Stopping and ionization at few keV

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Stopping power

Bohr, 1913 & 1948	Classical stopping
Bethe, 1930	Bethe-formula
Fermi and Teller, 1947	Velocity prop.
Barkas, 1956	Range of $\pi^- > \pi^+$ so $(dE/dx)^- < (dE/dx)^+$
1963	$\Sigma^\pm \mu^\pm \Rightarrow (dE/dx)$ not prop. to Z^2
1969-1989	$(dE/dx)_\alpha < 4(dE/dx)_p$, $\mu^\pm$
1989 - 2002	LEAR, AD

Stopping power

$$-\frac{dE}{dx} = \frac{4\pi e^4 N Z_2}{mv^2} Z_1^2 L$$

- Bethe

$$L = L_{Bethe} = \ln\left(\frac{2mv^2}{\hbar\omega}\right) - \frac{C}{Z_2}$$

- Born series

$$L = L_0 + Z_1 L_1 + Z_1^2 L_2 + \ldots$$

$v >> v_0$

- Bohr

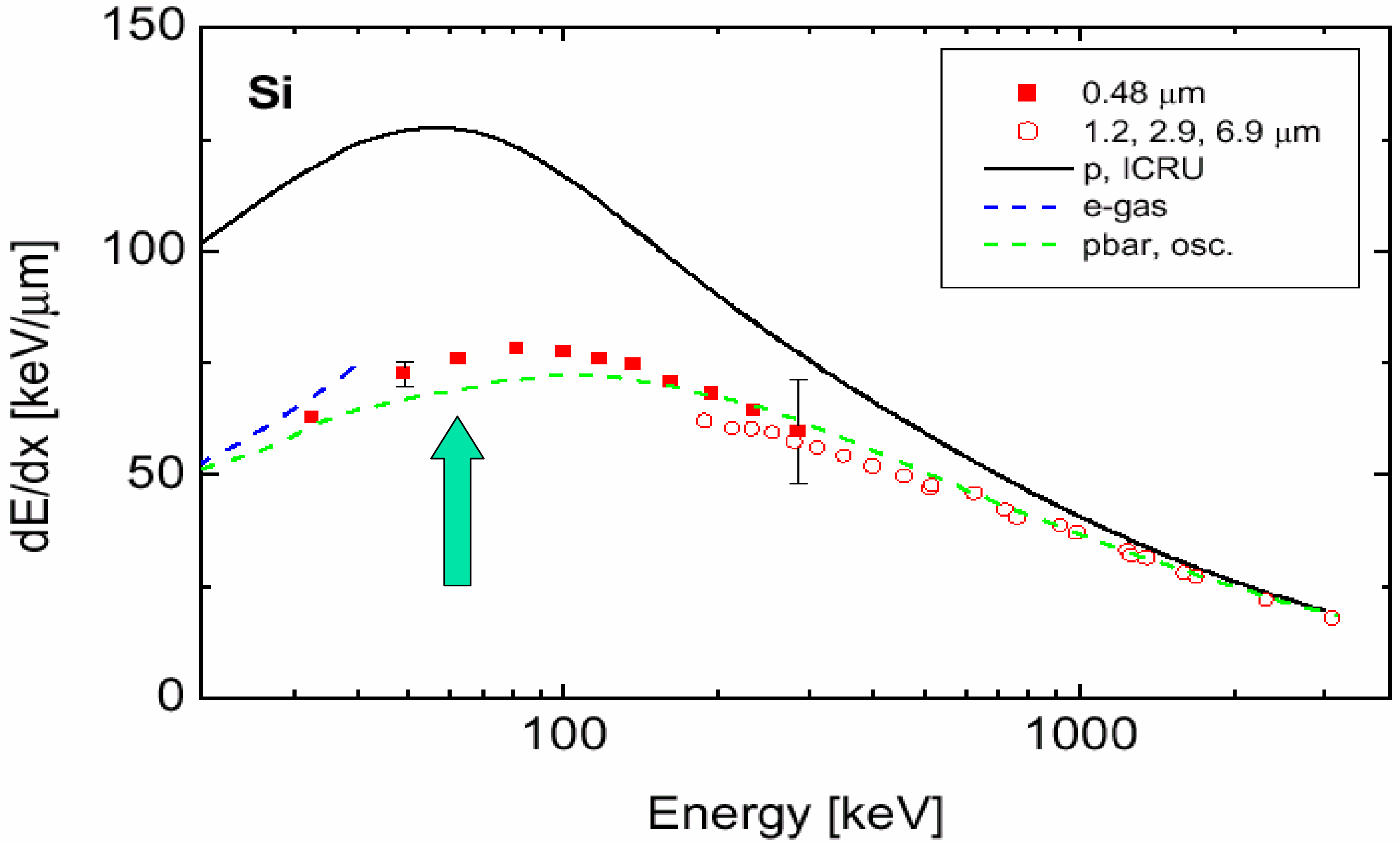
$$L = L_{Bohr} = \ln\left(\frac{Cmv^3}{Z_1 e^2 \omega}\right)$$

- Electron gas

$$-\frac{dE}{dx} = \frac{4}{3\pi} Z_1^2 C(\chi, Z_1) \frac{v}{v_0} \frac{e^2}{a_0^2}$$

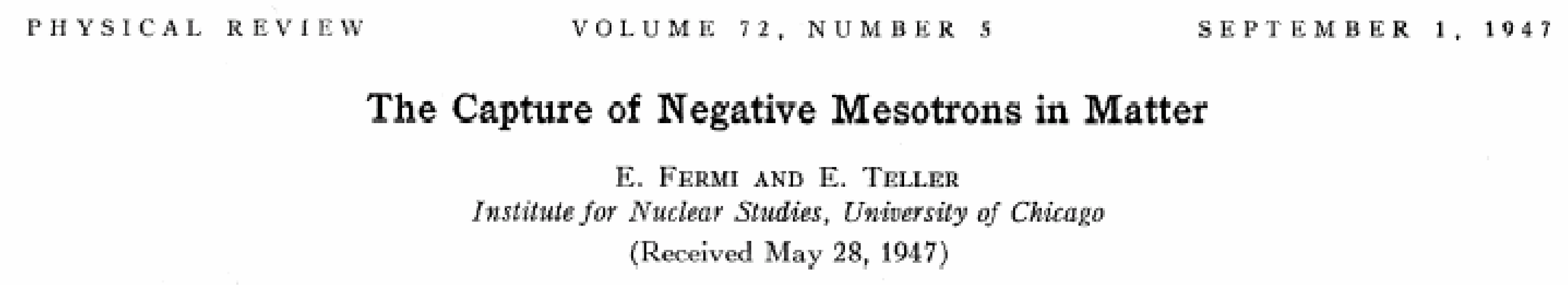
$v << v_0$

Barkas effect



Velocity proportionality

- Fermi and Teller, 1947



PHYSICAL REVIEW VOLUME 72, NUMBER 5 SEPTEMBER 1, 1947

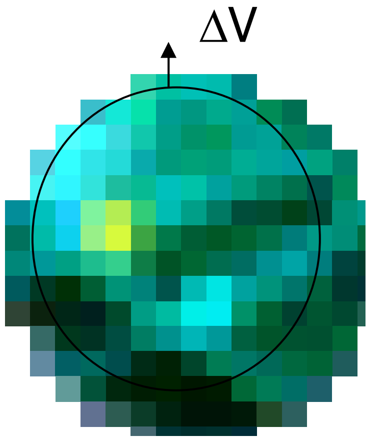
The Capture of Negative Mesotrons in Matter

E. FERMI AND E. TELLER
Institute for Nuclear Studies, University of Chicago
(Received May 28, 1947)

- Degenerate electrons in a Fermi sphere

Velocity ch.: $\Delta V \approx V \ll v_F$
Density $n \approx m^3 v_F^2 V/\hbar^3$
Cross sect. $\sigma \approx a_0^2 = (e^2/mv_0^2)^2$
Energy loss: $\Delta E \approx m v_F V$ $V \ll v_F$

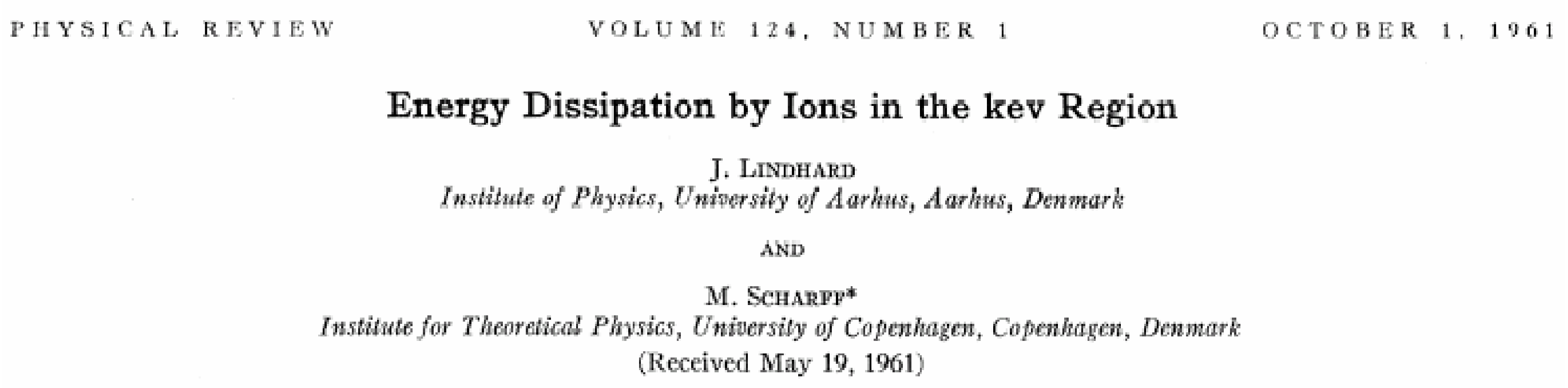
$dE/dt \approx \Delta E n \sigma v_F \approx m^2 e^4 V^2/\hbar^3$



