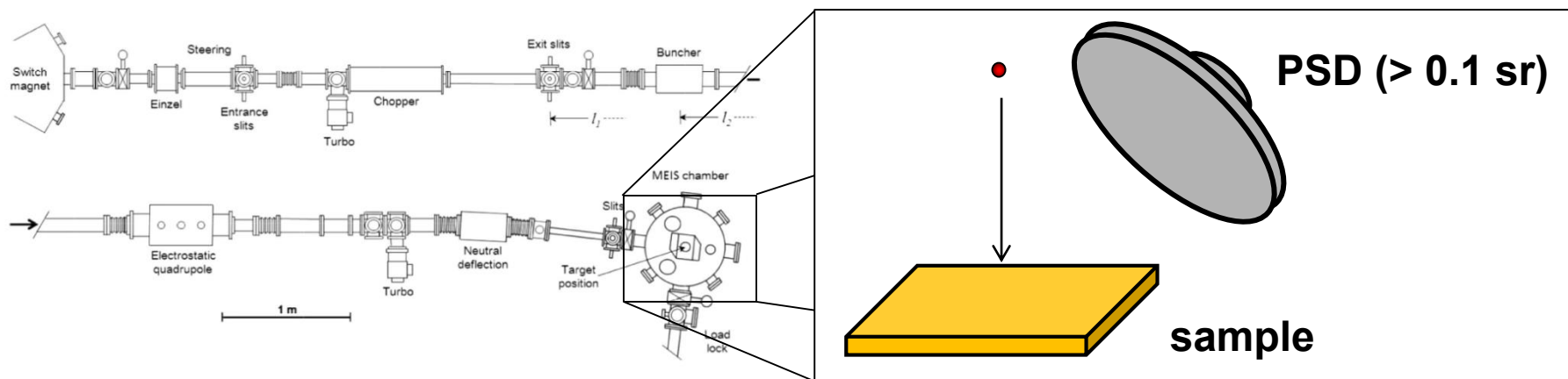
High resolution depth profiling: Ion energies: keV/amu

Possible complications:

- Contribution from nuclear energy loss along trajectories becomes relevant
- Low ion energy $\leftrightarrow$ low energy transfer to electrons
- Excitation of valence and conduction electrons $\leftrightarrow$ chemical effects
- Ion velocity comparable to electron velocity $\leftrightarrow$ response of system
- Increased weight of surface (contaminations, deviations from bulk stoichiometry)

- **Motivation: Stopping power research at keV energies**
- **Stopping power experiments by TOF-techniques**
 - **Heavy ions (Ne, I) in noble metals (Au, Ag, Pt)**
 - **Light ions in hafniumdioxide HfO_2**
- **Conclusions/Summary**

The Uppsala TOF-MEIS: an ideal tool



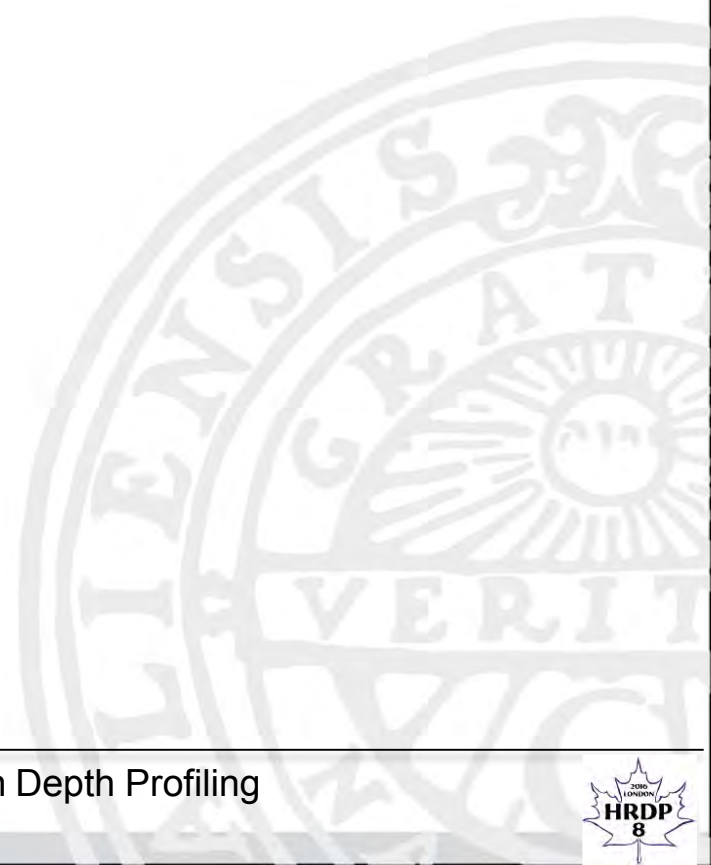
M. Linnarsson et al., Rev. Sci. Instr. (2012)

- Almost any ion, 20-350 kV acceleration voltage
- Microchannelplate detector + TOF: No problem with charge states
- Large solid angle: Extremely low dose!

Heavy ions... Ne!



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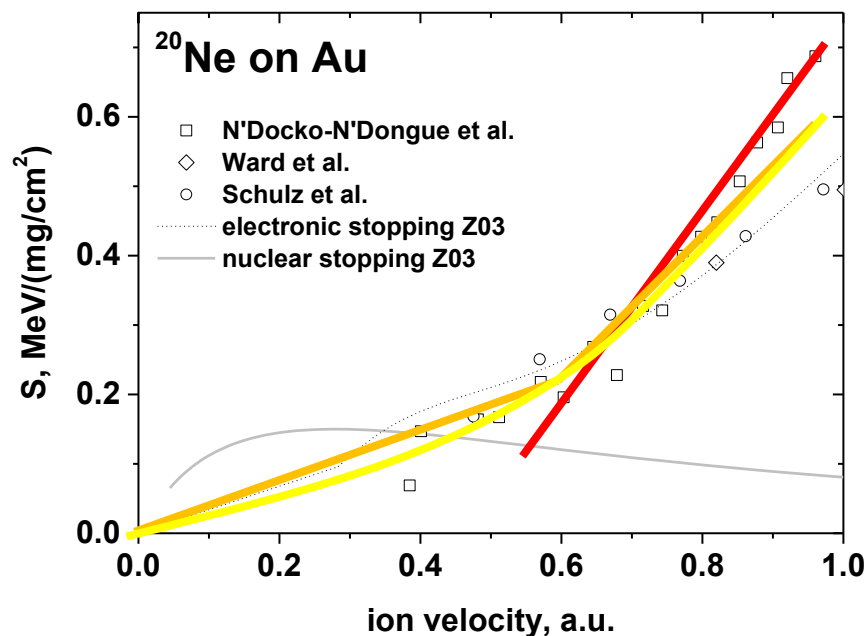
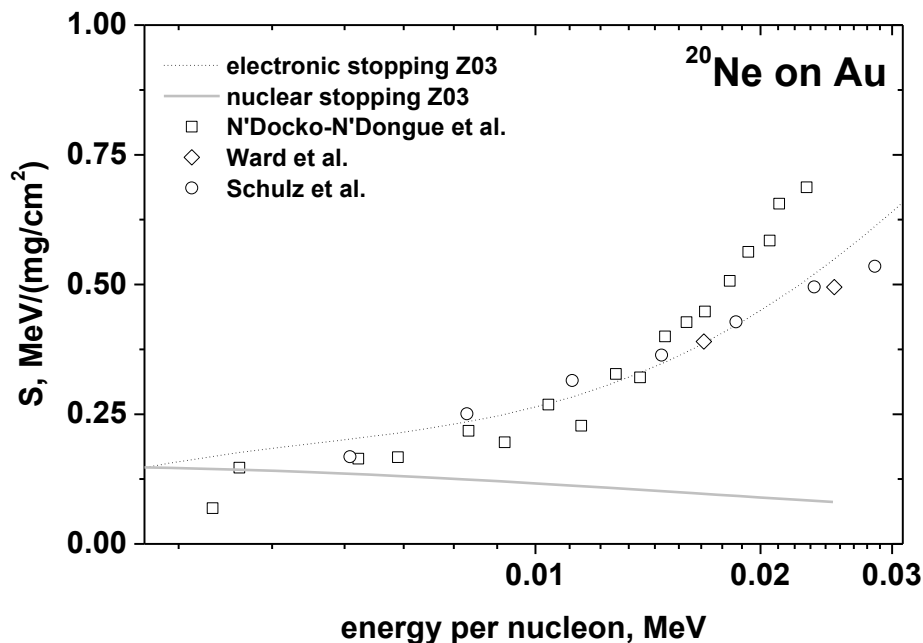




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Heavy ions... Ne!

At low energies ($< 1\text{MeV}$):



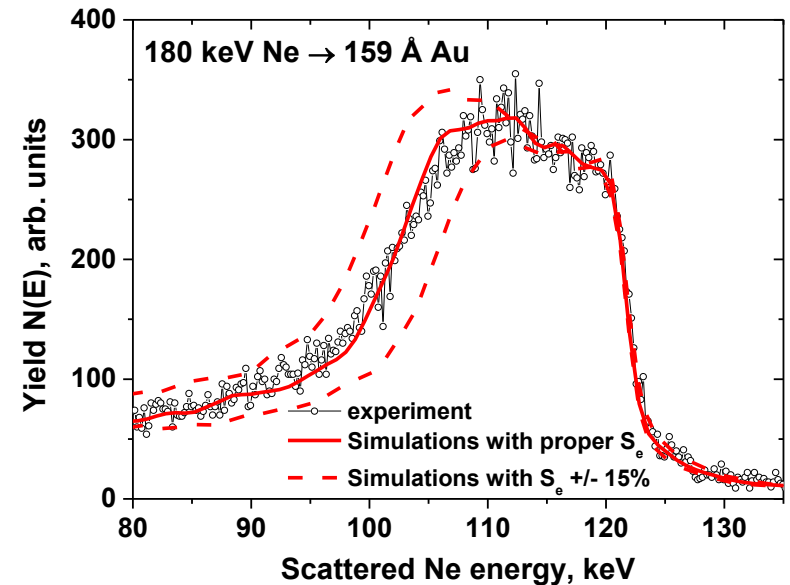
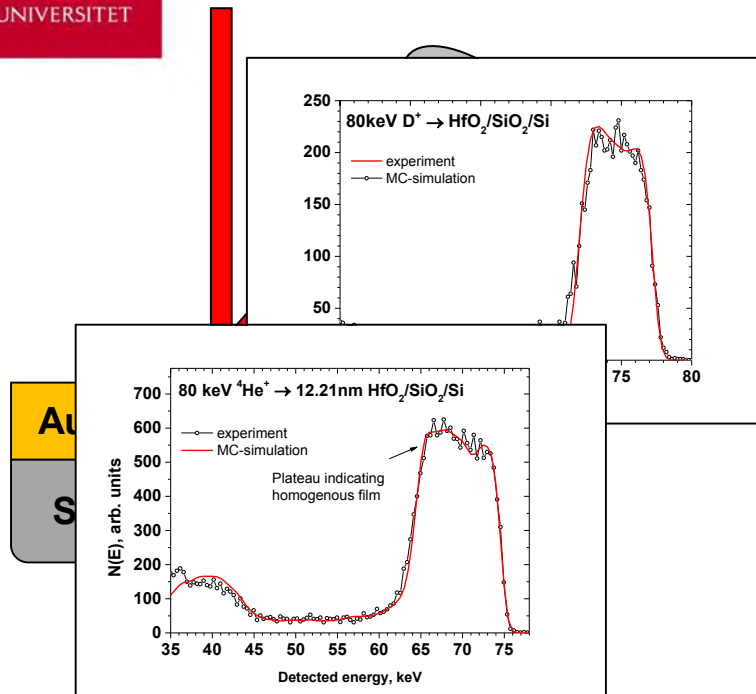
- Set of 3 transmission experiments from the literature
- Data shows a clear non-linear velocity dependence

N'Docko-N'Dongue et al.
Ward et al.
Schulz et al.
electronic stopping
nuclear stopping



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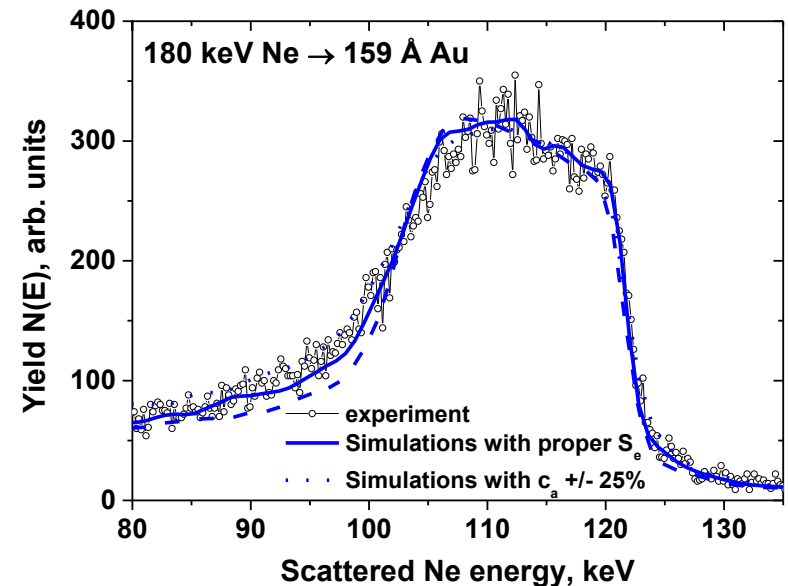
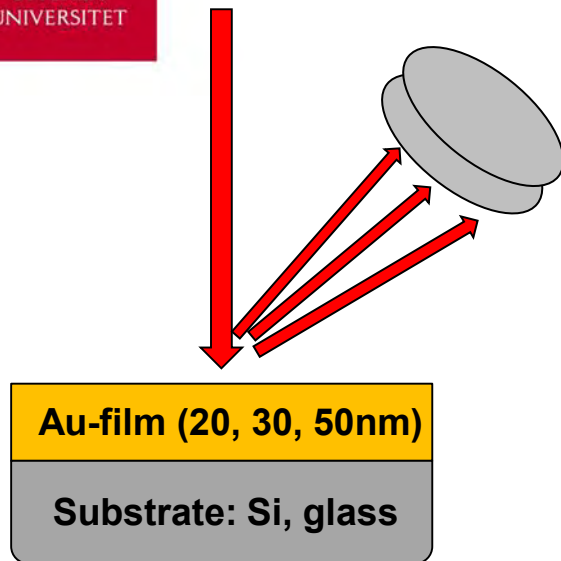
Backscattering of Ne: dE/dx



D. Primetzhofer, Nucl. Instr. Meth. B (2013)

- Electronic stopping can be obtained with high precision
- Multiple scattering affects low-energy edge of spectrum

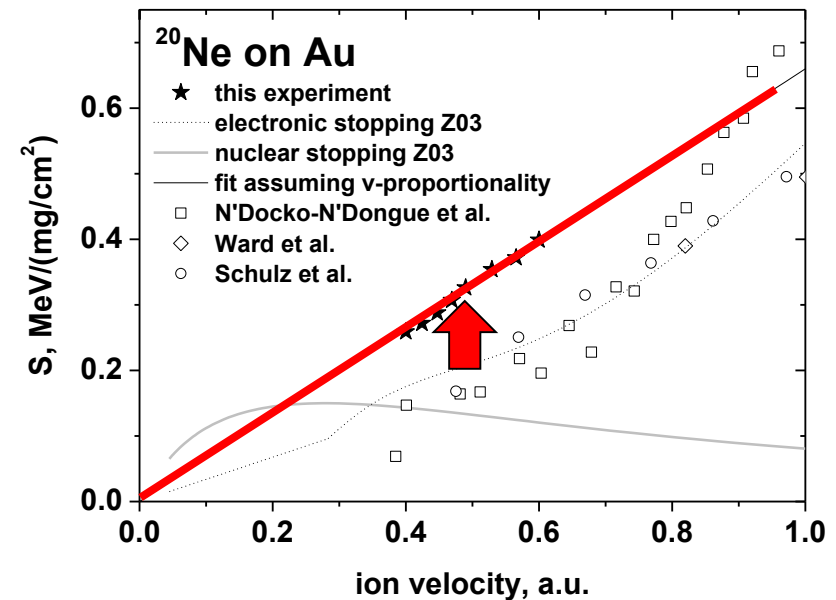
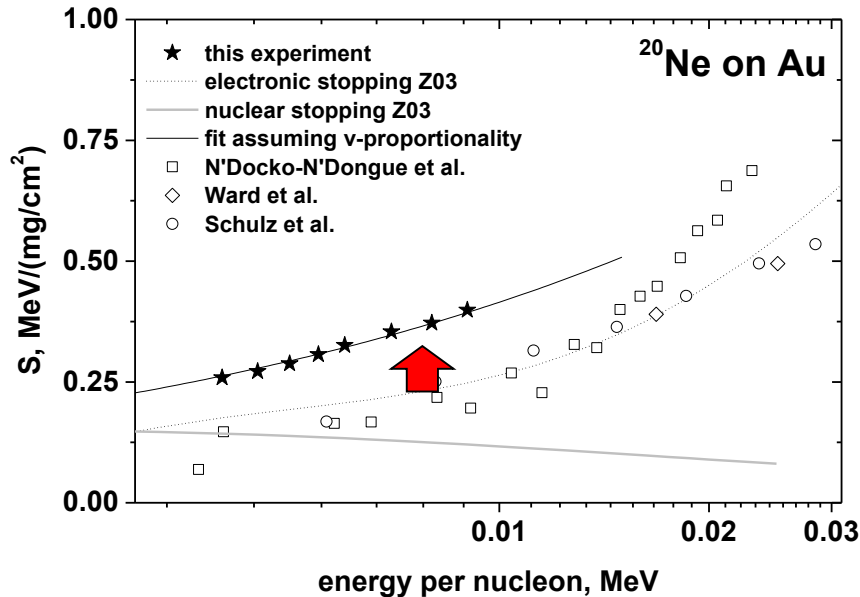
Backscattering of Ne: $d\sigma/d\Omega$