Velocity-proportional dE/dx

Velocity proportionality

- Lindhard and Scharff, 1961



PHYSICAL REVIEW VOLUME 124, NUMBER 1 OCTOBER 1, 1961

Energy Dissipation by Ions in the kev Region

J. LINDHARD
Institute of Physics, University of Aarhus, Aarhus, Denmark

AND

M. SCHARFF*
Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark
(Received May 19, 1961)

$$dE/dR = dE/v\,dt = dp/dt = F$$

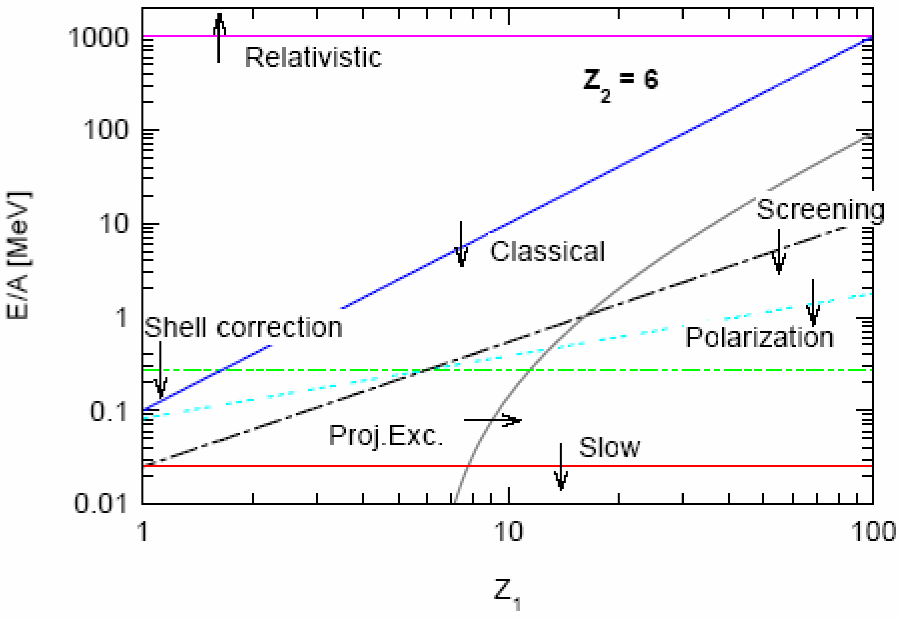
Ohm's law:

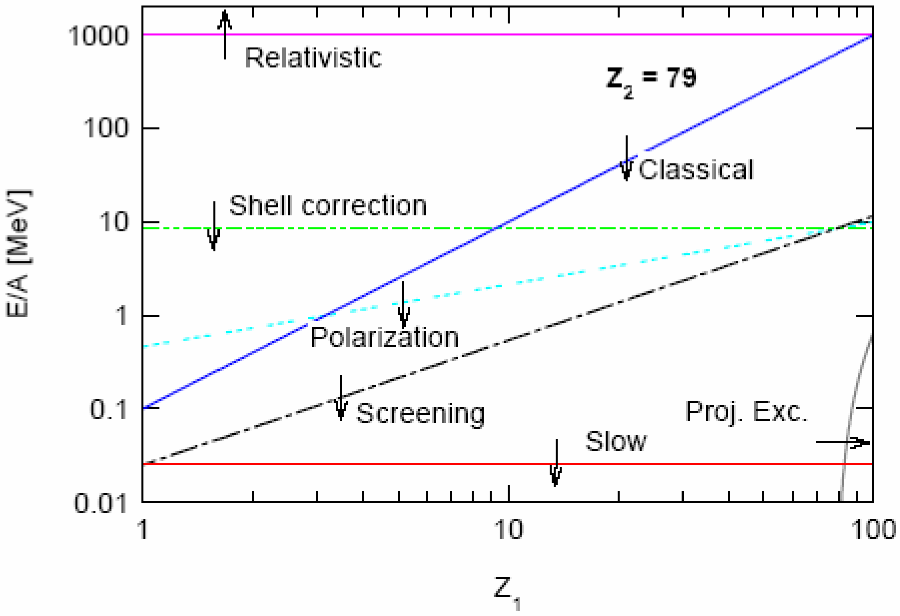
$$I = -env$$

$$F \propto \rho I$$

$$dE/dR \propto v$$

Binary theory





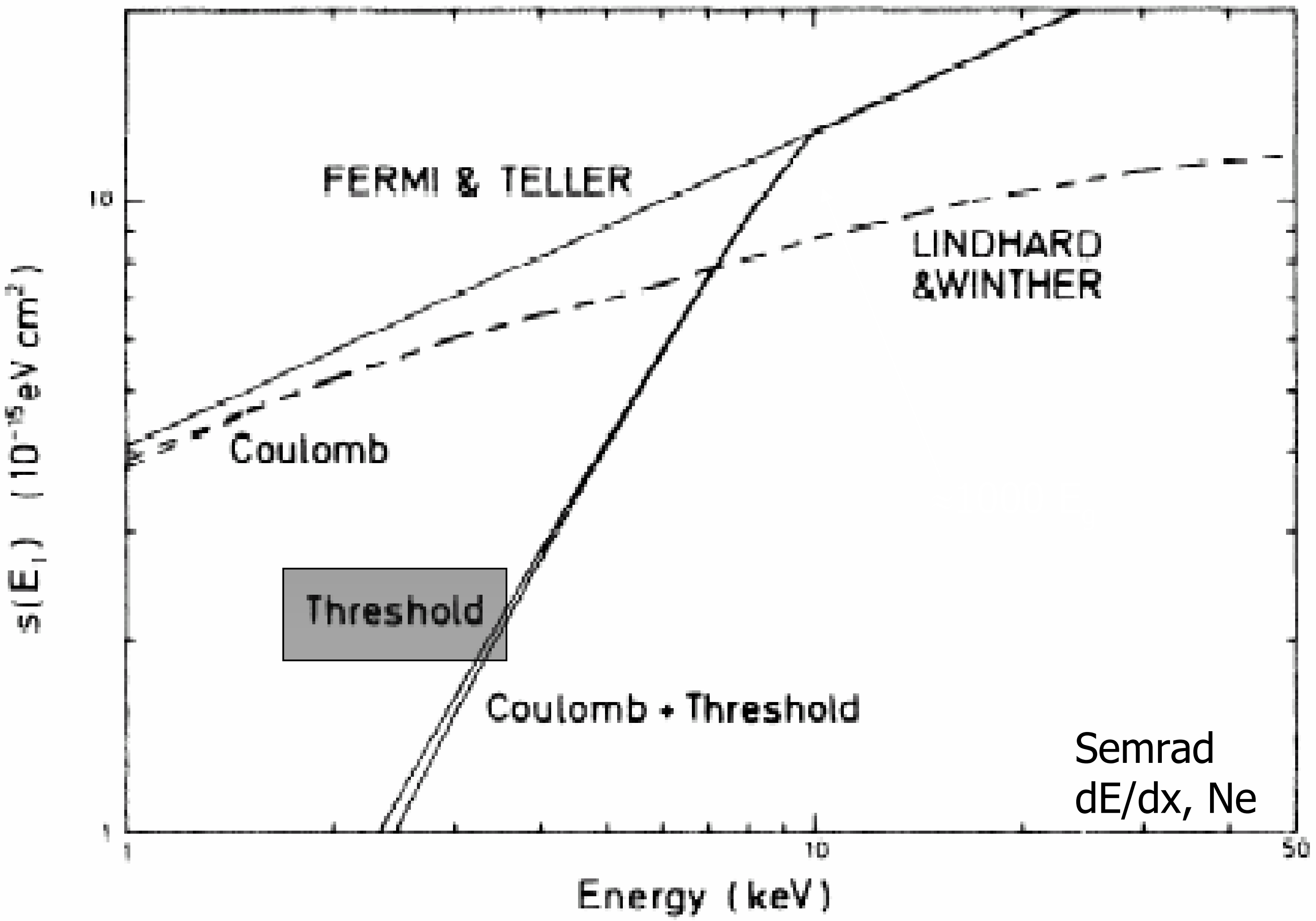
Bohr model = Rutherford scattering truncated at:

$$a_{\mathrm{ad}} = v/\omega$$

Ansatz: Try binary scattering with Yukawa potential

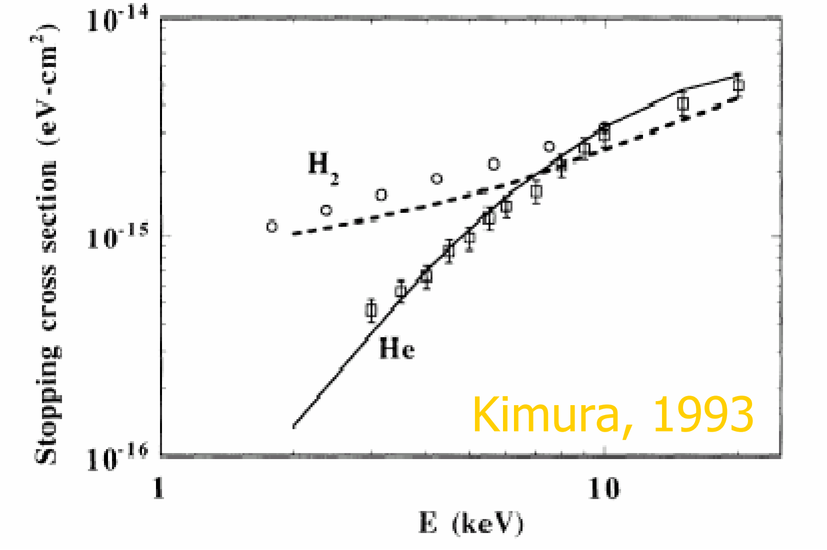
$$V_{\mathrm{eff}}(r) = -\frac{Z_1 e^2}{r} e^{-r/a_{\mathrm{ad}}}$$

Velocity proportionality

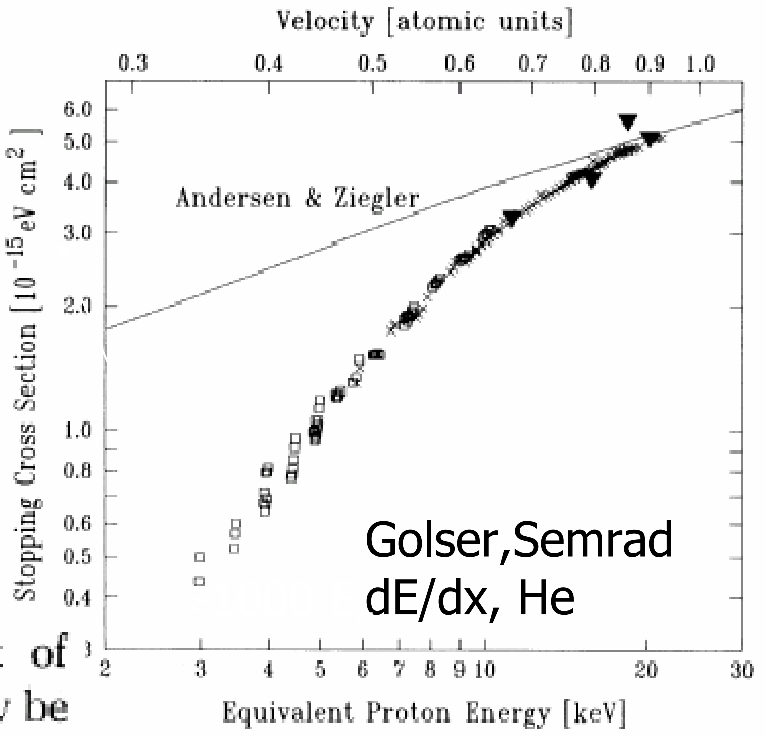


Semrad
dE/dx, Ne

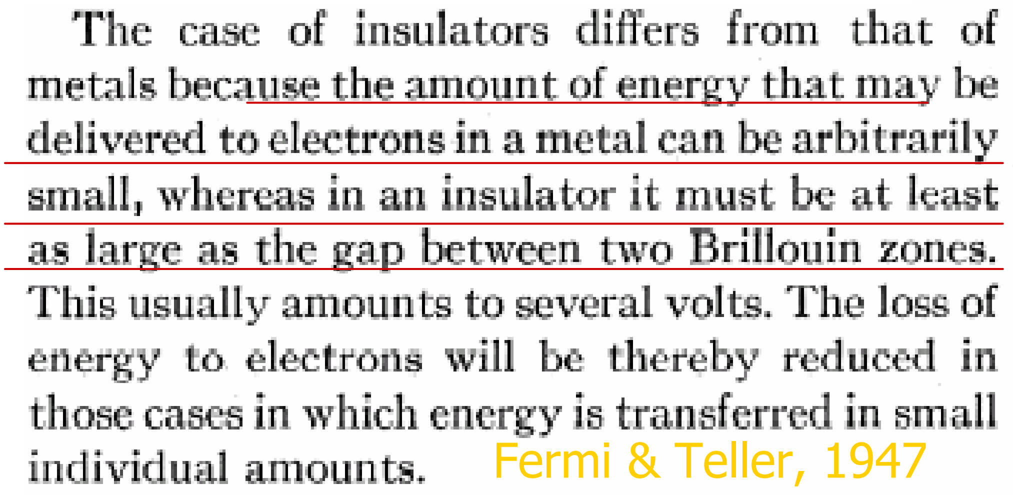
Velocity proportionality



Kimura, 1993



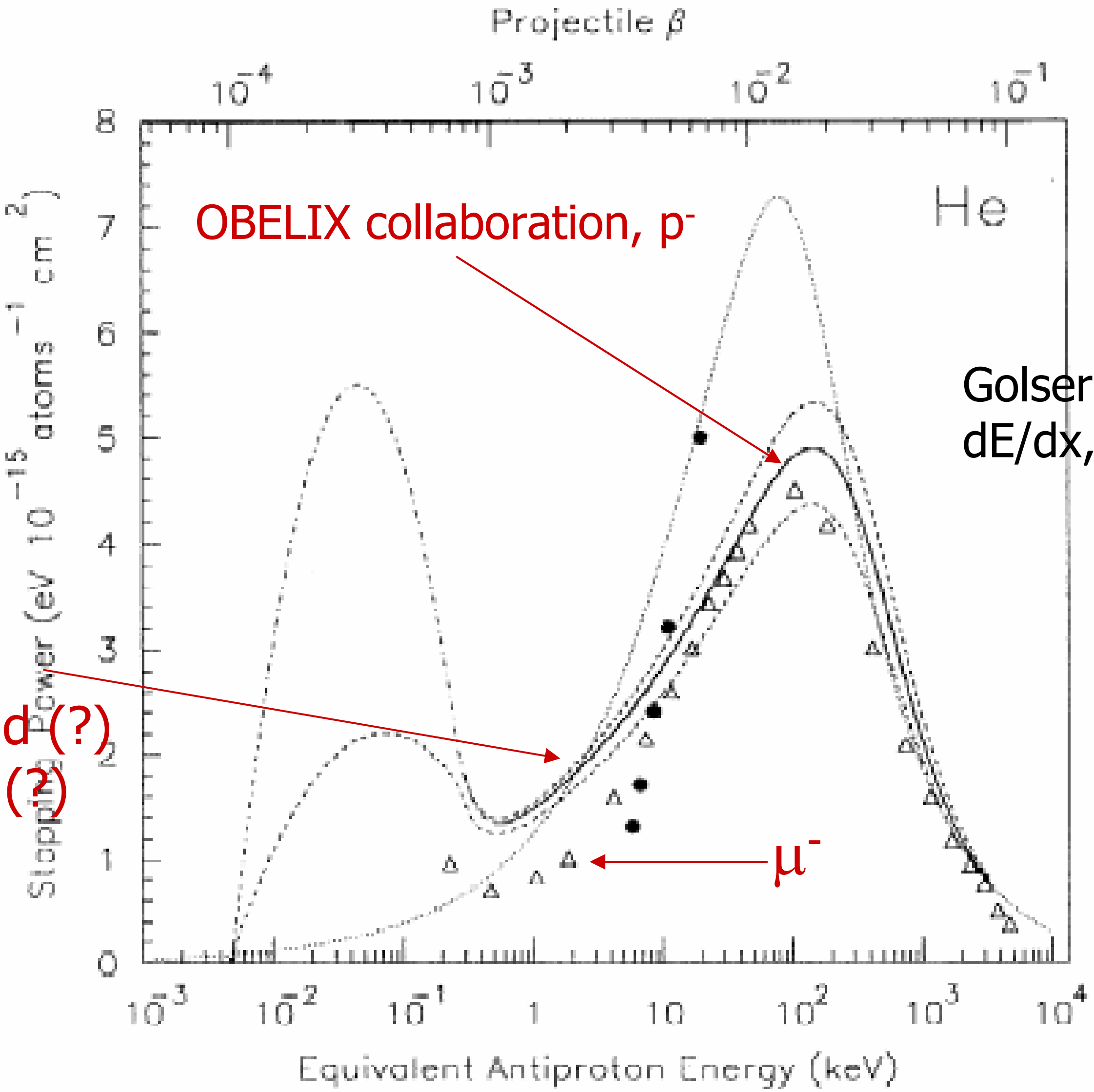
Golser,Semrad
dE/dx, He



The case of insulators differs from that of metals because the amount of energy that may be delivered to electrons in a metal can be arbitrarily small, whereas in an insulator it must be at least as large as the gap between two Brillouin zones. This usually amounts to several volts. The loss of energy to electrons will be thereby reduced in those cases in which energy is transferred in small individual amounts.

Fermi & Teller, 1947

Stopping in gases (H_2, He)