D. Primetzhofer, Nucl. Instr. Meth. B (2013)

- Electronic stopping can be obtained with high precision
- Multiple scattering affects low-energy edge of spectrum
- Spectrum width unaffected by change in potential strength

Experimental stopping powers for ^{20}Ne :

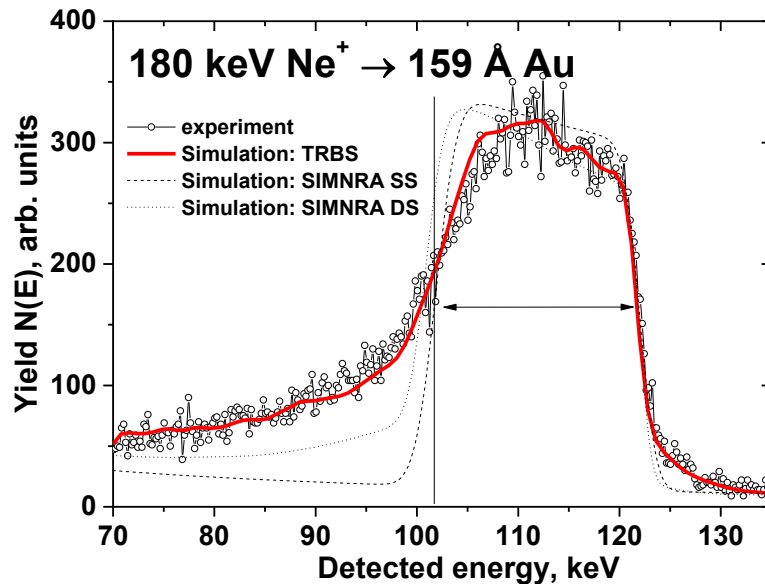


D. Primetzhofer, Nucl. Instr. Meth. B (2013)

- Values deduced in backscattering are exceeding values in transmission
- Velocity proportionality of stopping cross sections



Evaluation by different models:



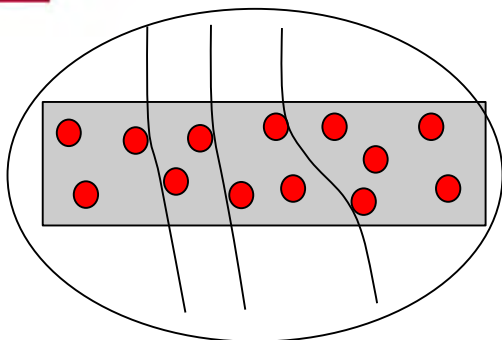
- Single scattering model by SIMNRA
- Dual scattering model by SIMNRA
- Hands-on evaluation (Warter's method)
- MC-simulation by TRBS

→ Almost equivalent results!

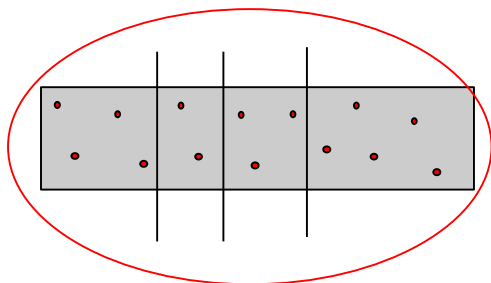
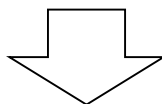
THUS:

- Nuclear stopping contribution to this experiment is apparently small!
- Contribution in transmission is expected to be even smaller!

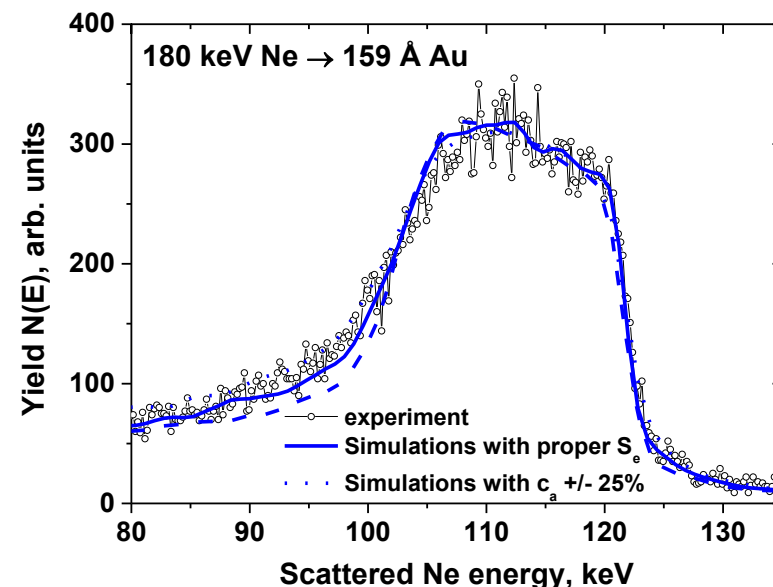
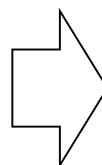
Monte-Carlo: nuclear stopping?



"Realistic" interaction potential $\pm 25\%$



Reducing/turning off
the interaction potential



D. Primetzhofer, Nucl. Instr. Meth. B (2013)

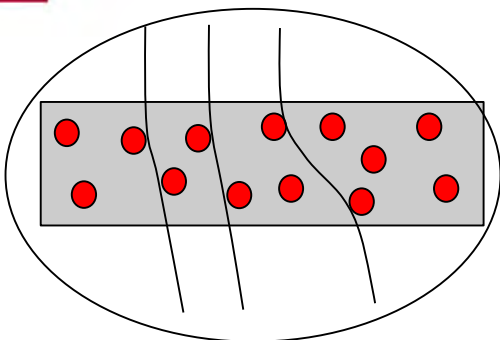
Electronic stopping exclusively...



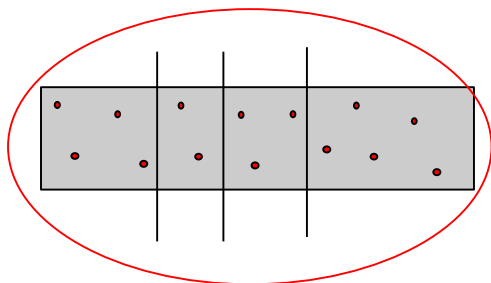
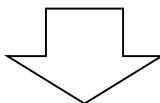
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Monte-Carlo: nuclear stopping?

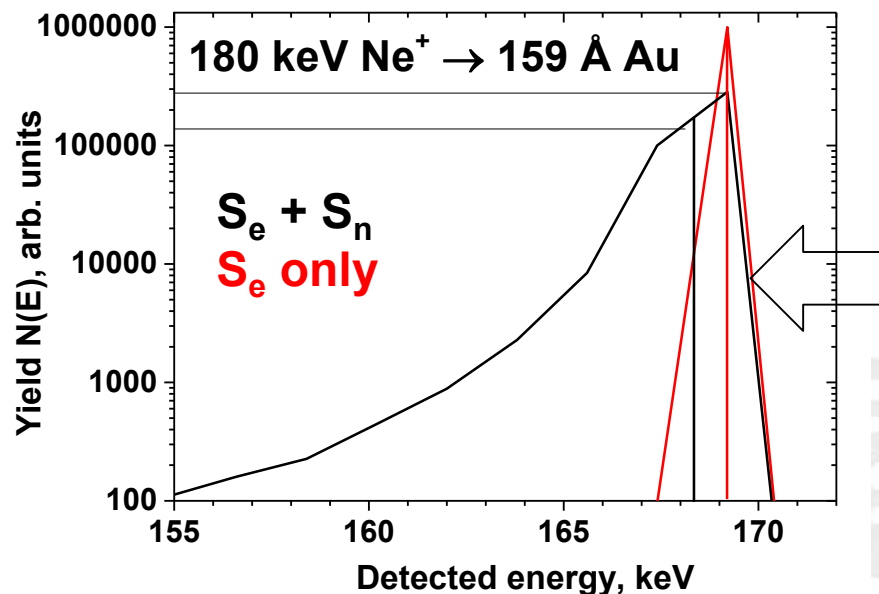
In transmission:



"Realistic" interaction potential +/- 25%



Reducing/turning off
the interaction potential

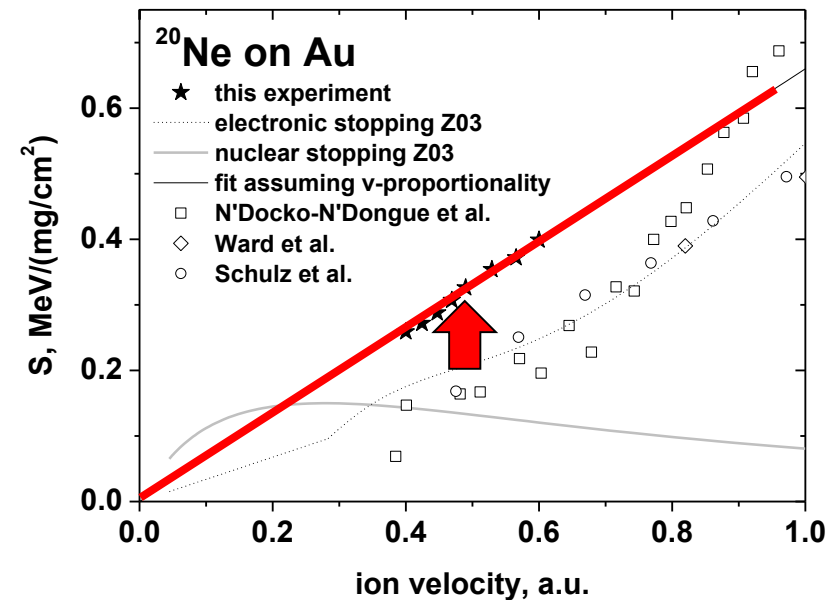
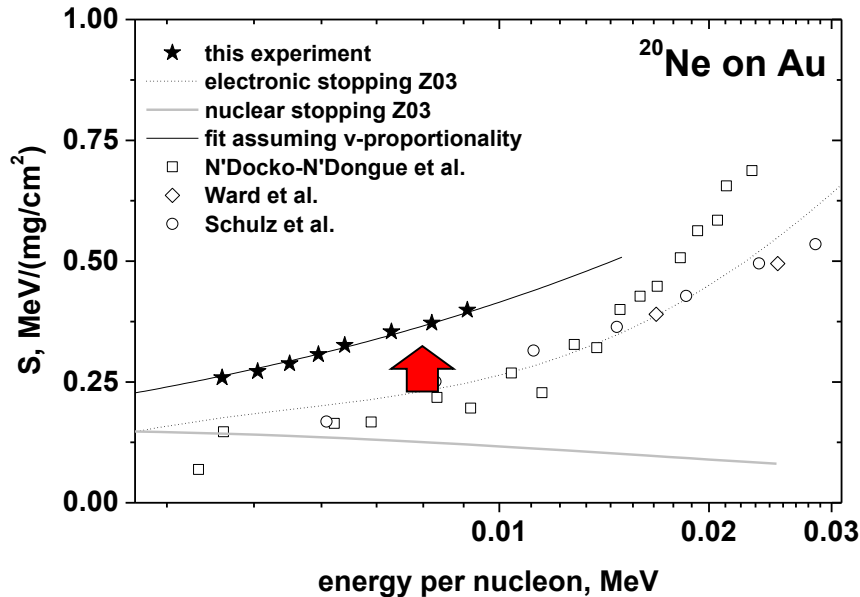


- Electronic stopping shifts spectrum
- Broadening due to nuclear stopping

BUT: only minor shift of median

$$S_{\text{nucl}} < S_{\text{elec}}/10$$

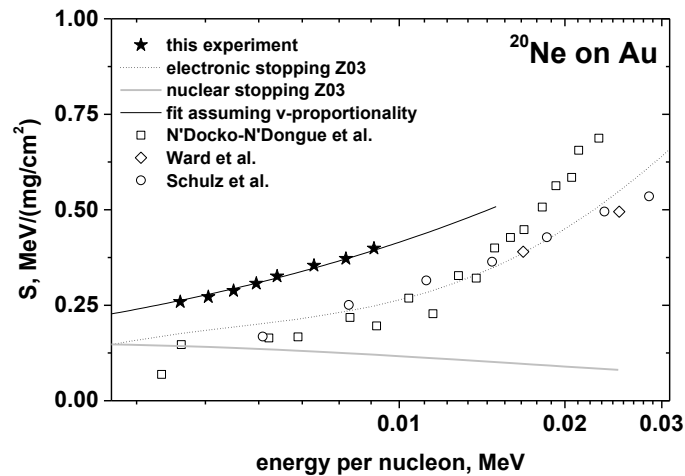
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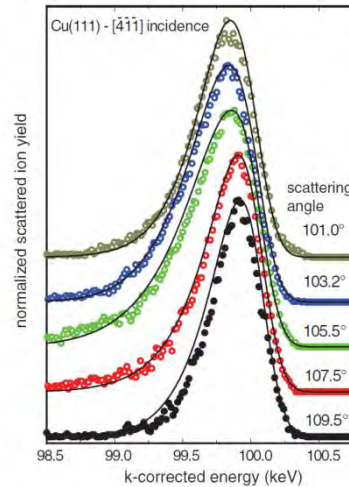
D. Primetzhofer, Nucl. Instr. Meth. B (2013)

- Values deduced in backscattering are exceeding values in transmission
- Velocity proportionality of stopping cross sections

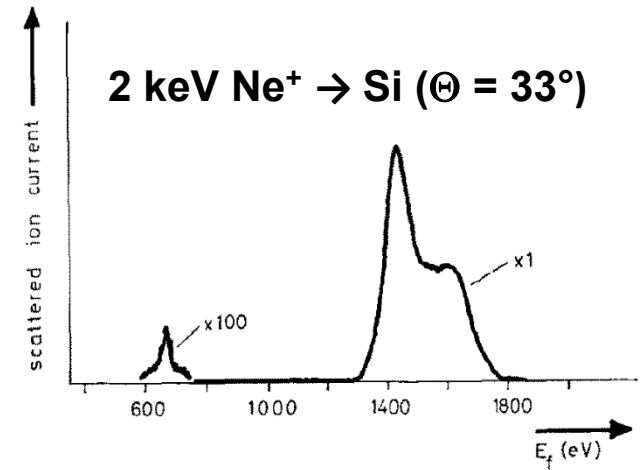
Experimental data - revisited:



D. Primetzhofer, Nucl. Instr. Meth. B (2013)



A. Hentz et al., PRL (2009)



H.H. Brongersma et al., Surf. Sci. (1973)

Enhanced electronic stopping:

- Different impact parameters: backscattering vs. transmission
- Different charge state distribution: backscattering vs. transmission

Other systems: Pt, Ag

- **Platinum results compare well with Au
similar electronic structure – similar kinematics**
- **Silver: very different scattering kinematics**



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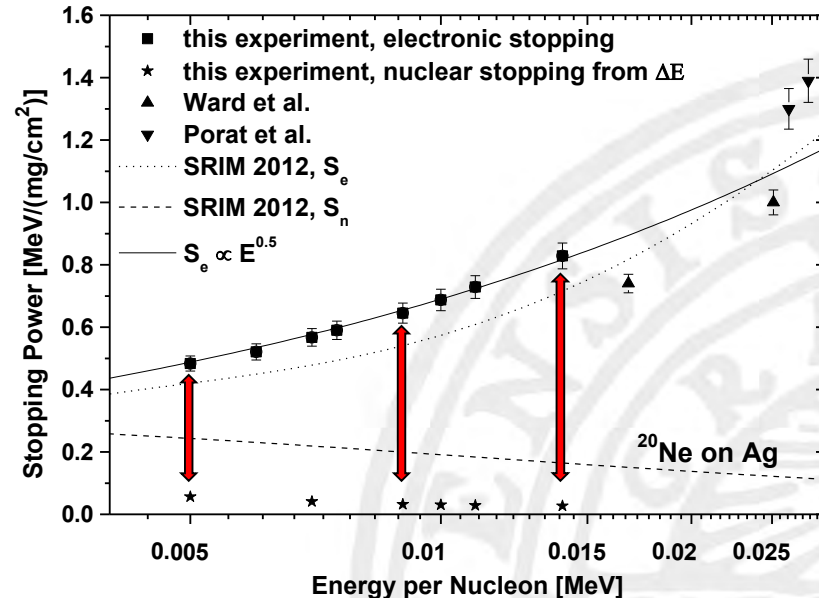
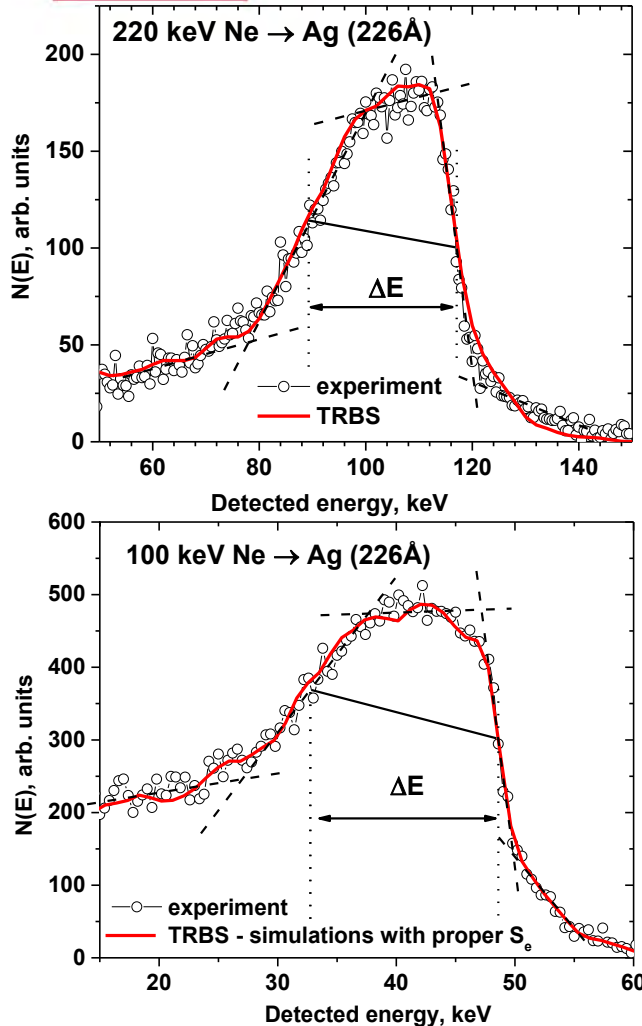
Ne: Evaluating S_n for Ag in backscattering