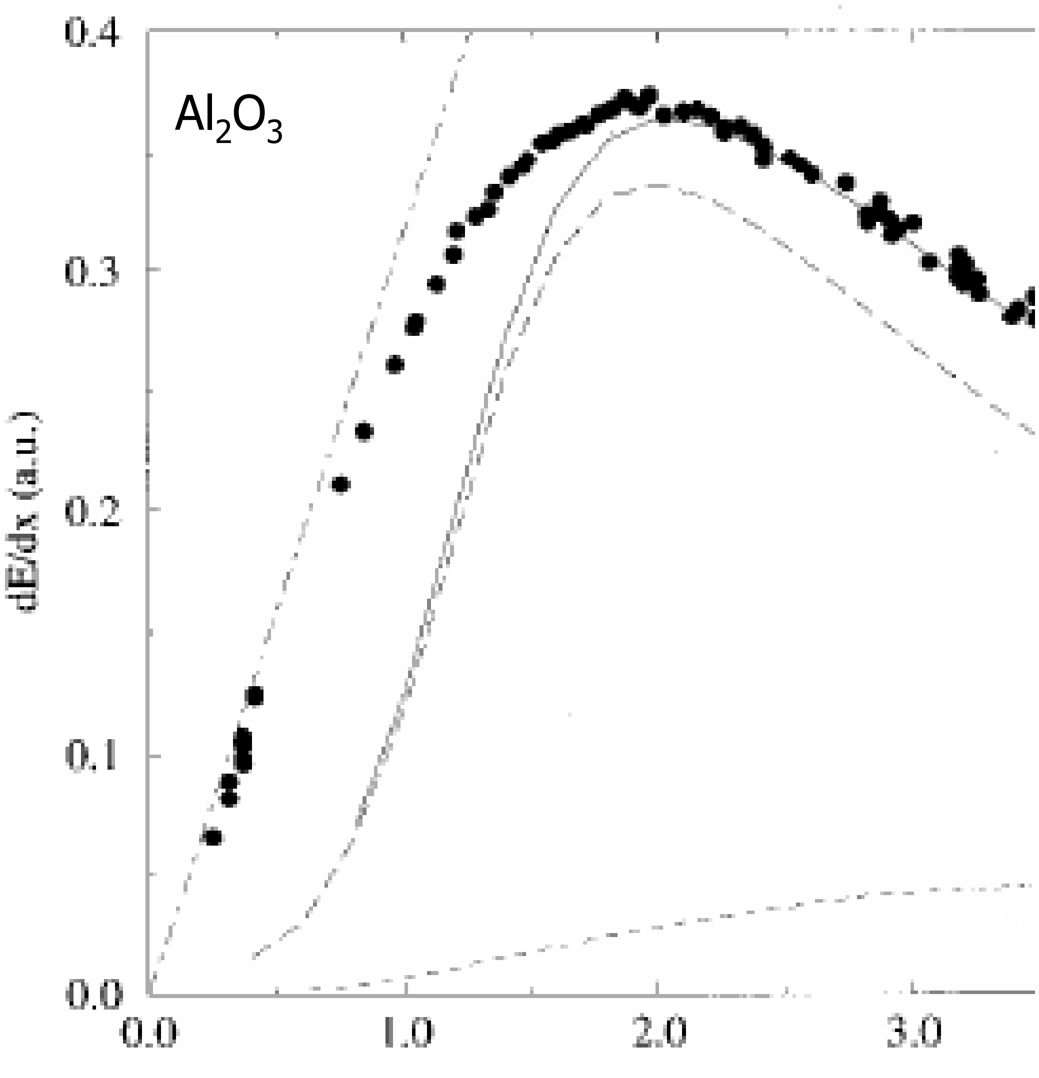
OBELIX collaboration, p^-

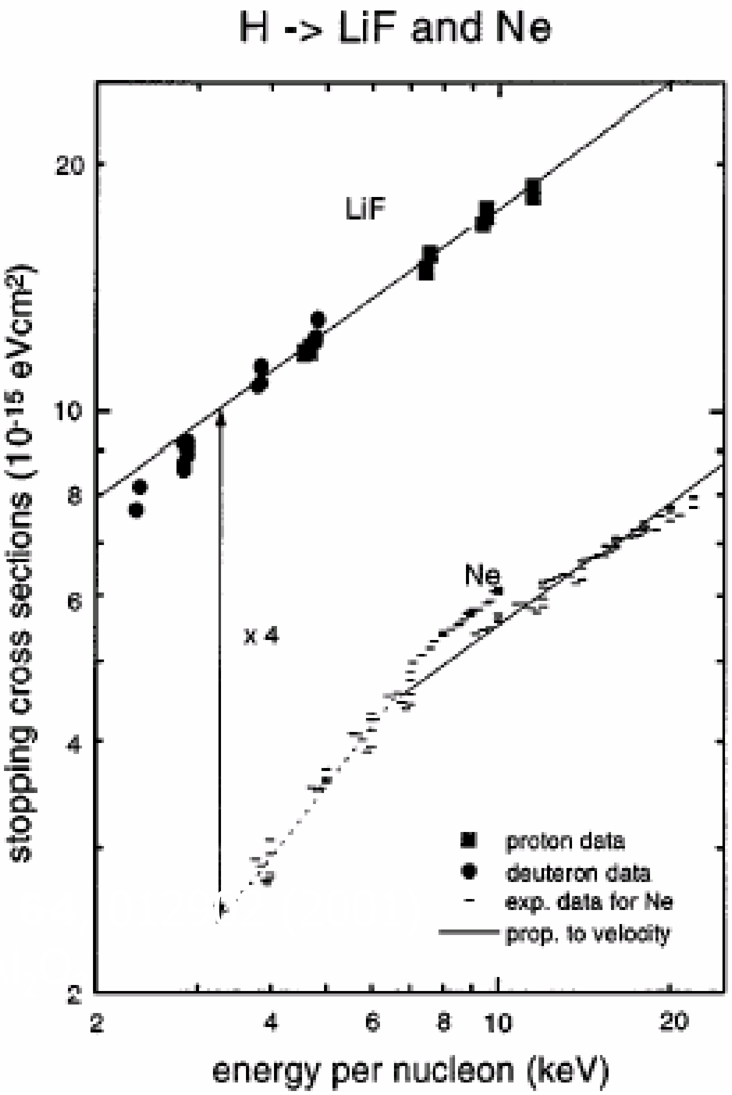
Golser,Semrad
dE/dx, He ●

$dE/dx \propto v^{0.6}$
Anti-threshold (?)
Nucl. Stopp. (?)

μ^-

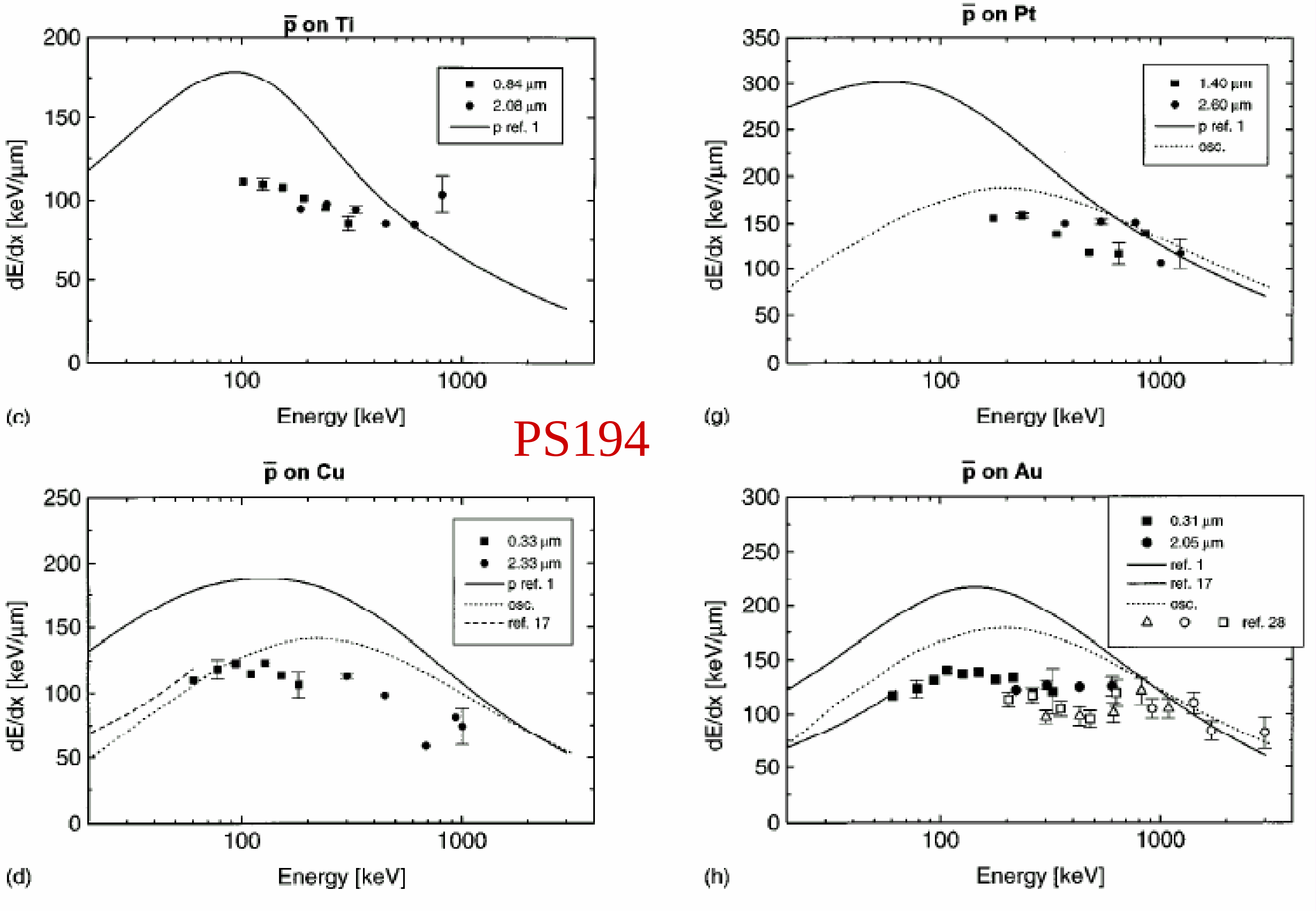
Threshold effect - ?





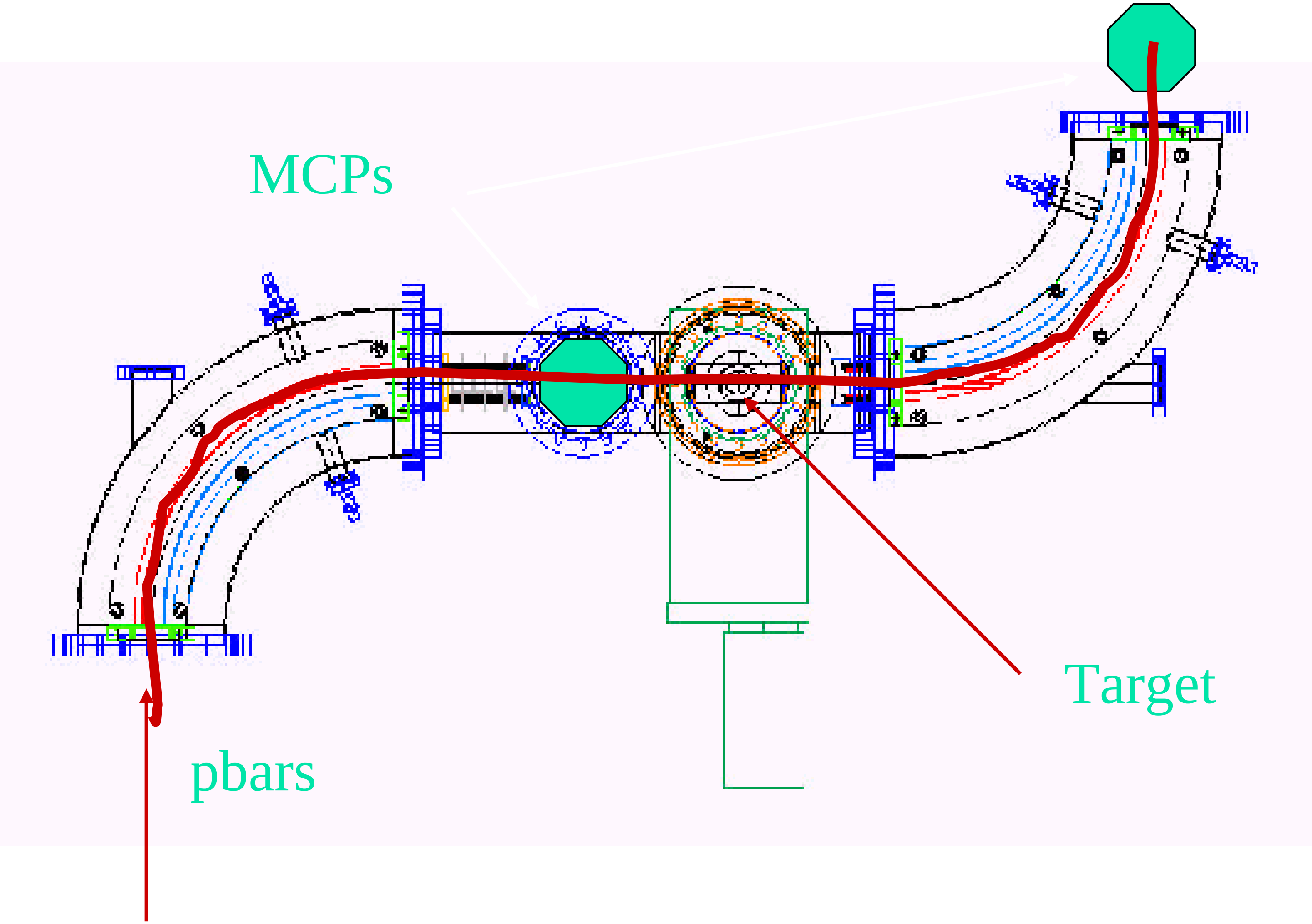
No threshold. Conclusion: 'Molecular orbitals' reduce E_g