Assumption 1: MC works correct

$$\Delta E = \Delta E_{elec.(TRBS)} + \Delta E_{nuclear}$$

Assumption 2: S_n scales as in SRIM

$$\Delta E_{nuclear} = k \cdot \chi \cdot S_n^{in} + \frac{\chi}{\cos \theta} \cdot (c \cdot S_n^{in})$$



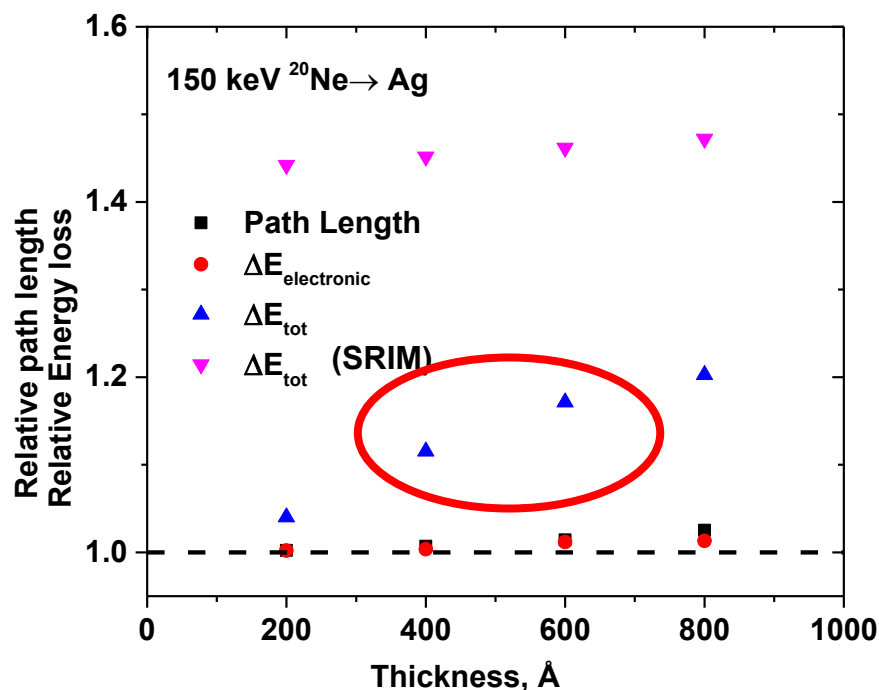
Naqvi et al. Nucl. Instr. Meth. B (2016)

S_n is only about 15% of S_e in this experiment



Comparing with transmission (MC)

TRIM: Transmission - exit angle 0 – 2 deg.



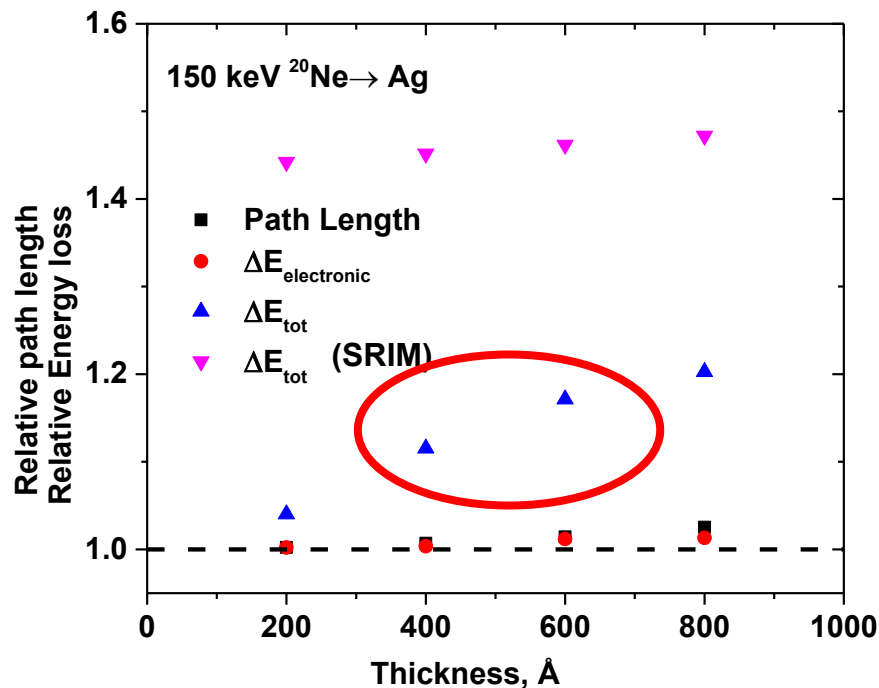
- Path length grows only slightly relative to thickness x .
- Electronic energy loss grows in accordance with path length
- Total energy loss shows increasing nuclear contribution.

Naqvi et al. Nucl.Instr. Meth. B (2016)

Almost identical nuclear contribution of about 10-15% for relevant thickness

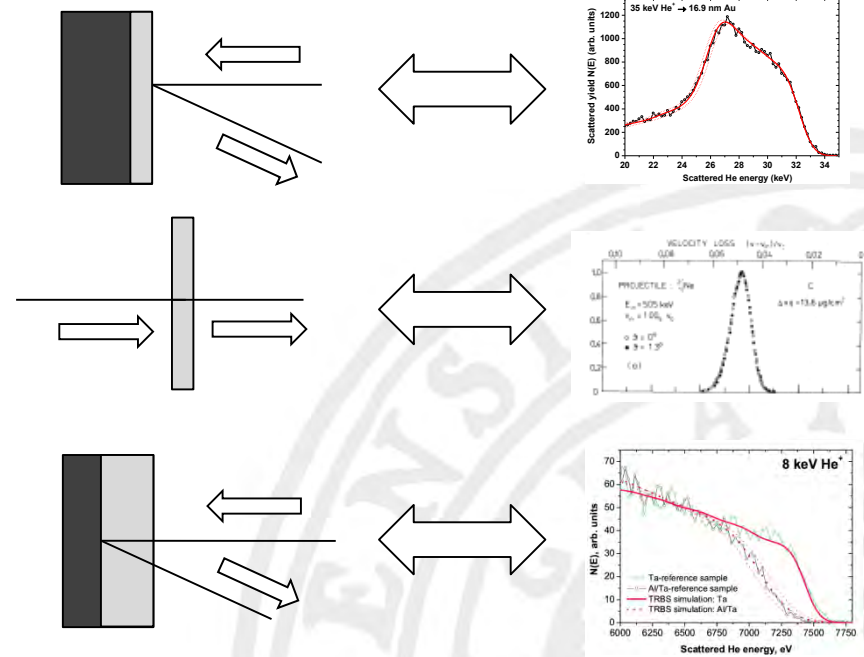
Comparing with transmission (MC)

TRIM - Transmission



Naqvi et al. Nucl.Instr. Meth. B (2016)

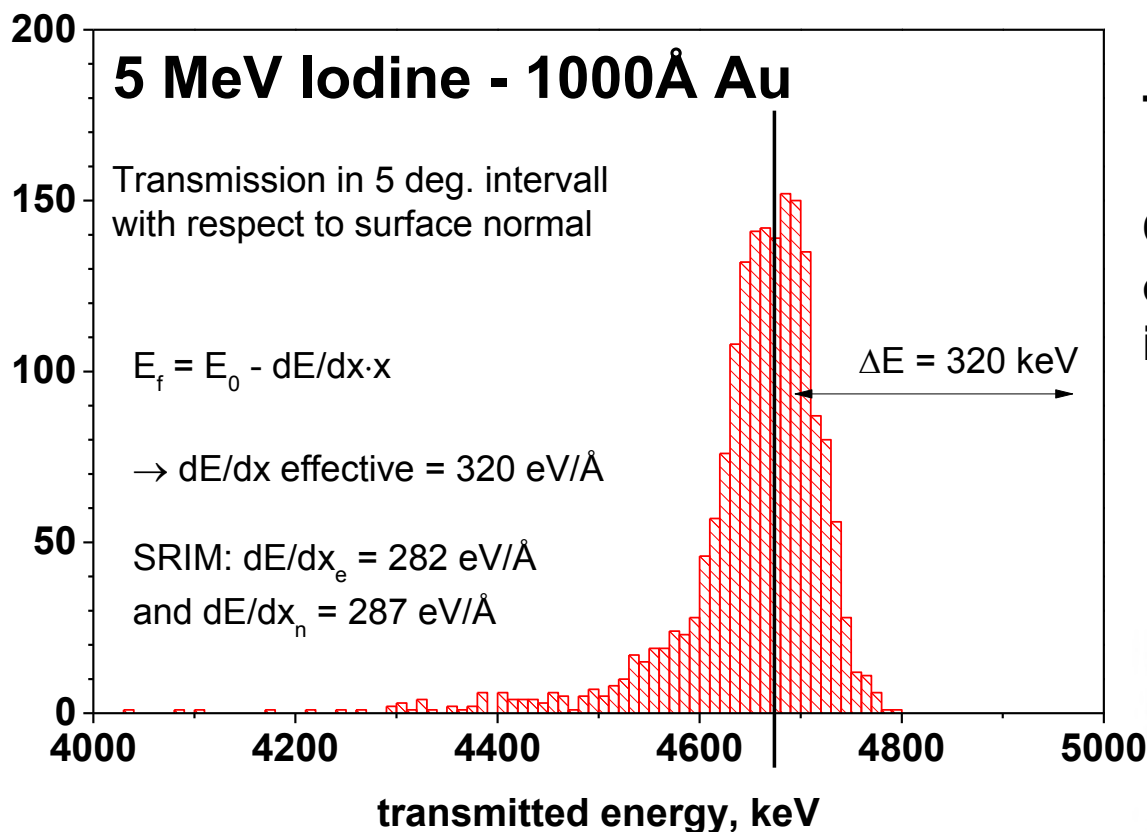
Any experiment is trajectory selective...



...when looking on characteristic spectral features!

Applicable for even heavier ions?

- MeV ions like Bromine, Iodine employed in ERD

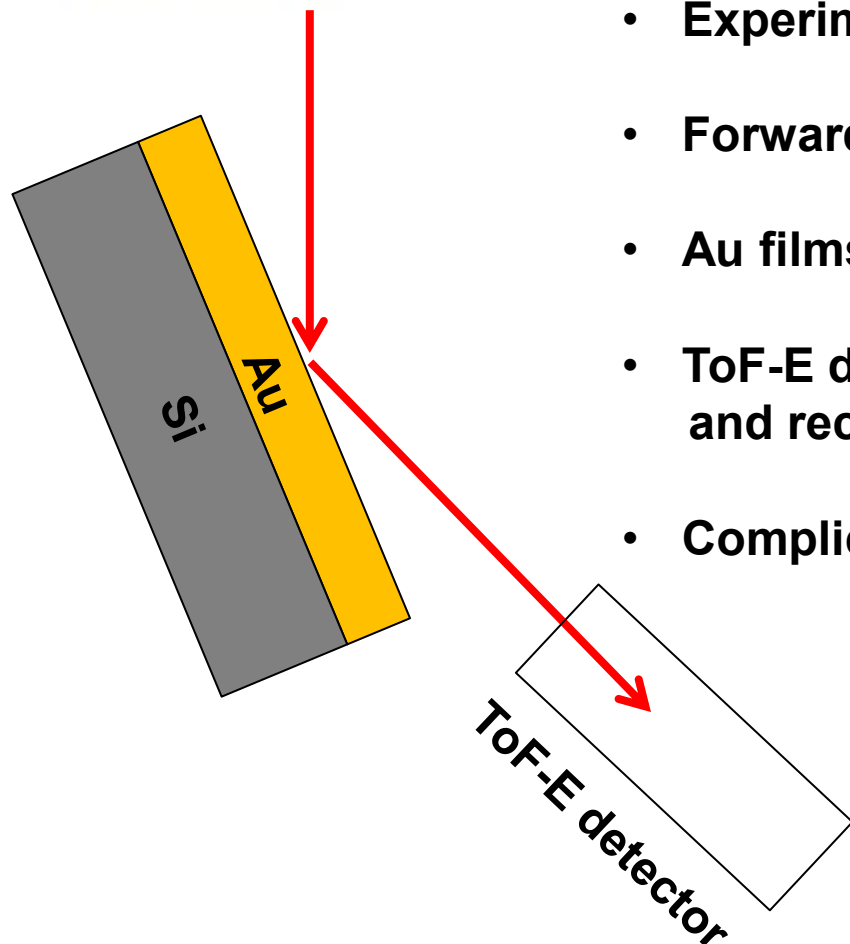


TRIM-simulations:

Only very minor contribution
of dE/dx_n for films
in transmission

What do we see
experimentally?

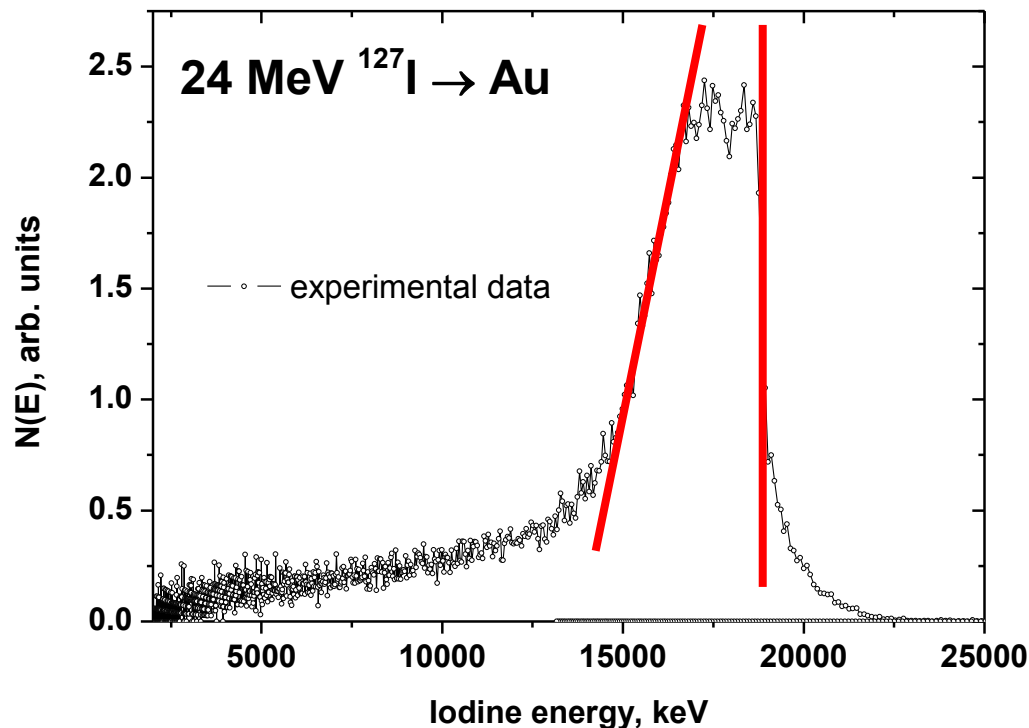
Forward scattering of Iodine



- Experiment performed with 5 MV NEC Tandem
- Forward scattering under 45 degrees
- Au films of up to 50 nm thickness
- ToF-E detector for discrimination of scattered and recoiling particles
- Complication: no 2π -symmetry (simulations)