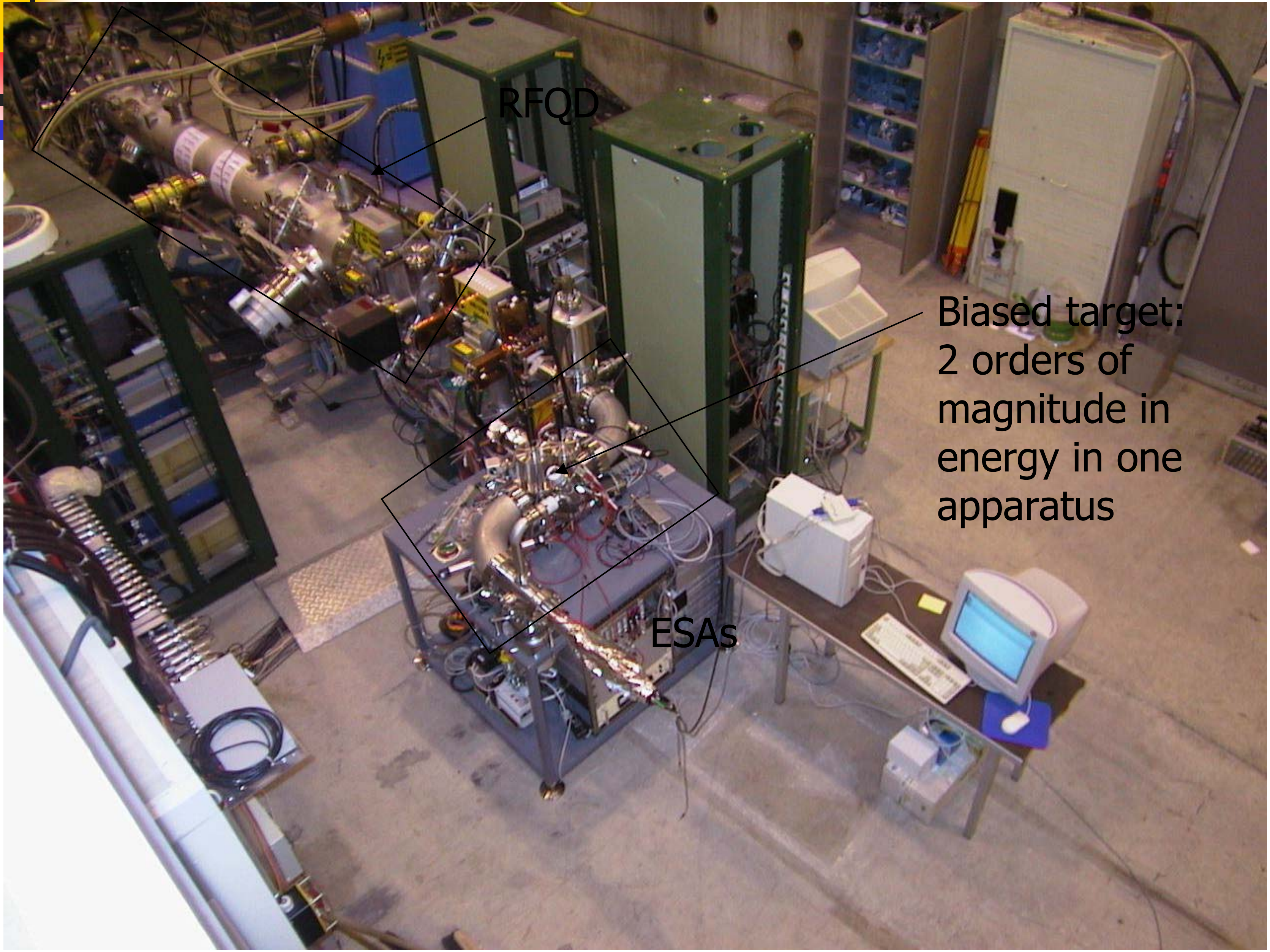
LEAR – Barkas effect



PS194

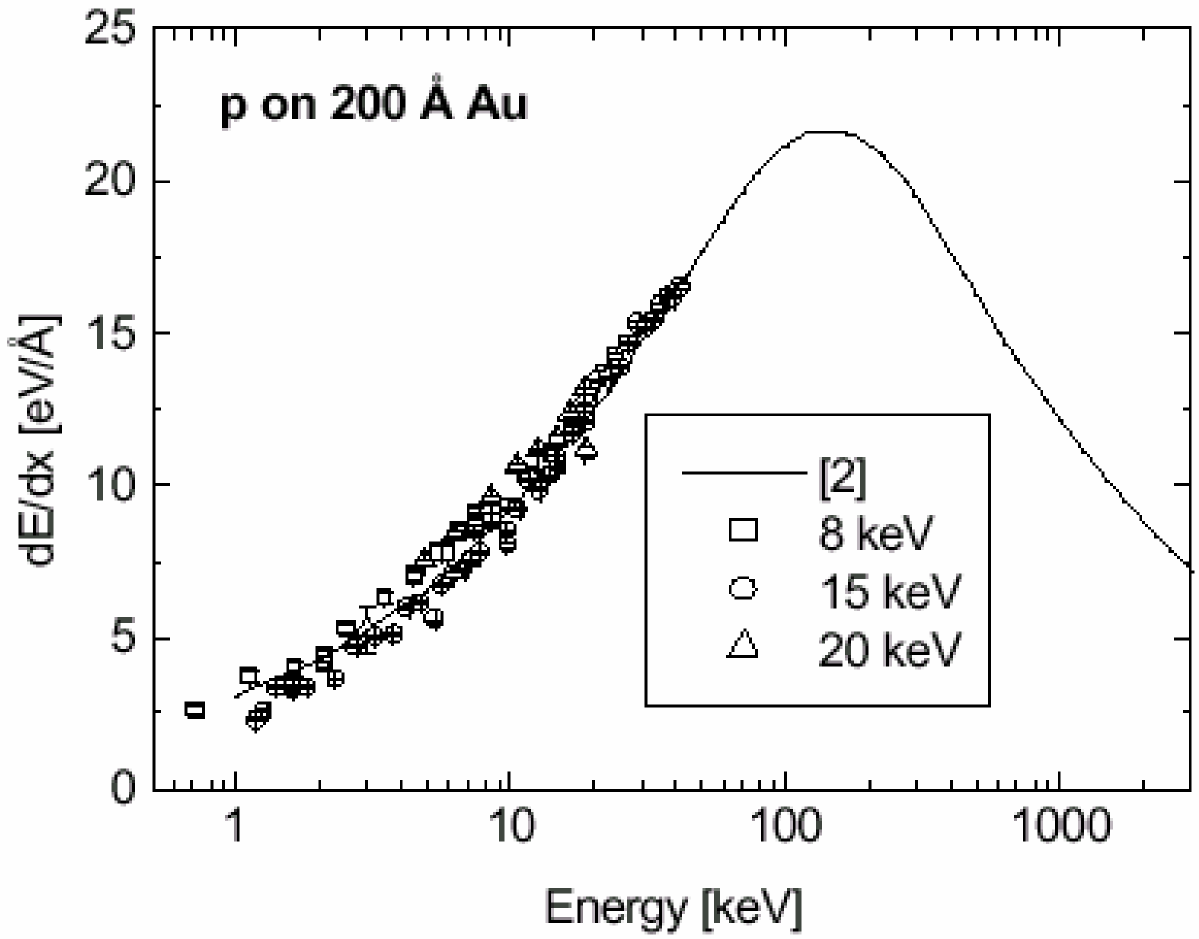
Electrostatic Analyzers (ESAs)



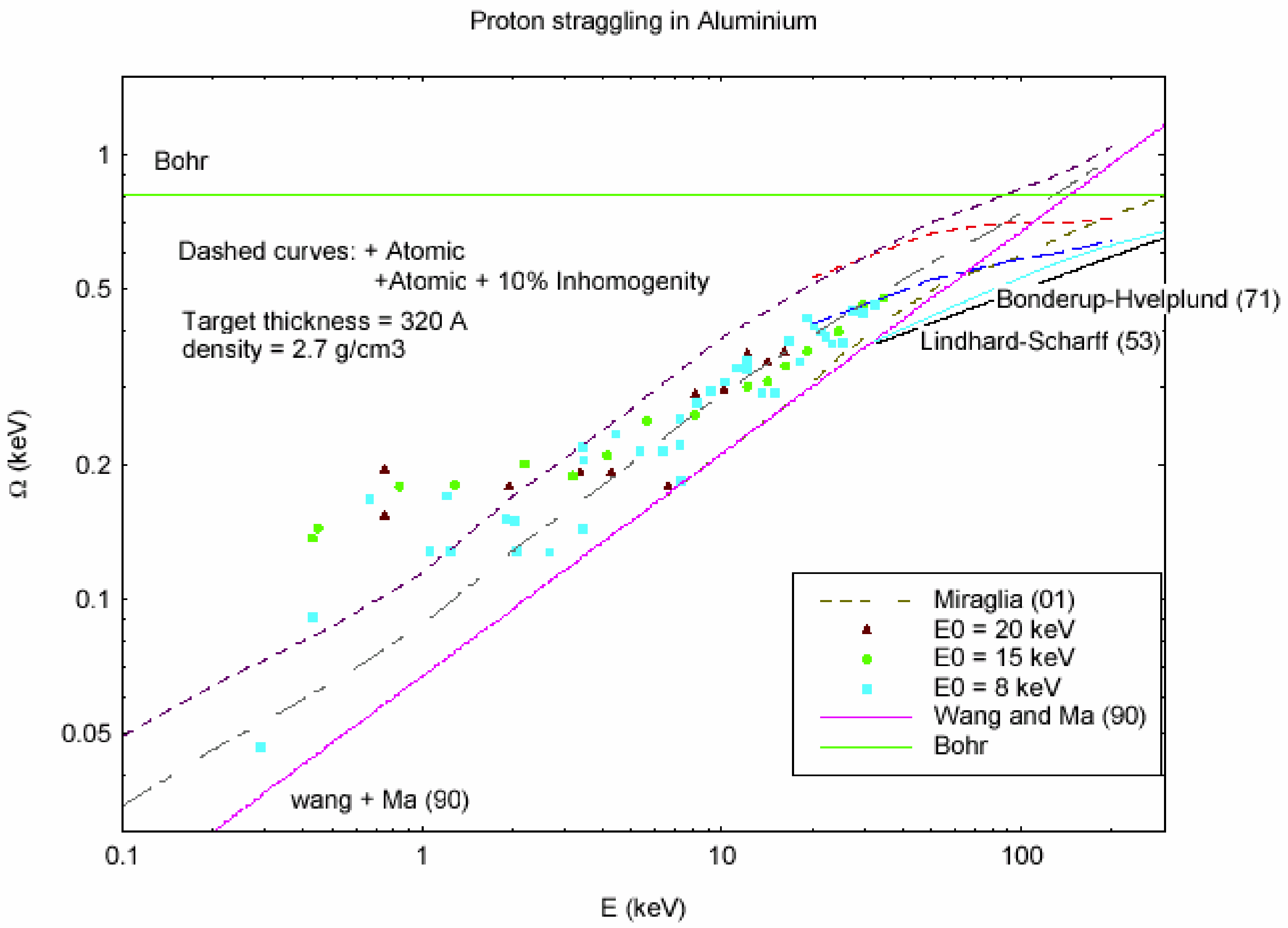


Biased target:
2 orders of
magnitude in
energy in one
apparatus

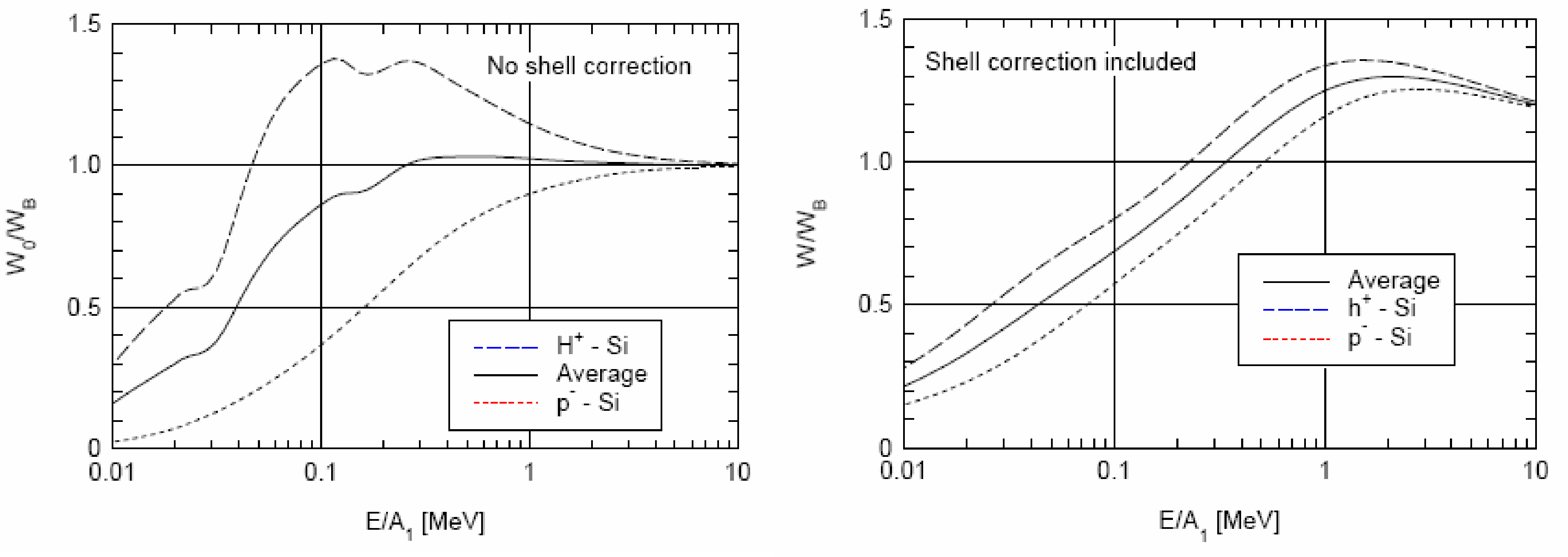
Results - protons, energy loss



Results - protons, straggling

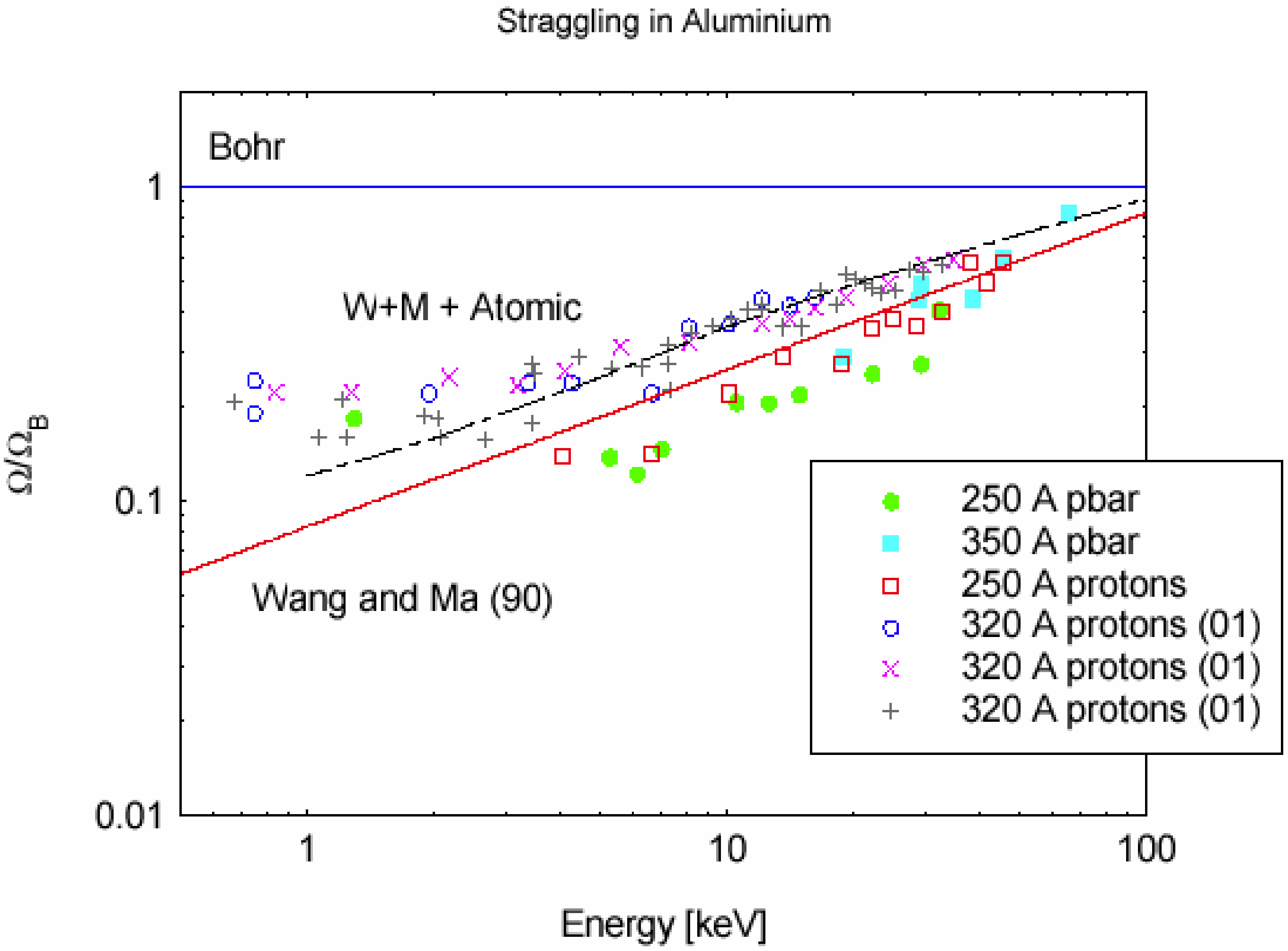


Results - antiprotons, straggling



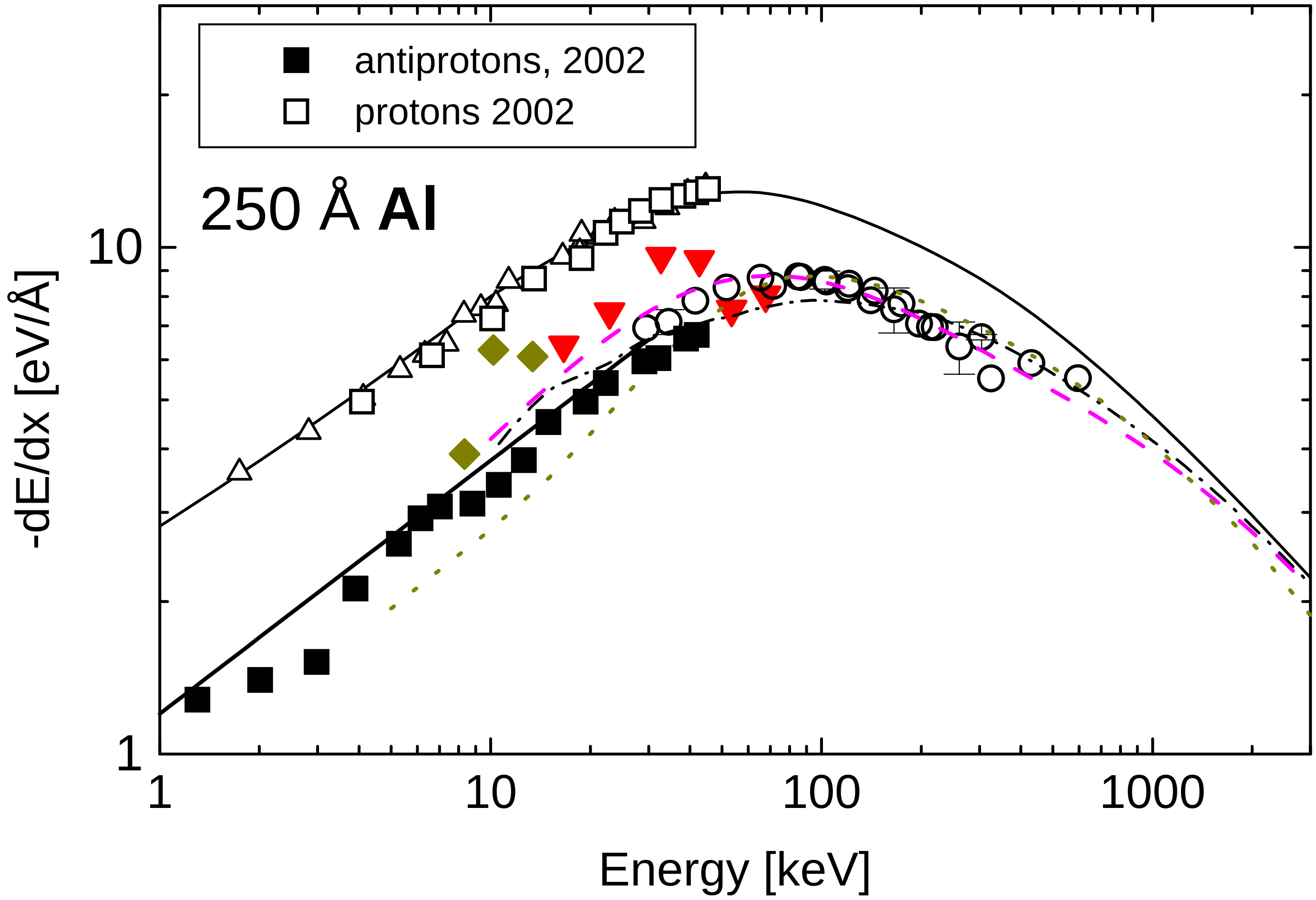
Binary theory (2003):