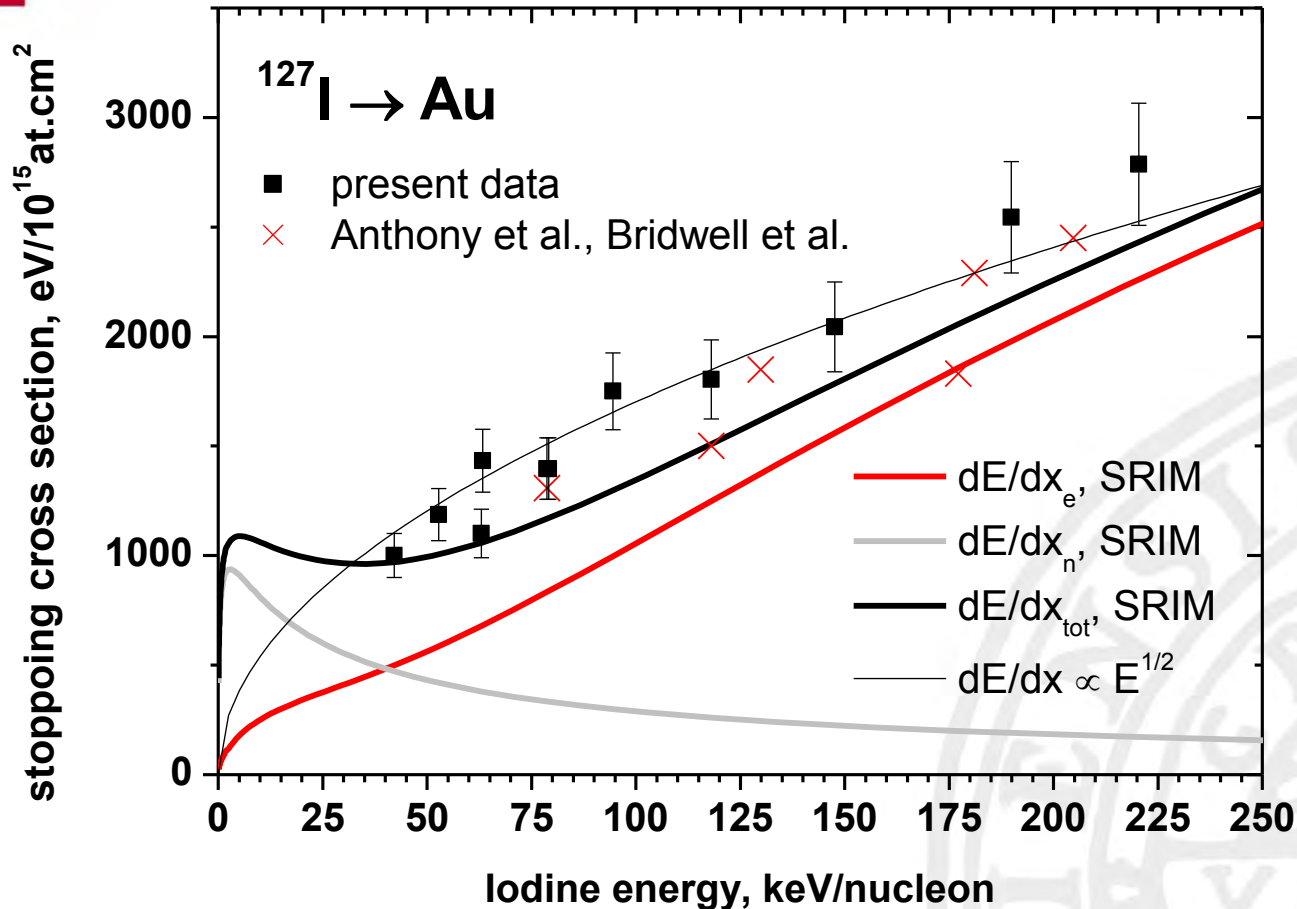
Forward scattering of Iodine: spectra



- Spectra resemble RBS-spectra for thin films
- Reasonable definition of ΔE
- Stopping power evaluation performed as for Ne



Total stopping power deduced for I in Au

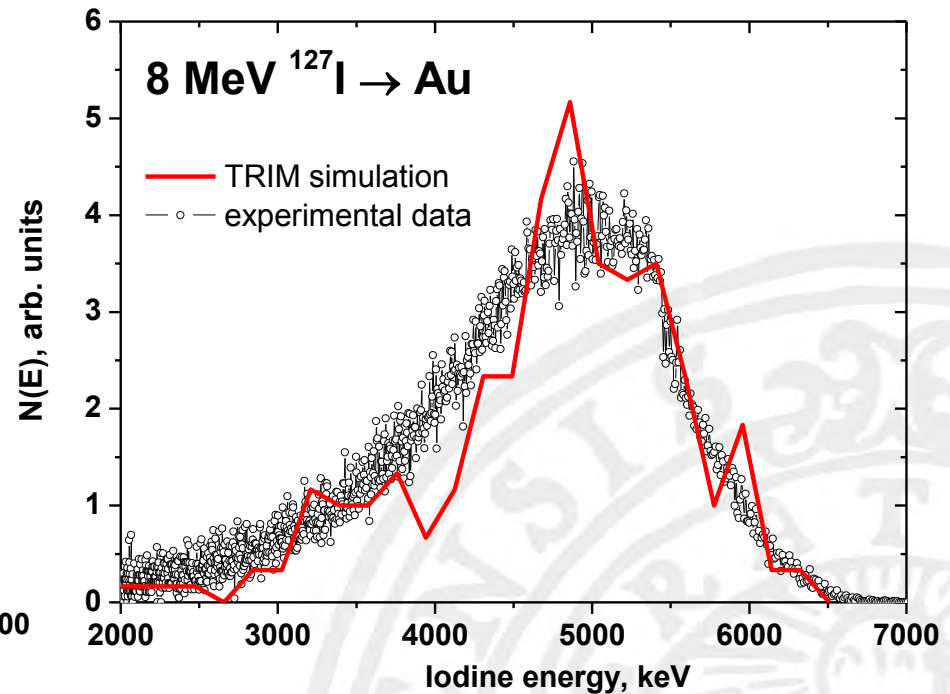
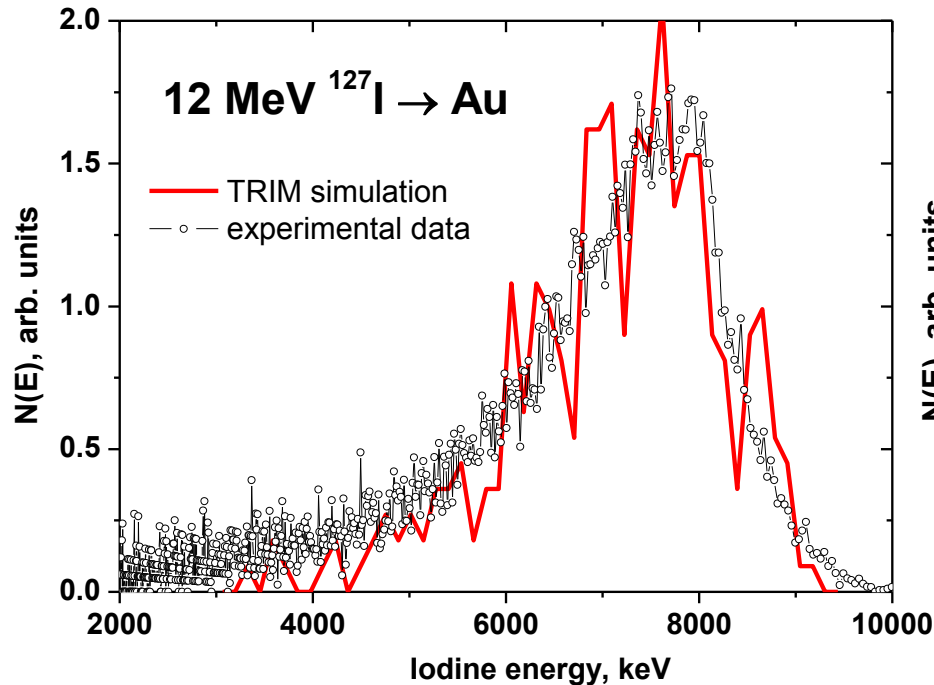


- High absolute total stopping power with reasonable v/E scaling



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Future steps: simulation by TRIM and evaluation of the relative contributions

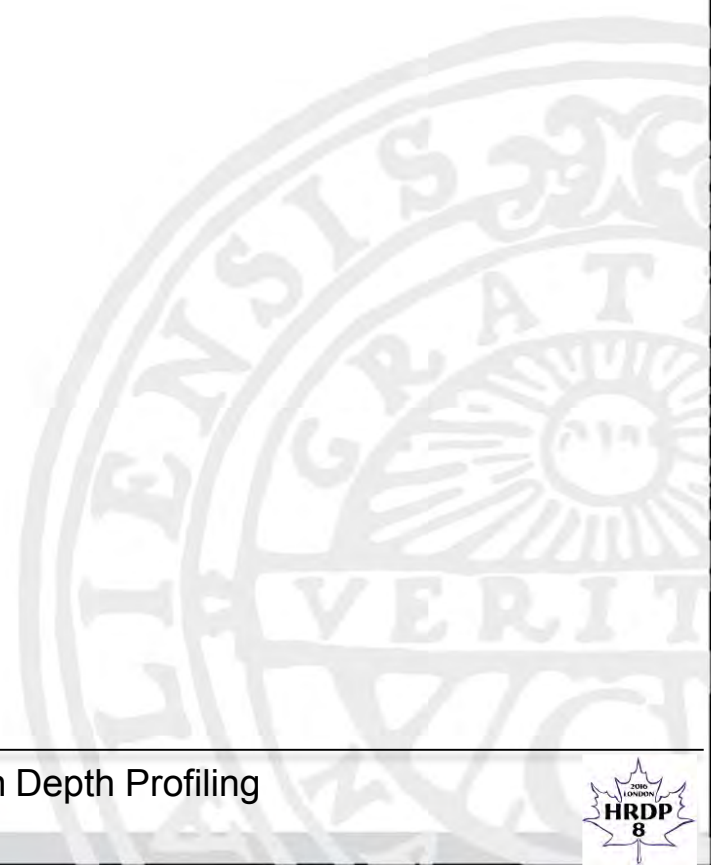


1. Simulation by TRIM
2. Characterization of trajectories: separate dE/dx_e and dE/dx_n



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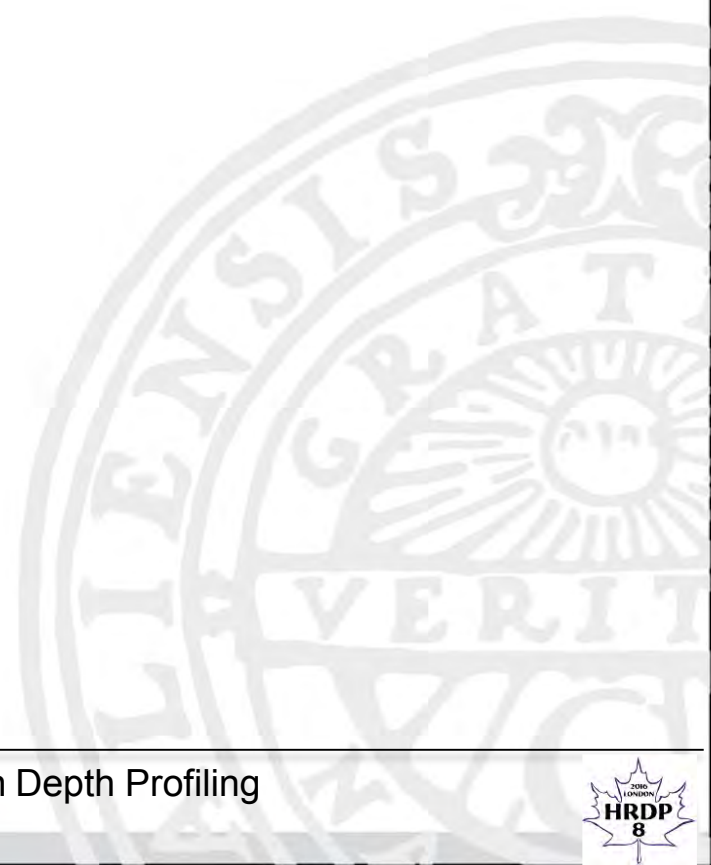
Energy loss of light ions: H and He



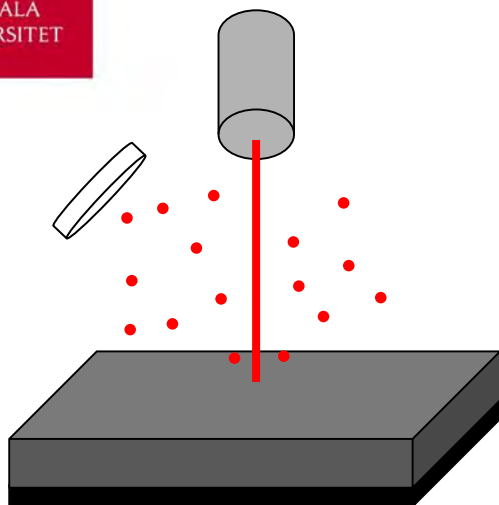


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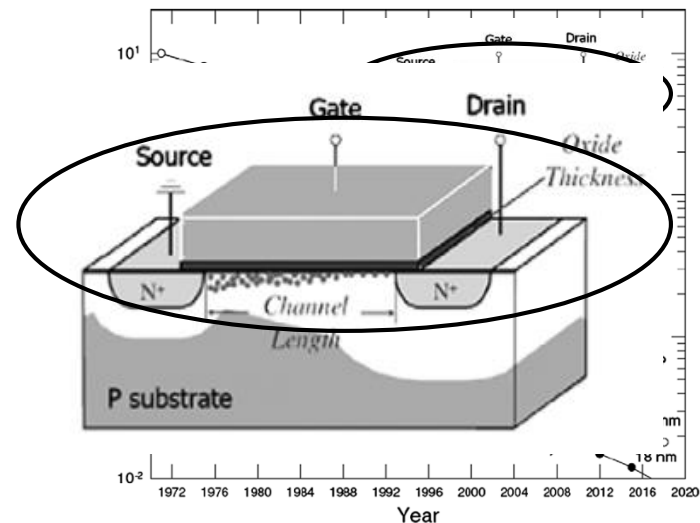
Energy loss of light ions: H and He in HfO₂



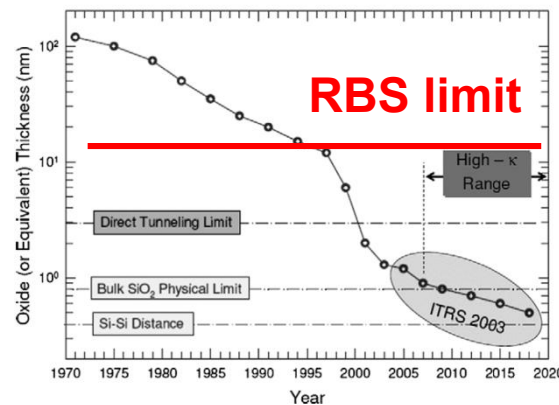
Why HfO₂ at keV energies?



- Ion scattering for depth profiling
- Thin films from e.g. electronics (gate-stacks)
- 90's: Ongoing miniaturization: Film thickness below resolution limits for "conventional" RBS
- Last decade: high-k materials – good scatterers
- Higher $\Delta E/E$: → development of MEIS



H. Wong, H. Iwei, Microelec. Eng. (2006)



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NIM B
Beam Interactions
with Materials & Atoms

applied
surface science



...a MEIS-success story...



Cross characterization of ultrathin interlayers in HfO_2 -high-k stacks by angle resolved x-ray photoelectron spectroscopy, medium energy ion scattering, and grazing incidence extreme ultraviolet reflectometry

Matias Barysh^{a,b} and Larissa Juschkina^a
^aRWTH Aachen University, Chair for Technology of Optical Systems, Steinbachstr. 55, 52074 Aachen, Germany and ^bJARA-Fundamentals of Future Information Technology, Research Centre, Jülich 32425, Germany

Eric Bersch, Daniel Franca, Michael Liehr, and Alain Diebold
 College of Nanoscale Science and Engineering (CNSE), 255 Fuller Rd., Albany, New York, 12203
 (Received 29 July 2011; accepted 26 April 2012; published 21 May 2012)

In order to miniaturize metal oxide semiconductor field effect transistors even further and improve their performance, channel lengths and gate dielectric thicknesses must be decreased. Traditionally,



Nuclear Instruments and Methods in Physics Research B 303 (2011) 146–153

High-resolution depth profiling of ultrathin gate oxide by medium-energy ion scattering

T. Gustafsson^a, H.-C. Lu, B.W. Busch, W.H. Schulte, E. G.

^aDepartment of Physics and Chemistry, and Laboratory for Surface Modification, Rensselaer State University, Troy, New York 12180, USA

Received 31 October 2009

Research
 Received 18 Aug
 (www.interscience)

A co-specimen
 HF-b

L. Sygel
 and S. I.

1. Introduction

Medium-energy ion scattering (MEIS) is a complicated and expensive analysis method. It

Ultra-thin high-k layers based on HfO_2 or Hf -silicates in combination with Si-compatible gate dielectrics. XPS has been applied on a range before and after decoupled plasma nitridation (DPN) at 1073 K. The true individual layer thicknesses of the multilayer stack taking into account the procedure adhered to the prescriptions of ISO18118:2004(E) for elastic corrections thereof, using film material properties, like density were taken throughout as 90% of the respective IMFP, whereas an (RSP) was used. The XPS-derived thicknesses were compared with cor scattering (MEIS) measurements on the same series of specimens in order to quantify layer information with sub-nanometer resolution. The XPS deduced layer structures within the respective experimental uncertainty layer parameters of the high-k nanofilms. Copyright © 2010 John Wiley & Sons, Ltd.