Shell corrections substantially reduce Barkas effect in straggling

Results - antiprotons, straggling



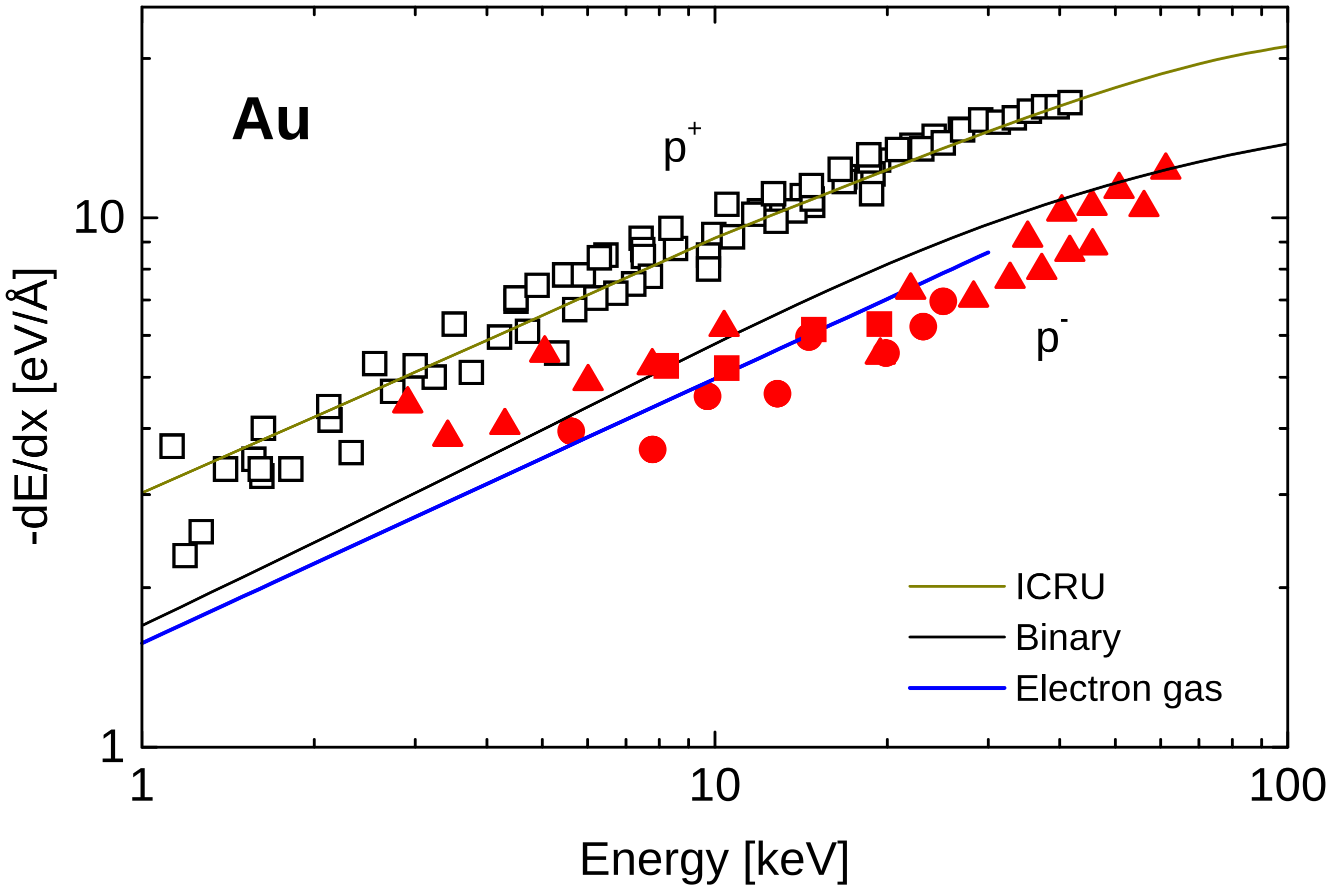
<u>Binary theory (2003):</u>
Shell corrections substantially reduce Barkas effect in straggling

Results - antiprotons on Al



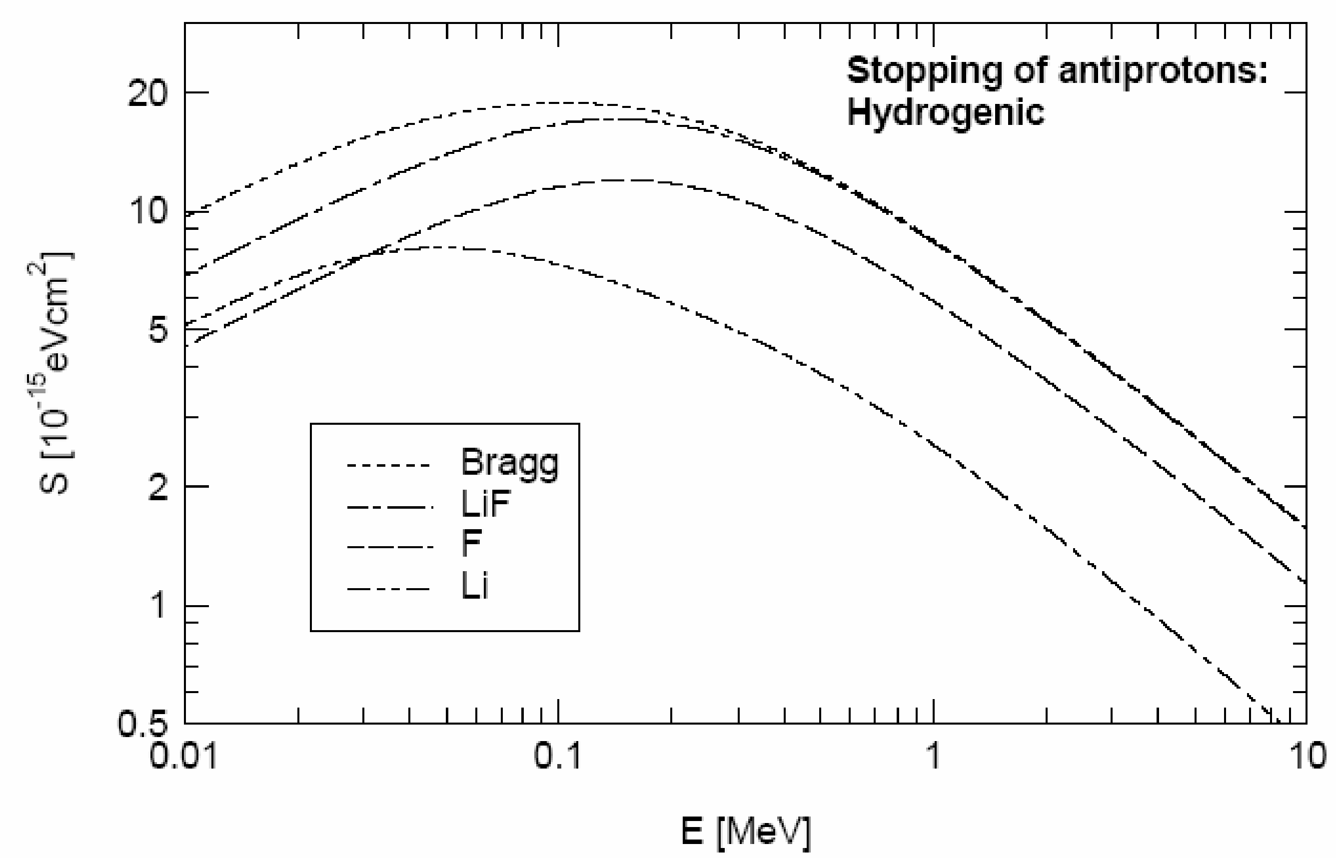
Constant Barkas effect at low energies (as predicted by electron-gas model)