Keywords: high-k nanofilms; HfO_2 /hafnium silicate; XPS; MEIS; layer thickness

Introduction

Significant research effort has been recently directed toward replacing the conventional SiO_2 nanofilms with ultra-thin high-k layers based on HfO_2 or Hf -silicates, in combination with sub-

discrete as well as below; obtained; within the ARPA project on the same series of samples.²⁶



High resolution medium energy ion scattering analysis for the quantitative depth profiling of ultrathin high-k layers

M. A. Reading^{a,b}, J. A. van den Berg, P. C. Zalm, and D. G. Armour
^aInstitute for Materials Research, University of Suffolk, Suffolk IP5 4WY, United Kingdom
^bP. Bailey and T. C. O. Noakes
 STFC Daresbury Laboratory, Daresbury W44 4AF, United Kingdom

Received 10 October 2009; accepted 1 March 2010

High resolution medium energy ion scattering (MEIS) analysis for the quantitative depth profiling of ultrathin high-k layers

High resolution medium energy ion scattering (MEIS) analysis for the quantitative depth profiling of ultrathin high-k layers

Applied Surface Science 253 (2009) 1591–1594

Contents lists available at ScienceDirect

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Journal homepage: www.elsevier.com/locate/apusci



APPLIED PHYSICS LETTERS

VOLUME 91, NUMBER 14

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Characterization and control of the $\text{HfO}_2/\text{Si}(001)$ interfaces

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^aDepartment of Physics, Kansai University, Suita-shi, Osaka 565-0871, Japan
 K. Yamamoto, S. Hayashi, and M. Niwa
 Matsushita Electric Industrial Co., Ltd., Nishikigyo-Kaigakicho, Atsuta-ku, Kyoto 601-8413, Japan
 (Received 14 June 2007; accepted 6 August 2007)

The $\text{HfO}_2/\text{Si}(001)$ interfaces formed by reactive dc sputter deposition of Hf buffer layer followed by HfO_2 stacking were analyzed by high-resolution transmission electron microscopy, medium energy ion scattering (MEIS), and photoelectron spectroscopy using synchrotron-radiation light. The present MEIS analysis determined the elemental depth profiles and revealed that no Hf buffer layer resulted in growth of SiO_2 at the interface, and that the presence of the Hf layer led to the formation of Si-rich silicate-like interlayers. The binding energy shifts of $\text{Si} 2p_{3/2}$ identified the chemical bonds of the interfacial layers and confirmed the formation of SiO_2 (no buffer layer) and silicate layers (presence of the buffer layers) at the interfaces. The Hf-buffer layer suppresses the O diffusion toward the interface and thus the thicker the buffer layer, the thinner the Hf-silicate interlayer. The deposition conditions of HfO_2 (1.3 nm/Hf (1.3 nm) has achieved the highest permittivity of 28 for HfO_2 (3.6 nm) and 8 for the silicate layer (1.7 nm). © 2007 American Institute of Physics [DOI: 10.1063/1.2710941]

High-k dielectric metal oxide films have attracted much attention as promising candidates for the forthcoming gate dielectric materials of metal-oxide-silicon field-effect transistors, in place of SiO_2 films. The microelectronics industry requires a high dielectric constant k and a stable and abrupt interface. So far, many efforts have been made to suppress the interfacial layer of SiO_2 and/or silicates.^{1–8} Unfortunately, however, how to control the high-k film/ $\text{Si}(001)$ interface is still unknown.

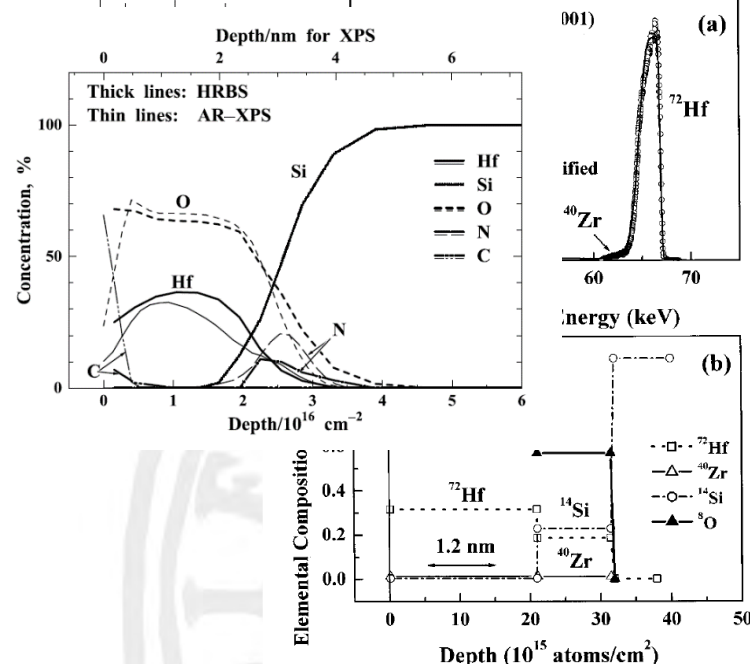
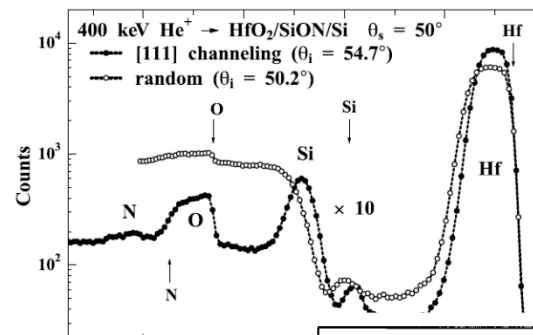
HfO_2 is one of the most suitable materials, because it has a high- k value of about 25 and expected to be stable in within the ARPA project on the same series of samples.²⁶

precise analysis of the chemical bonding of the interlayers, we prepared thin thermal oxides of SiO_2 , HfO_2 , Hf -silicates, and Hf -silicates (HfSi and HfSi_2) as the standards for PES analysis. All the above thin films were grown on $\text{Si}(001)$ substrates. Their elemental compositions and absolute thickness were determined by Rutherford backscattering (RBS) using 7.0 MeV He^+ beams and these RBS data calibrated the MEIS spectra.

The surfaces of on-axis p-type $\text{Si}(001)$ substrates were chemically treated with an HF solution and then annealed at 400 °C for 10 min in N_2 ambient. This procedure is known



and high-resolution RBS analysis of



- Investigations of stacks containing HfO_2 are common





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Appl. Surface Science 203–204 (2003) 418–422

applied
surface science

M. A. Reading,⁽¹⁾ J. A. van den Berg, P. C. Zalm, and D. G. Armour
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I. S. De Gendt
of 75, 3001 Leuven, Belgium

une 2009; accepted 21 September 2009; published 1 March 2010)

layers such as hafnium oxide (HfO_2) in combination with a subnanometer SiO_2 on emerged as Si compatible gate dielectric materials. Medium energy ion scattering is has been carried out on a range of such metal oxide chemical vapor deposition SiO_2 and HfSiO_3 (60% Hf)/ SiO_2 gate oxide films of thickness between 1 and 2 nm on

Applied Surface Science 255 (2008) 1561–1564

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(Received 14 June 2002; accepted 6 August 2002)

The $\text{HfO}_2/\text{SiO}_2$ (stack) interface formed by reactive dry sputter deposition of Hf-buffer layers followed by HfO_2 stacking were analyzed by high-resolution transmission electron microscopy, electron energy loss scattering (EELS), and photoelectron spectroscopy using synchrotron-radiation light. The present EELS analysis determined the elemental depth profiles and revealed that no Hf-buffer layer resulted in growth of the interface. However, the presence of the Hf-buffer led to the formation of a thin silicate layer at the interface. The analysis also showed that the thickness of the chemical bonds of the interfacial layers and confirmed the formation of SiO_2 (no buffer) and silicate layers (presence of the buffer layers) at the interfaces. The Hf-buffer layer suppresses the O diffusion toward the interface and thus the thicker the buffer layer, the thinner the Hf-silicate layer. The thickness of the Hf-silicate layer was 1.1 nm for Hf (1.3 nm) and 1.3 nm for Hf (1.3 nm). The high-resolution photoelectron spectroscopy of 2p (10.6 ± 0.6 eV) and 2s (2.6 eV) of the Hf-buffer layer (1.7 nm) © 2002 American Institute of Physics [DOI: 10.1063/1.1510941]

High- k dielectric metal oxide films have attracted much attention as promising candidates for the forthcoming gate dielectric materials of metal-oxide-silicon field-effect transistors, in place of SiO_2 films. The microelectronics industry requires a high dielectric constant k and a stable and abrupt interface. So far, many efforts have been made to suppress the interfacial layer of SiO_2 and/or silicates.¹⁻⁴ Unfortunately, however, how to control the high- k film/ Si(001) interface is still unknown.

HfO₂ is one of the most suitable materials, because it has a high-*k* value of about 25 and expected to be stable in ANNA project on the same series of samples.^[8]

precise analysis of the chemical bonding of the interlayers, we prepared thin thermal oxides of SiO_2 , HfO_2 , Hf silicates , and Hf silicides (HfSi and HfSi_2) as the standards for PES analysis. All the above thin films were grown on $\text{Si}(001)$ substrates. Their elemental compositions and absolute thickness were determined by Rutherford backscattering (RBS) using 2.0 MeV He^+ beams and these RBS data calibrated the MEIS spectra.

The samples of on-axis *p*-type Si(001) substrates were chemically treated with an HF solution and then annealed at 400°C for 20 min in an NH_3 ambient. This resulted in forming

the depth expected to be BS as the thickness, $\text{O}_2/\text{SiO}_2/\text{Si}$ isolates the layer from



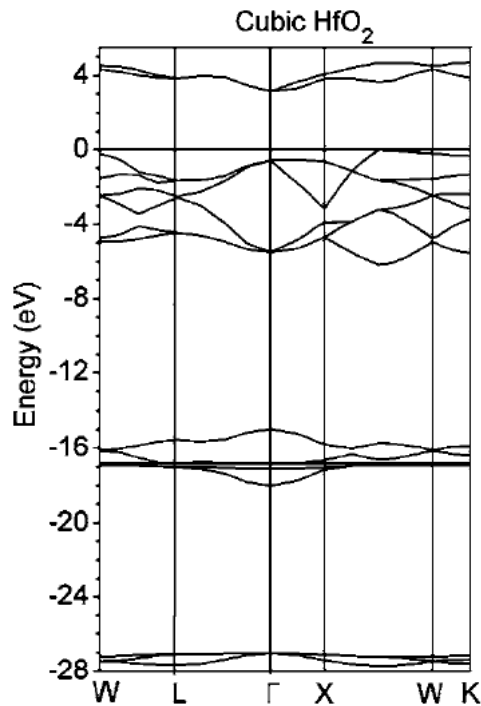
- **Experimental stopping data is scarce**



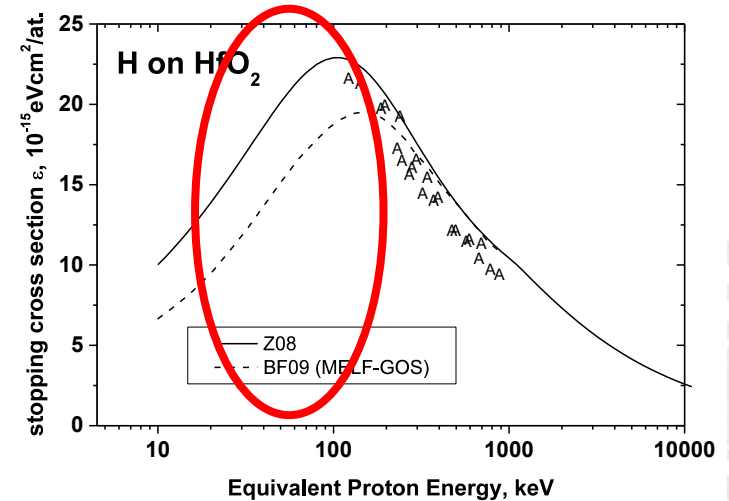
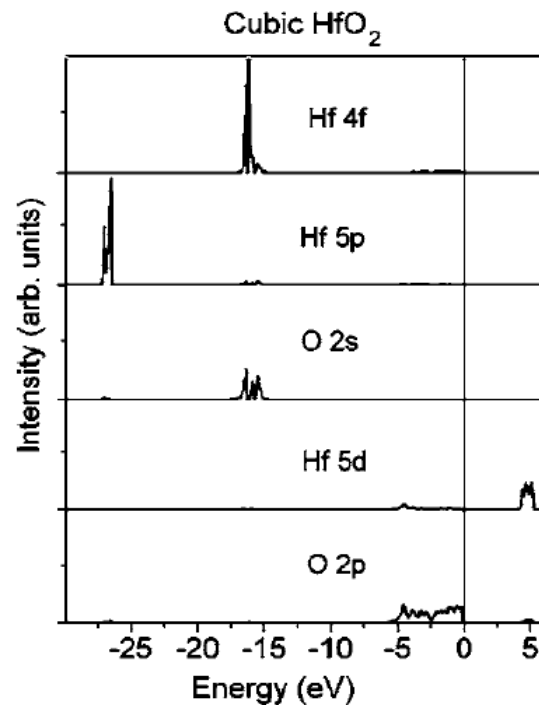


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...with open fundamental questions.



T.V. Perevalov et al., J. Appl. Phys. (2007)



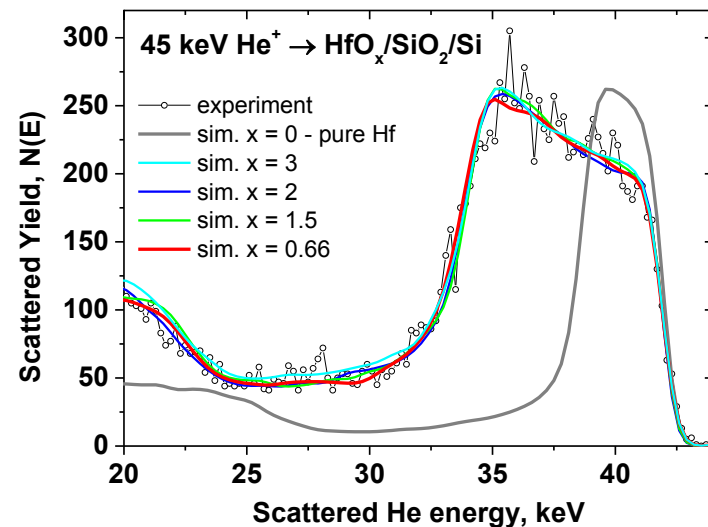
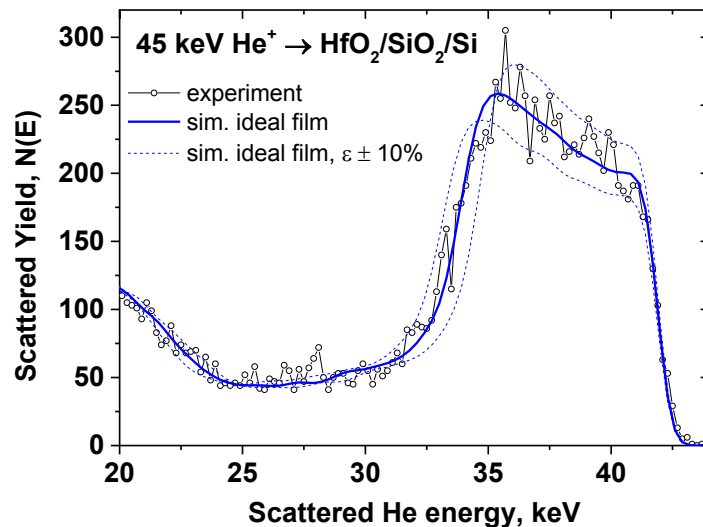
from H. Pauls stopping collection:
www-nds.iaea.org/stoppinggraphs/

- Experimental stopping data is scarce
- Insulator with $\sim 5\text{-}6$ eV gap

Relevance for analysis of thin films

Potential complications:

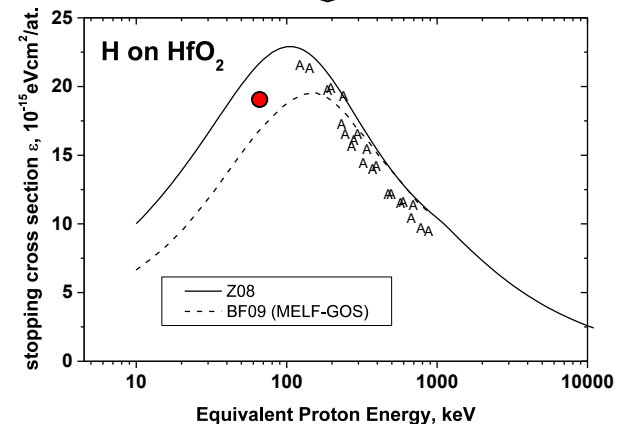
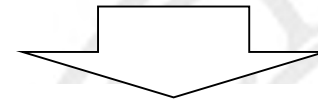
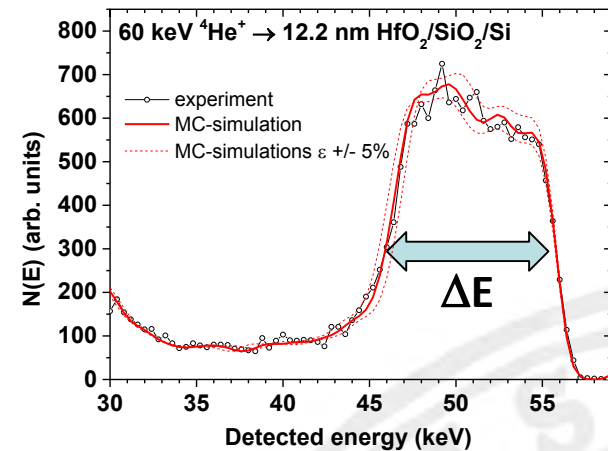
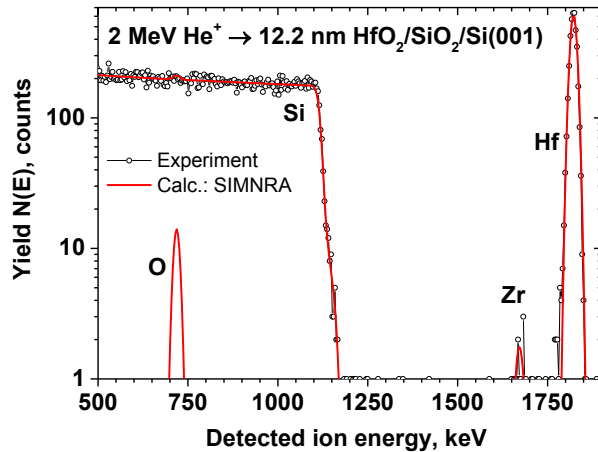
- Energy loss in the thin film ↔ Thickness calibration in MEIS
- Entanglement of compositional information and energy loss



D. Primetzhofer et al., Nucl. Instr. Meth. B 332 (2014)

Analysis of electronic energy loss in HfO_2

- Fit width of ToF-MEIS energy spectra



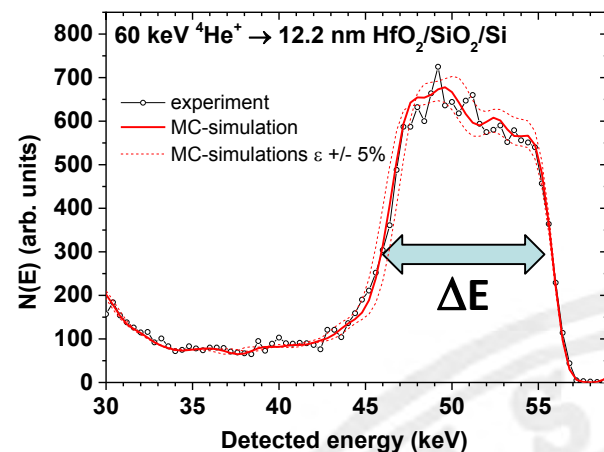
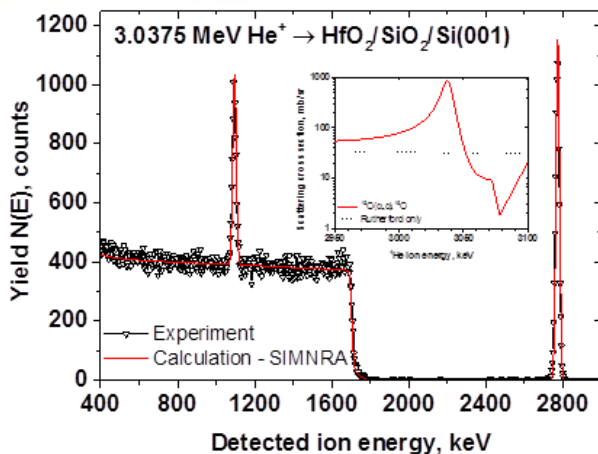
- Determine Hf content from RBS

Uncertainty from:

- Statistics
- Thickness calibration
- Composition

Analysis of electronic energy loss in HfO_2

- Fit width of ToF-MEIS energy spectra

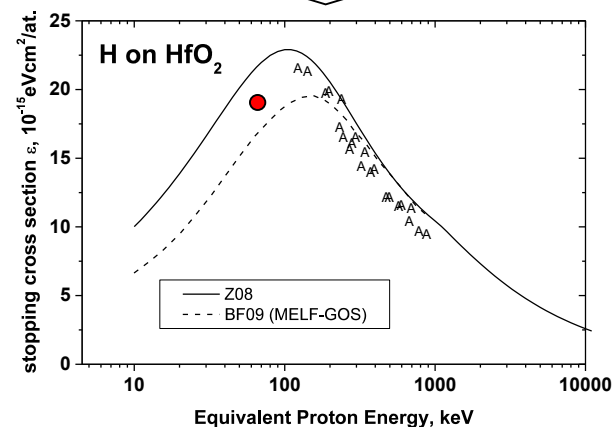


C.J. Zoller, *Nucl. Instr. Meth. B* 347 (2015)

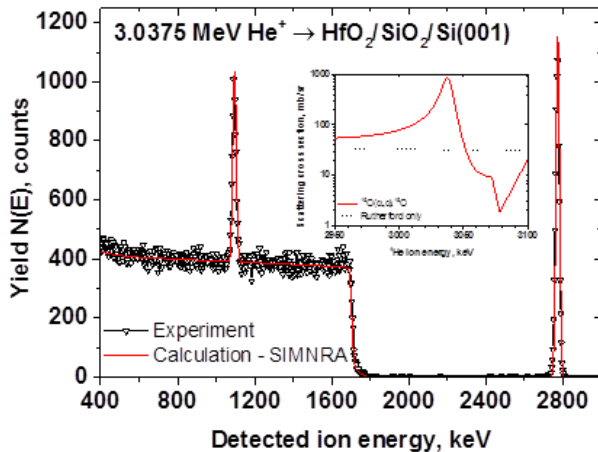
- Determine Hf content from RBS (check oxygen by e.g. EBS, channeling,...)

Uncertainty from:

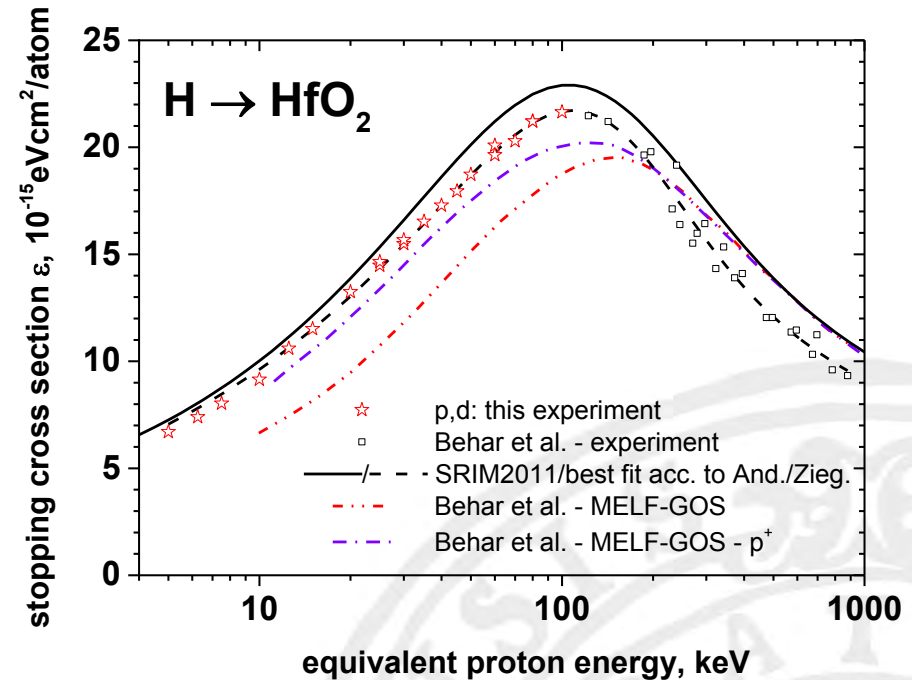
- Statistics
- Thickness calibration
- ~~Composition~~



Analysis of electronic energy loss in HfO_2



C.J. Zoller, *Nucl. Instr. Meth. B* 347 (2015)



D. Primetzhofer, *Nucl., Instr. Meth. B* 320 (2014)

- Determine Hf content from RBS

Uncertainty from:

- Statistics
- Thickness calibration
- ~~Composition~~

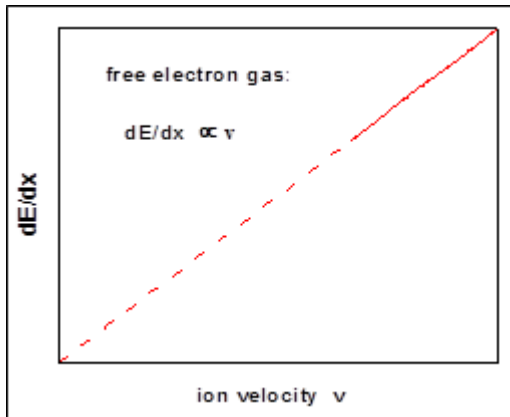
- Very good agreement with data of Behar et al.
 - $S \propto E^{1/2}$ down to 5keV/u.



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Analysis of electronic energy loss in HfO_2

Theory:



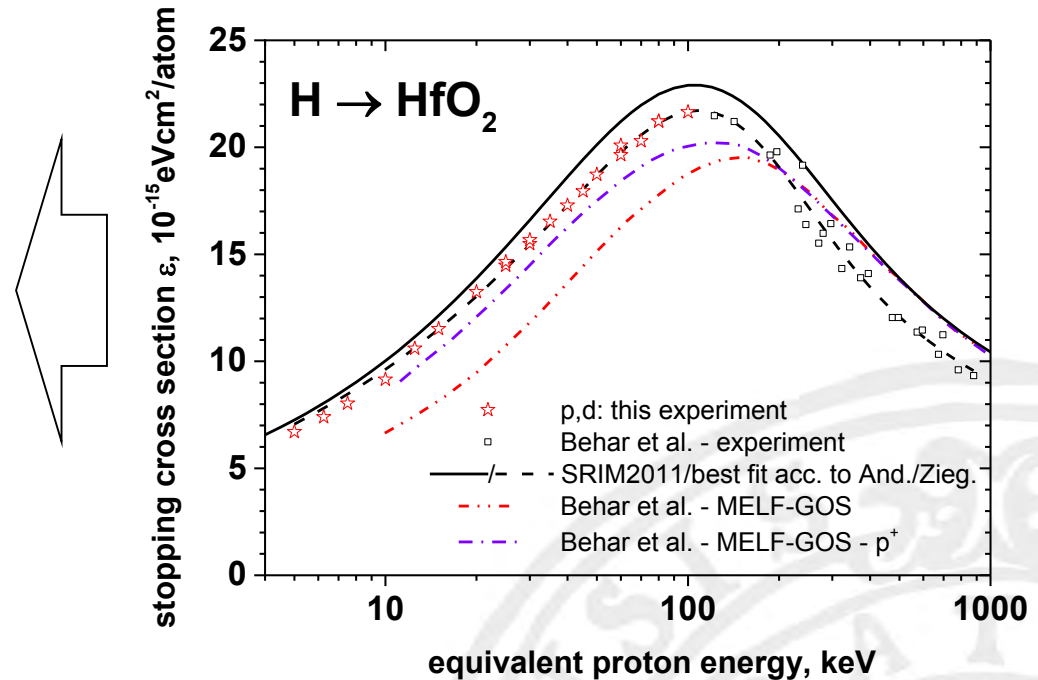
Fermi et al. Phys. Rev. (1947)

$$dE/dx = Q(r_s, \dots) \cdot v$$

$$\Delta E_{\max} \leq 2 \cdot m_e \cdot v \cdot v_F$$

**Maximum energy transfer
+ Excitation limits**

Effects on stopping

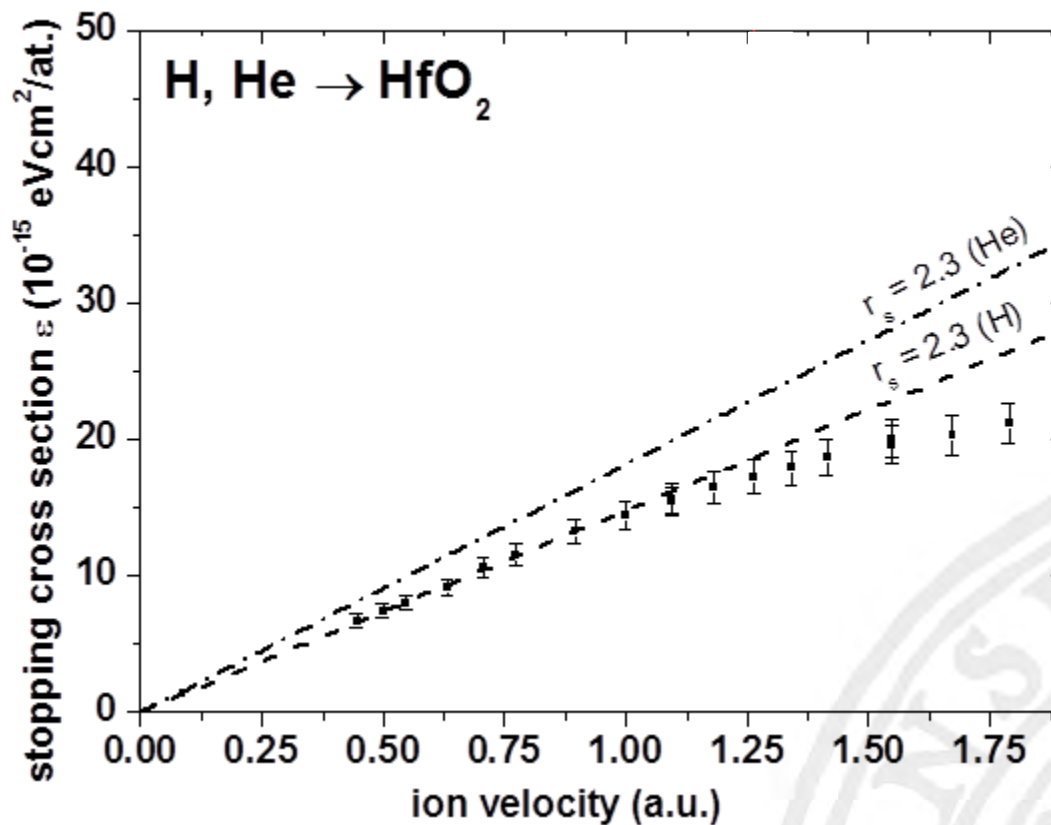


D. Primetzhofer, Nucl., Instr. Meth. B 320 (2014)

- Very good agreement with data of Behar et al.
- $S \propto E^{1/2}$ down to 5keV/u.

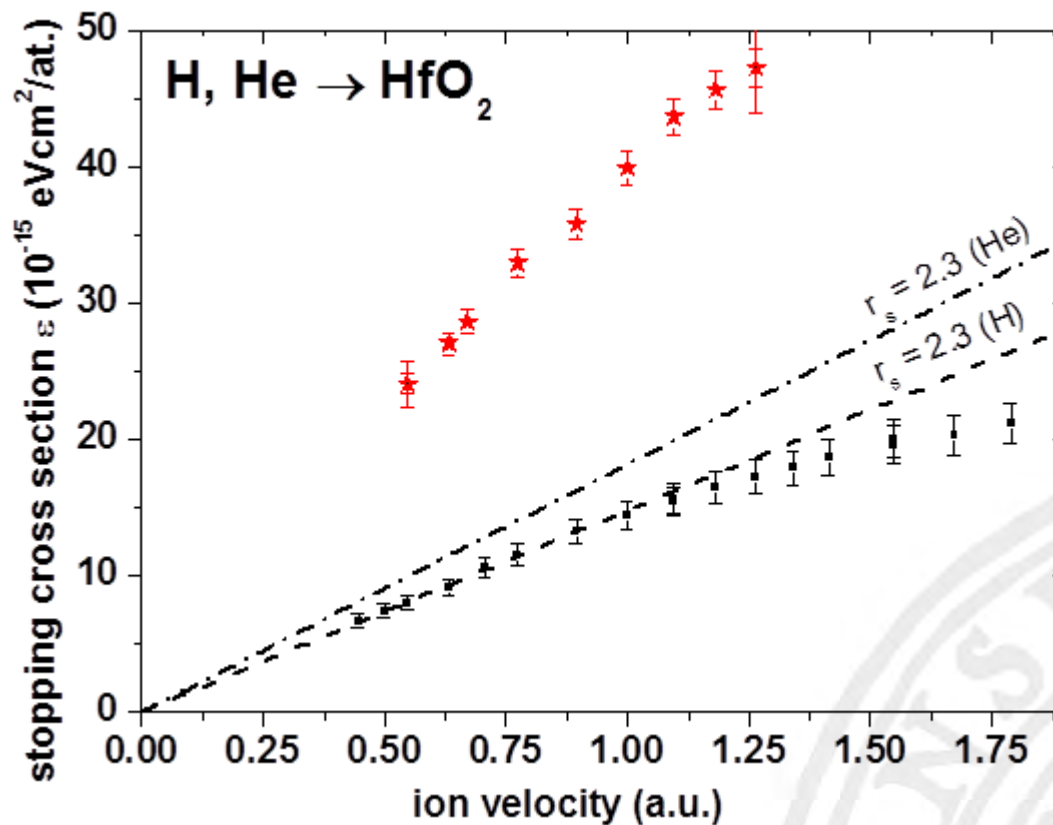


Electronic stopping in HfO_2 : He





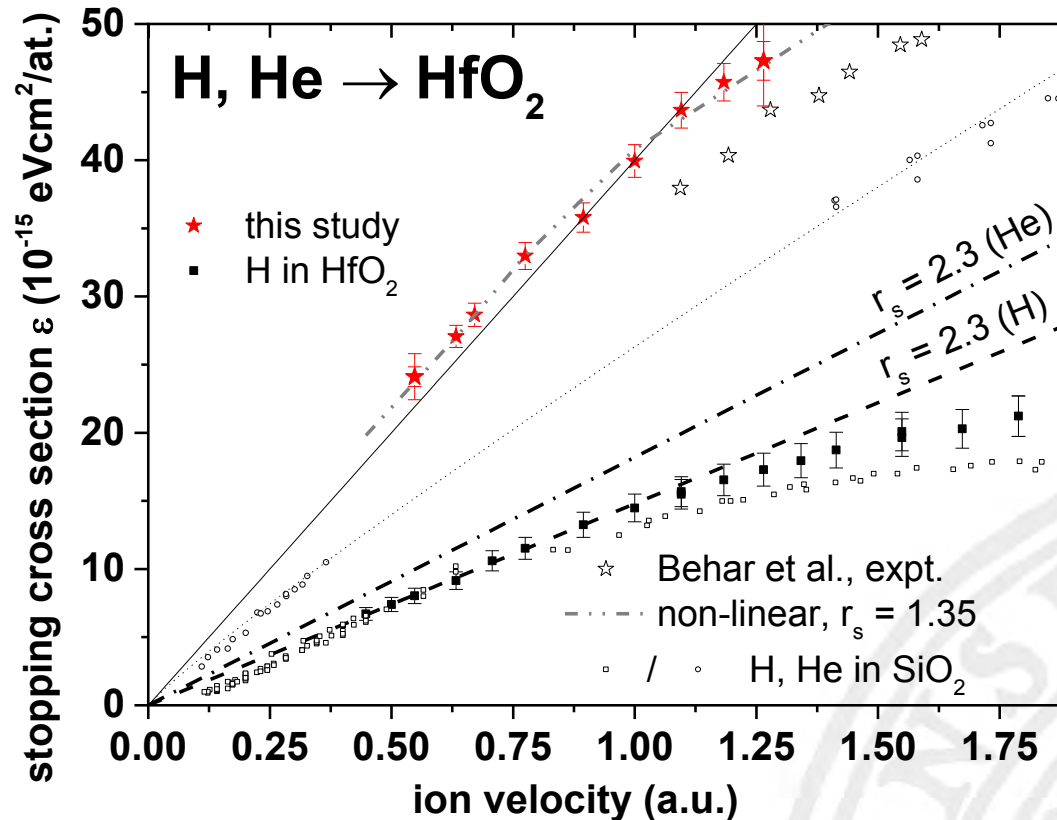
Electronic stopping in HfO_2 : He



- Totally different electron density in DFT-models necessary



Electronic stopping in HfO_2 : He



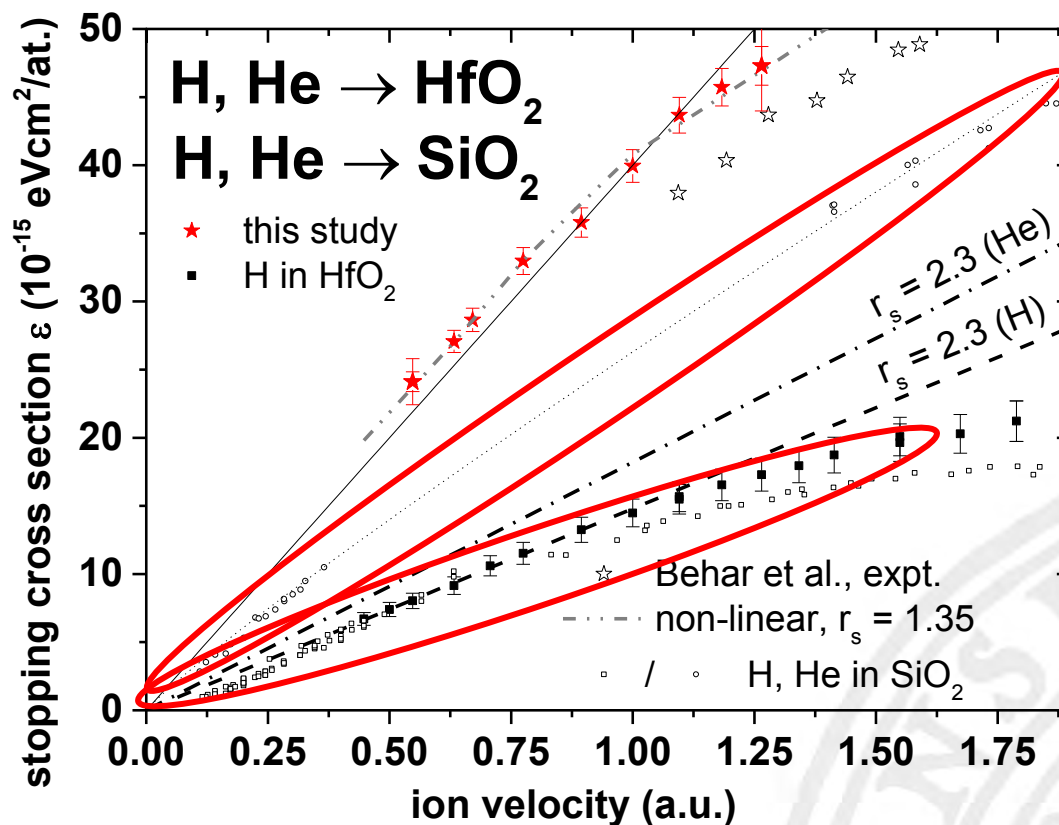
D. Primetzhofer, Phys. Rev A 89 (2014)

- Totally different electron density in DFT-models necessary
- Energy loss shows a non-linear behaviour!



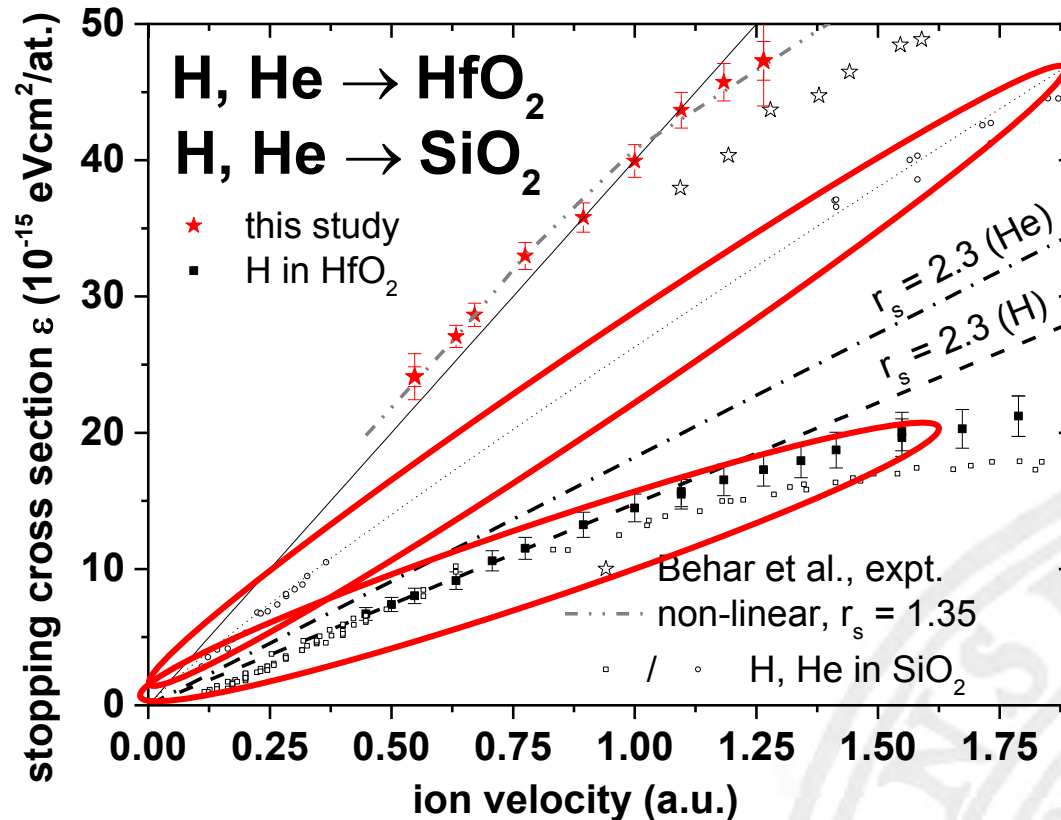
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Comparison: SiO_2 vs. HfO_2 : He



D. Primetzhofer, Phys. Rev A 89 (2014)

Comparison: SiO_2 vs. HfO_2 : He

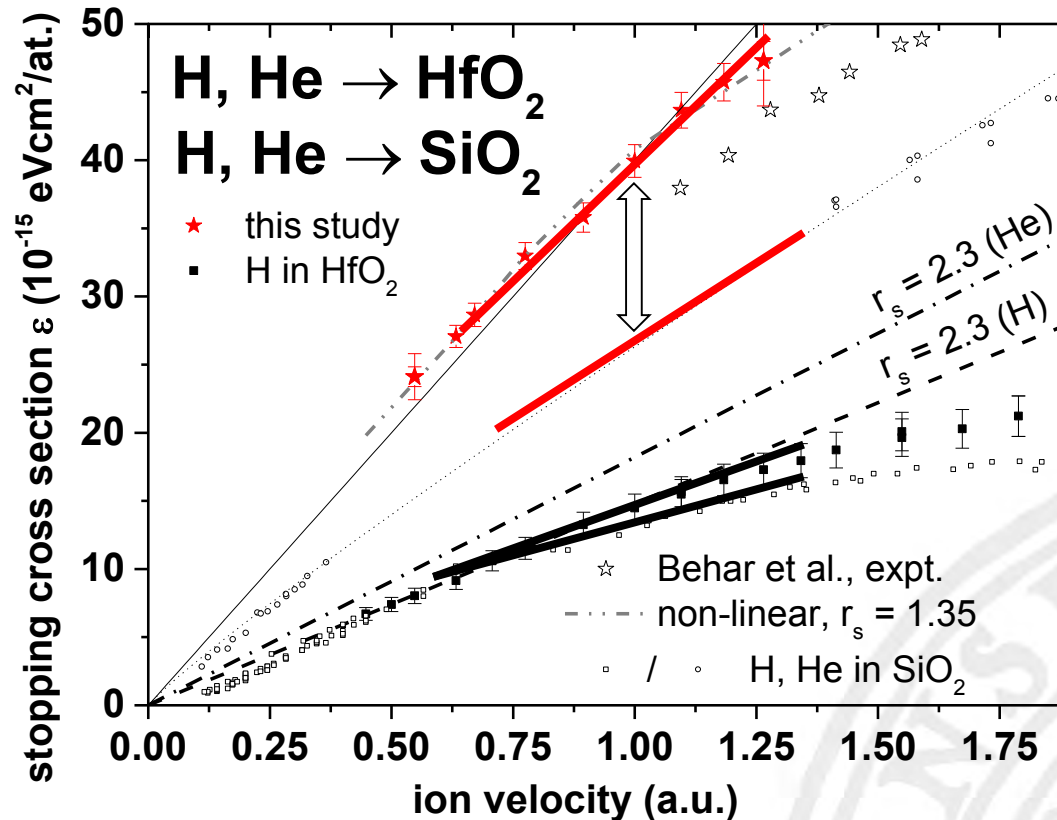


D. Primetzhofer, Phys. Rev A 89 (2014)

- Protons show no large discrepancy – excitation of O-2p states!?
- He-stopping high in both materials



Comparison: SiO_2 vs. HfO_2 : He



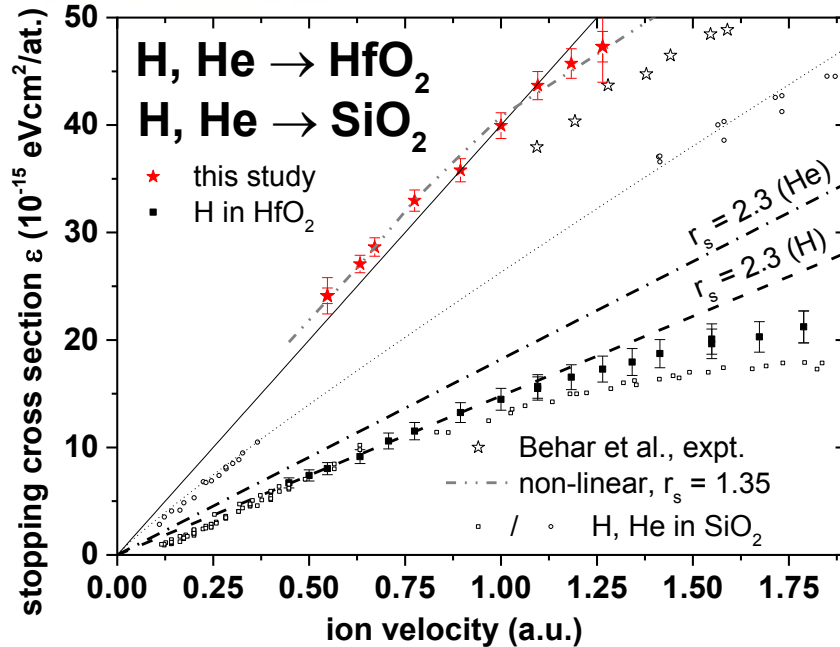
D. Primetzhofer, Phys. Rev A 89 (2014)

- Protons show no large discrepancy – excitation of O-2p states!?
- He-stopping high in both materials but much higher in HfO_2

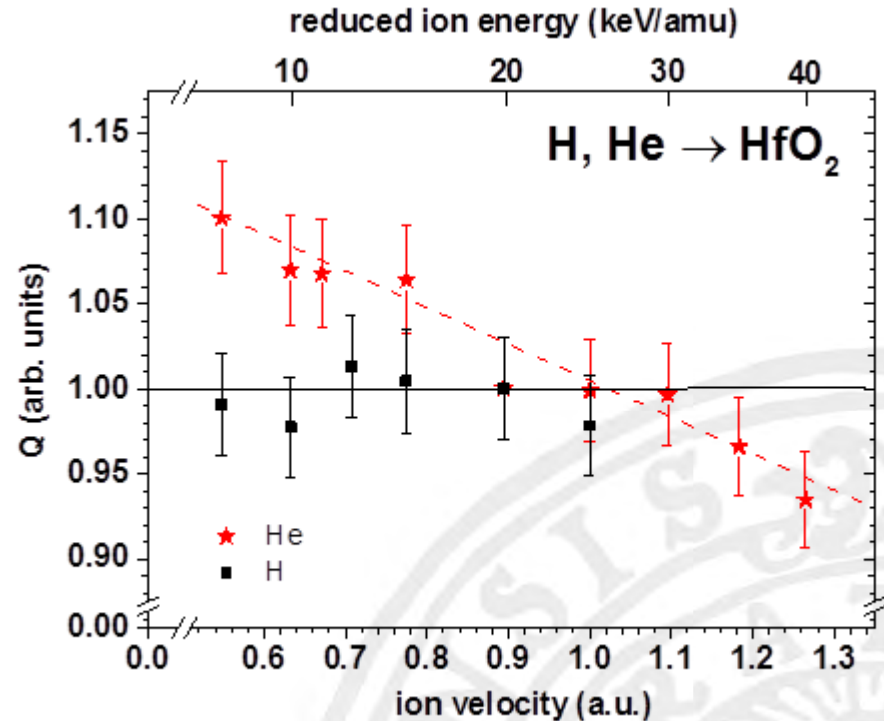


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Electronic stopping in HfO_2 : He



D. Primetzhofer, *Phys. Rev A* 89 (2014)

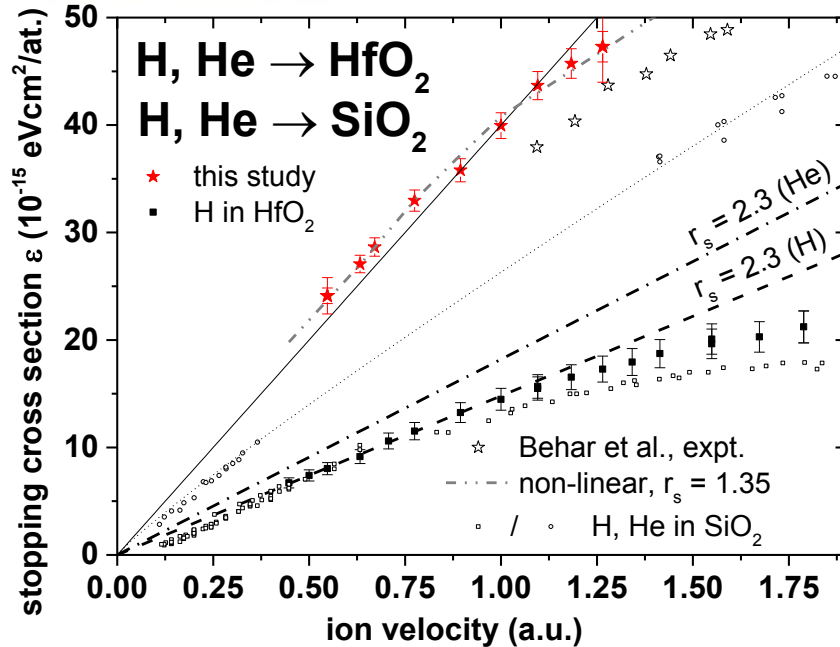


- Protons: $dE/dx \propto E^{0.5} \leftrightarrow$ He: non-linear velocity dependence
- Different electron density in DFT-models necessary
- Very high energy loss compared to SiO_2 – different from protons

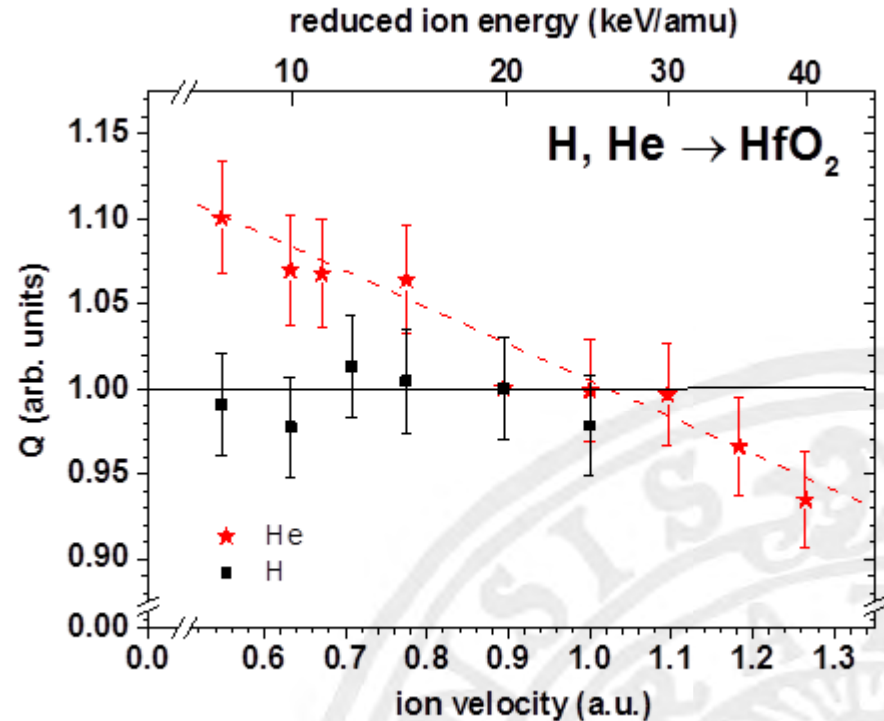


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Electronic stopping in HfO_2 : He

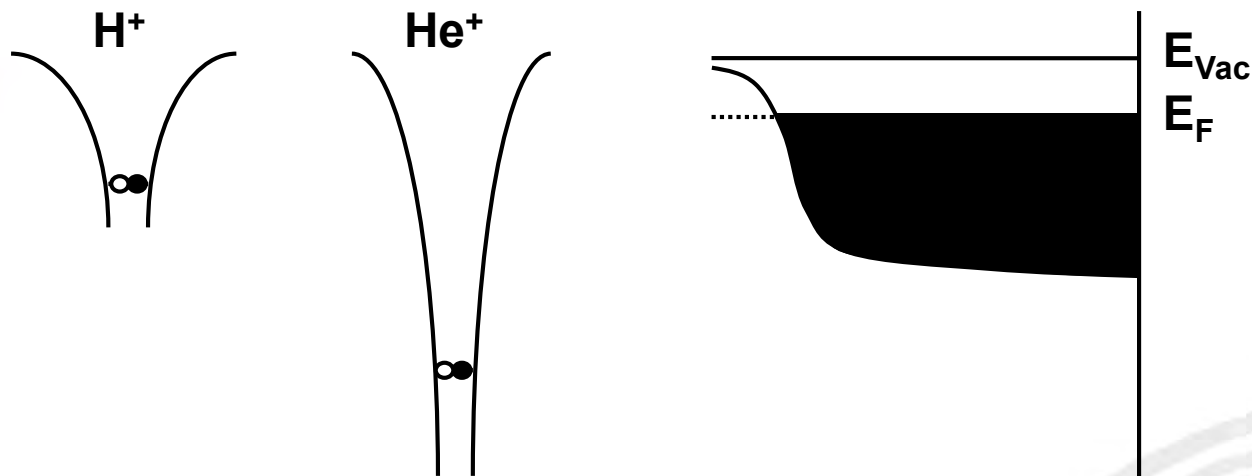


D. Primetzhofer, Phys. Rev A 89 (2014)



- Protons: $dE/dx \propto E^{0.5} \leftrightarrow$ He: non-linear velocity dependence
- Different electron density in DFT-models necessary
- Very high energy loss compared to SiO_2 – different from protons

So why is He so much different?

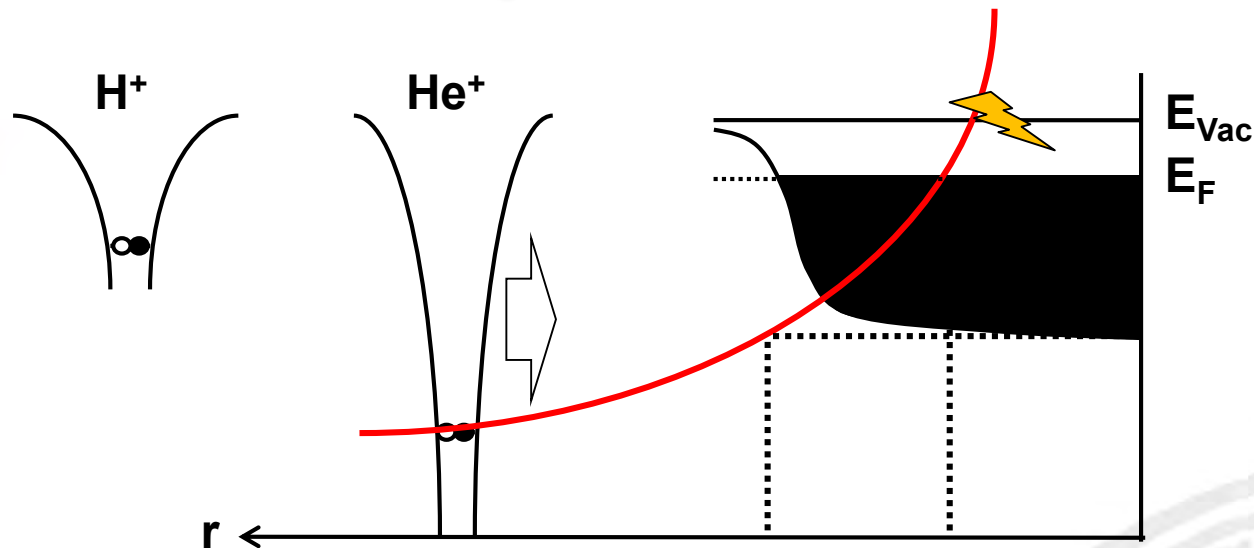


Difference in position of unoccupied atomic level:

$$\text{H}(1s) = 13.6 \text{ eV} \quad \text{vs.} \quad \text{He}(1s) = 24.4 \text{ eV}$$

H(1s) resonant with bands in solid ↔ He(1s) below lower band edge

So why is He so much different?



Difference in position of unoccupied atomic level:

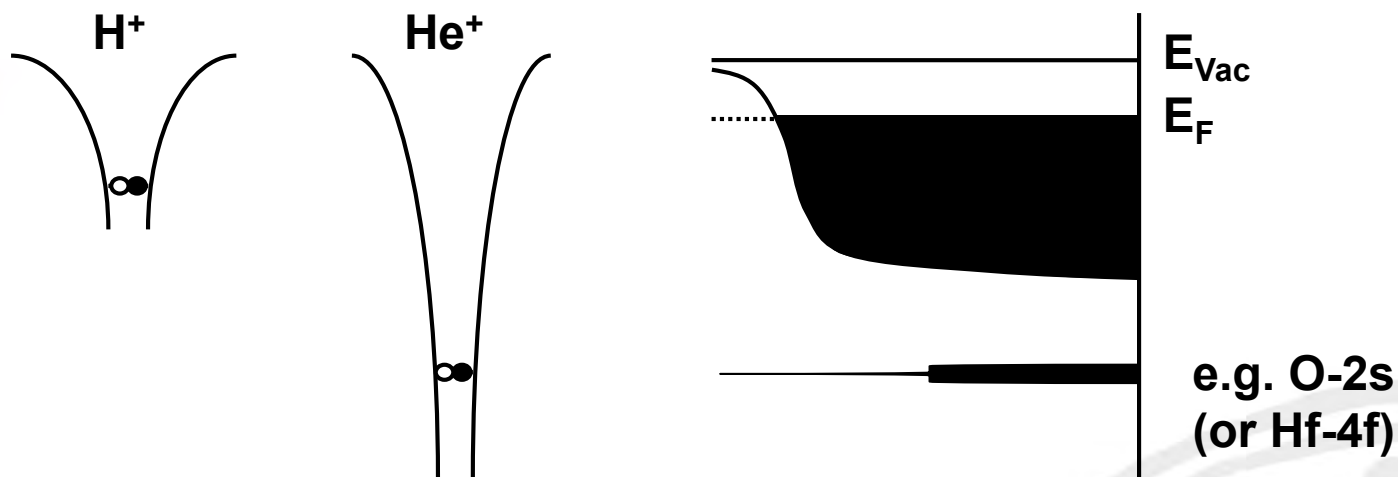
$$\text{H}(1s) = 13.6 \text{ eV} \quad \text{vs.} \quad \text{He}(1s) = 24.4 \text{ eV}$$

$\text{H}(1s)$ resonant with bands in solid $\leftrightarrow$ $\text{He}(1s)$ below lower band edge

Levels are dynamic: $E(r)$ with r = distance between nuclei

He: Critical distance for resonant neutralization and reionization

More possible differences:



Difference in position of unoccupied atomic level:

$$H(1s) = 13.6 \text{ eV} \quad \text{vs.} \quad He(1s) = 24.4 \text{ eV}$$

$H(1s)$ resonant with bands in solid $\leftrightarrow$ $He(1s)$ below lower band edge

Levels are dynamic: $E(r)$ with r = distance between nuclei

He: Quasi-resonant levels influence charge states

Reionization well known from LEIS

Thresholds for reionization:

O: 700 eV

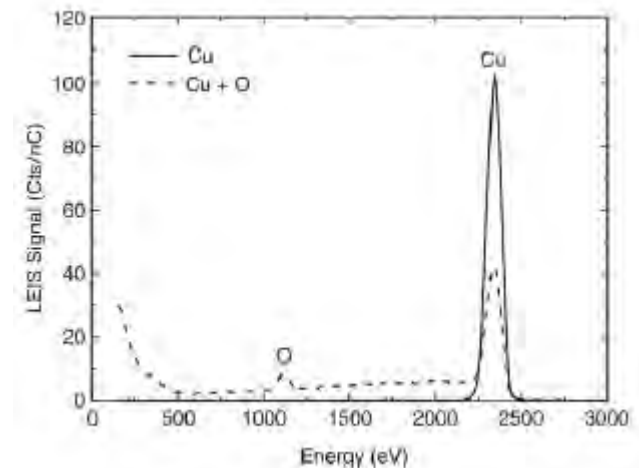
Determined from reionization tails

→ even lower in backscattering

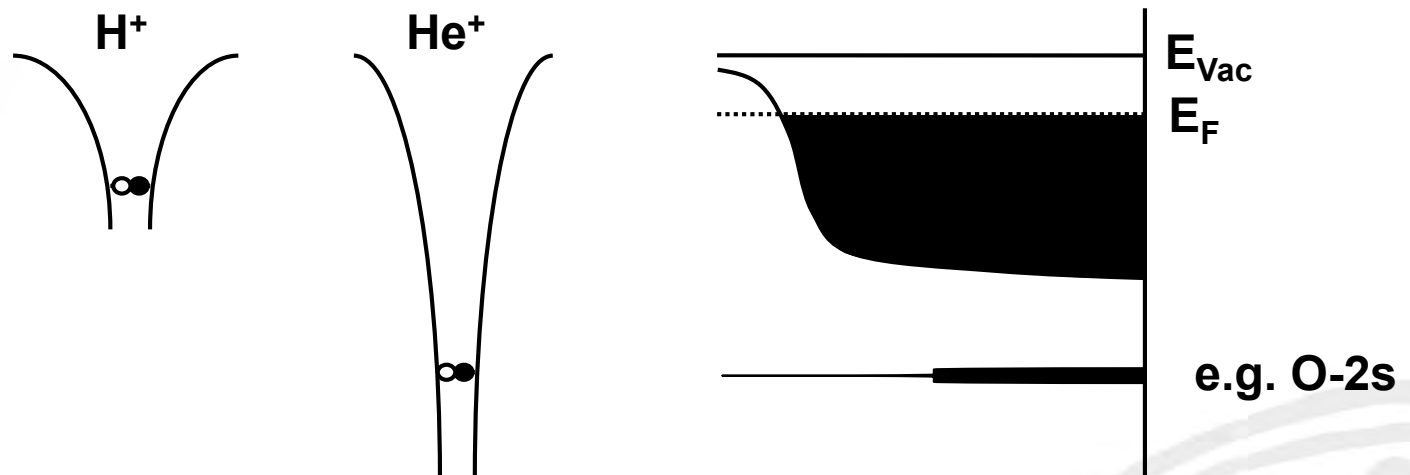
Table for reionization thresholds (see Section 6.3.3(b))

Element	He		
	Method 1	Method 2	Method 3
Ag	>2000 [113]	≤1500 [37]	
Al	300 [113]	≤500 [37]	400 [110]
Au		≤1000 [37]	
Ba	600 [114]		
C	200 [113]		
Mo	400 [113]	≤1000 [37]	900 [5]
Na	≤200 [113]		
Ni	>2000 [113]	≤1500 [37]	2300 [6]
O			700 [91]
Pb	>2000 [113]		
Pd		≤1000 [37]	1100 [115]

H.H. Brongersma et al., Surf. Sci. Rep. (2007)



More possible differences



Difference in position of unoccupied atomic level:

$$H(1s) = 13.6 \text{ eV} \quad \text{vs.} \quad He(1s) = 24.4 \text{ eV}$$

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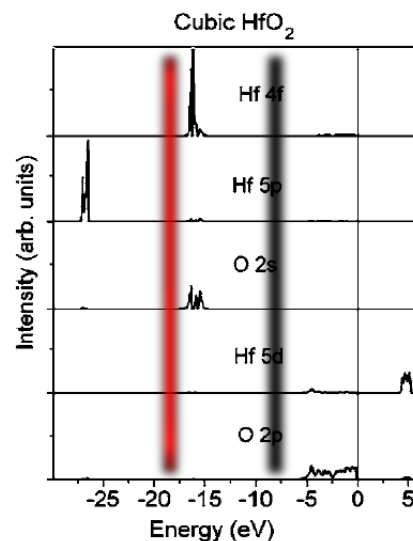
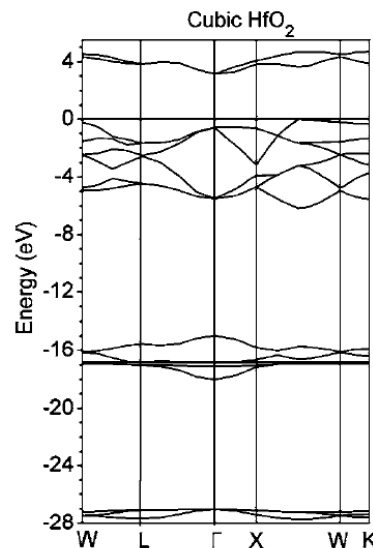
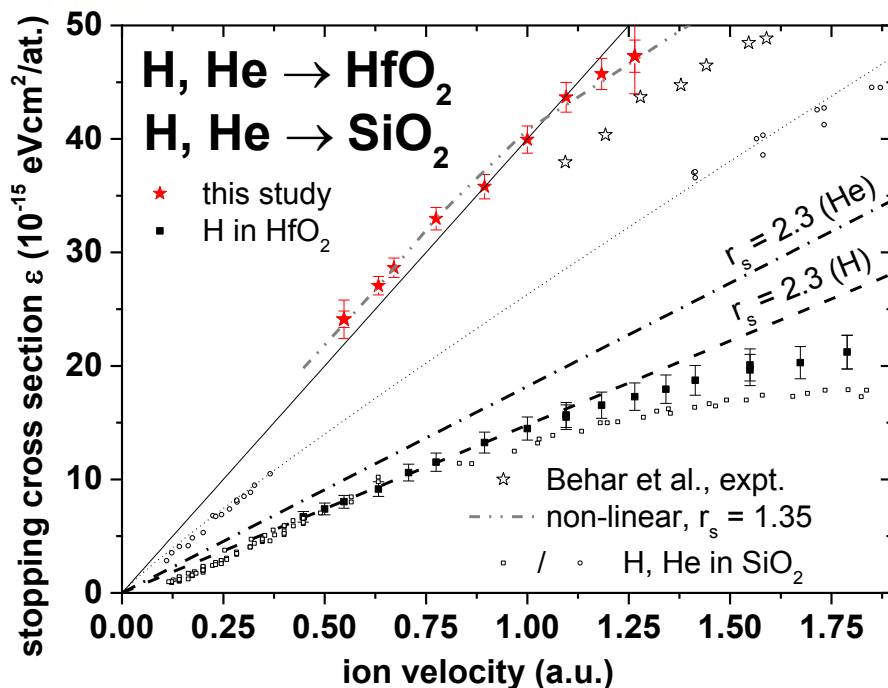
Levels are dynamic: $E(r)$ with r = distance between nuclei

He: Quasi-resonant levels influence charge state & dissipate energy



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Analysis of electronic energy loss in HfO_2



T.V. Perevalov et al., J. Appl. Phys. (2007)

- Interaction of He-1s with O-2s in both HfO_2 and SiO_2
- In HfO_2 additional interaction with heavily populated 4f-states

Conclusions (I):



- **(ToF-) MEIS offers an ideal tool for high-resolution thin film profiling.**
- **Energy loss at medium energies (quantification!) can be complex!**
- **Trajectory dependent loss in atomic collisions can be relevant (He, Ne).**

Conclusions (II):



- (ToF-) MEIS offers an ideal tool for high-resolution thin film profiling.
- Energy loss at medium energies (quantification!) can be complex!
- Trajectory dependent loss in atomic collisions can be relevant (He, Ne)..
- **Heavier ions: Nuclear stopping in backscattering experiments found low compared to SRIM (random trajectories).**
- **Inherent trajectory selectivity of each experiment affects energy loss.**
- **Selective mechanisms in backscattering almost as effective as in transmission.**
- **Monte Carlo calculations should be performed for relevant geometry. (Use TRIM not SRIM)**