Results - antiprotons on Au



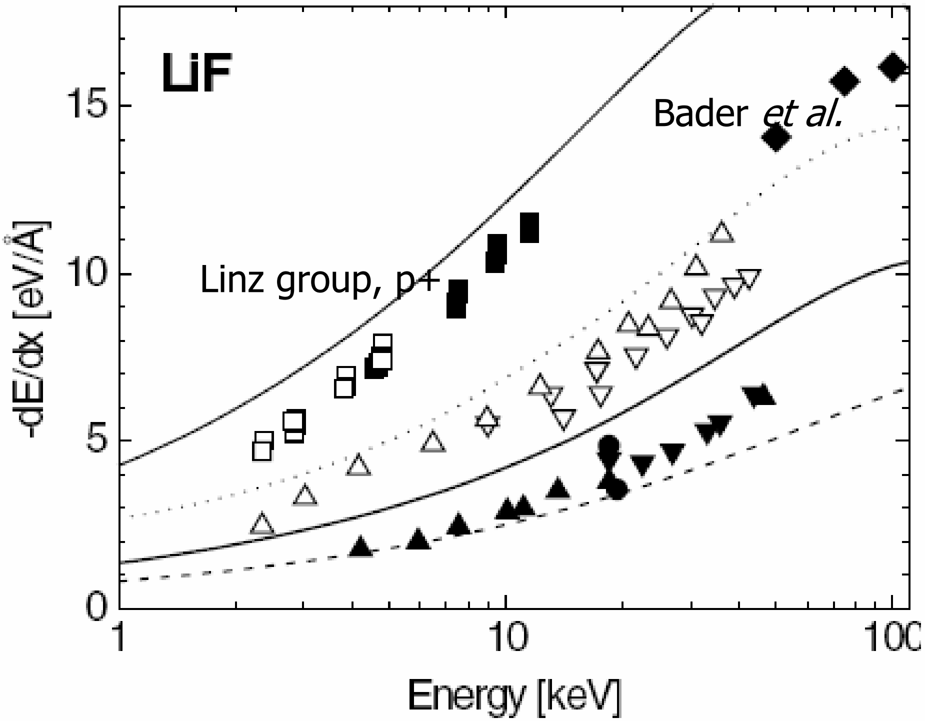
Bragg additivity

- Bragg additivity: Stopping independent of the chemical environment



Results - antiprotons on LiF

Conclusion: No threshold. Why? Not because of ’molecular orbitals’...

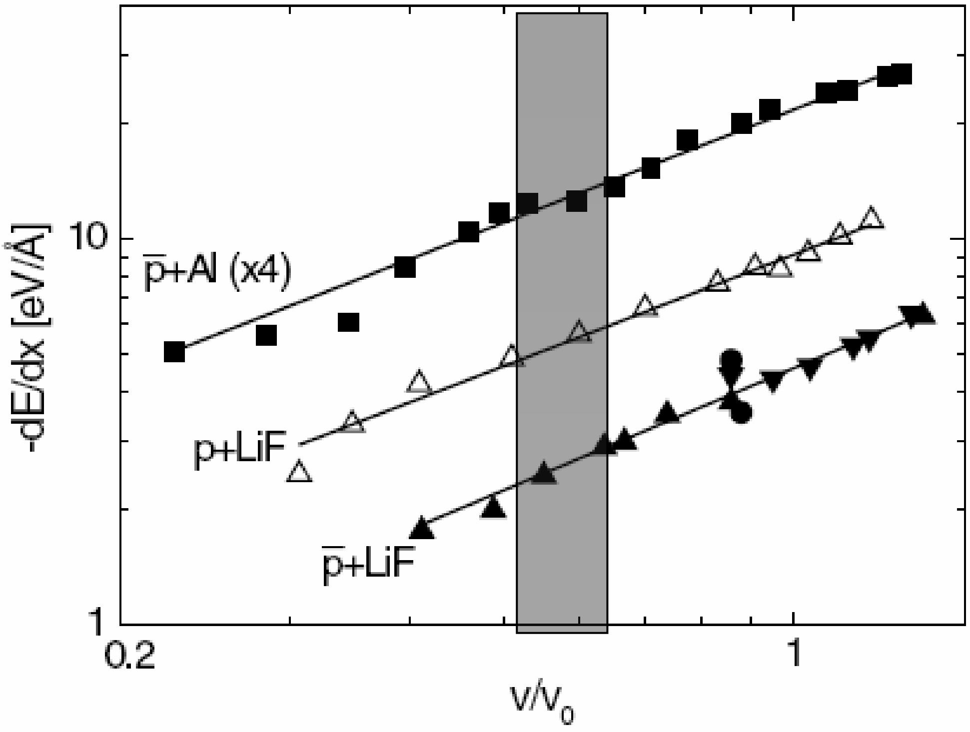


——— New binary p^+

……… ICRU p^+

——— New binary p^-

- - - - - Old binary p^-



Results of fits: $dE/dx \propto v^a$

LiF: $a(p^-)=1.05\pm0.07$, $a(p^+)=0.96\pm0.04$

Al: $a(p-)=0.97\pm0.03$

Antiparticle - atom collisions

- Comparison of particle- and antiparticle collisions in identical situations

  Mass and charge effects

- Antiproton =

  'Theorists favourite projectile‵ (no capture)

- Ionization
  - Single
  - Double
  - Ionization-excitation
  - Differential (COLTRIMS: Schmidt-Böcking, Dörner)
- Energy loss ~ integral of ionization and excitation

Sign of charge

- Born expansion:

  $$\sigma_{\mathrm{I}} \propto (a_1 Z + a_2 Z^2 + \ldots)^2$$

  $$= b_1 Z^2 + b_2 Z^3 + b_3 Z^4 + \ldots$$

  $$\tfrac{1}{2} m v^2 = T > V = Ze^2 / r \Rightarrow$$

  $$T > 2\ Z \cdot \tfrac{1}{2} m v_0^2 \quad (r = a_0)$$

  Bohrs $\kappa = 2Zv_0 / v < 1$

Capture / No capture

Polarization effect

Coulomb trajectory

Fermi-Teller effect

Mass effects (e^+, e^-, p^+, p^-)

- Kinetic energy $\propto m$

  $\Rightarrow$ Ionization threshold, $v_t \propto 1/m$

  $\Rightarrow$ 'trajectory influence' $\propto 1/m^{>0}$

- Production cross section

  peaks $\sim m_0c^2 \;\Rightarrow$

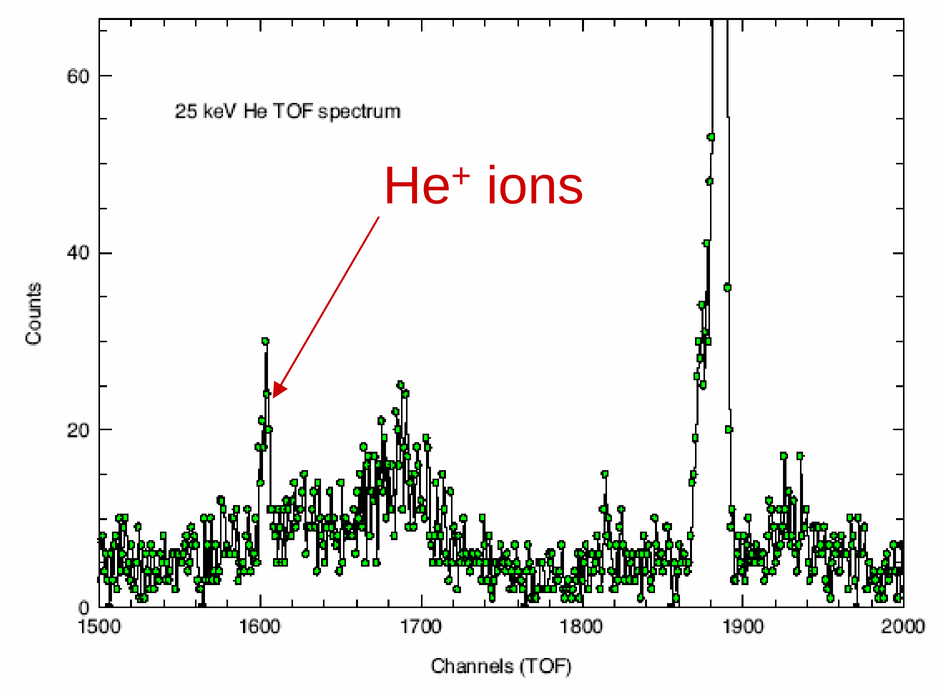
  moderators, decelerators for $T\sim ½ m v_0^2$

RFQD + MUSASHI (Unique combination)

Single ionization of He (preliminary)

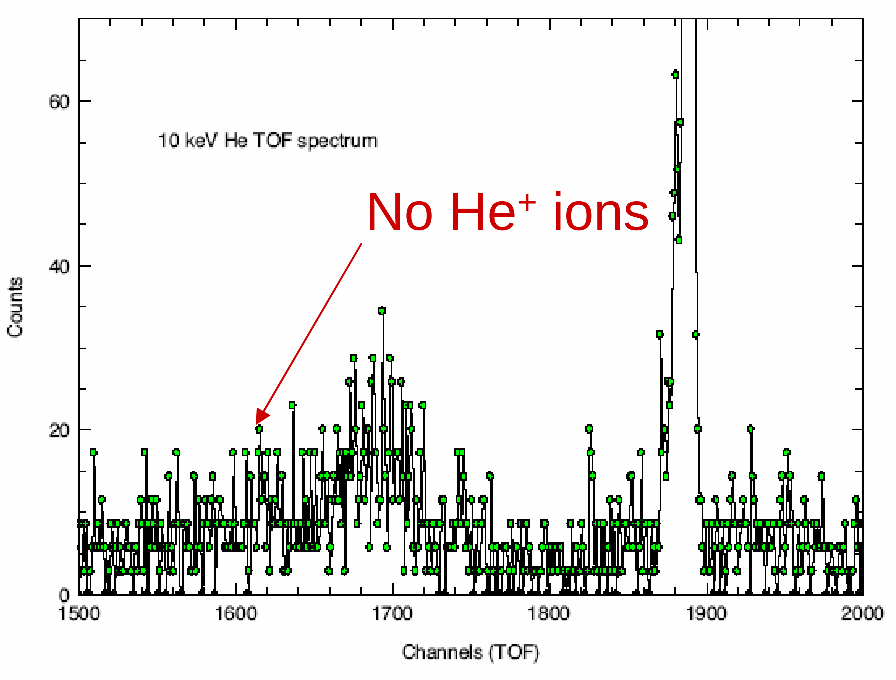
3 days of effective beam time

25 keV, raw



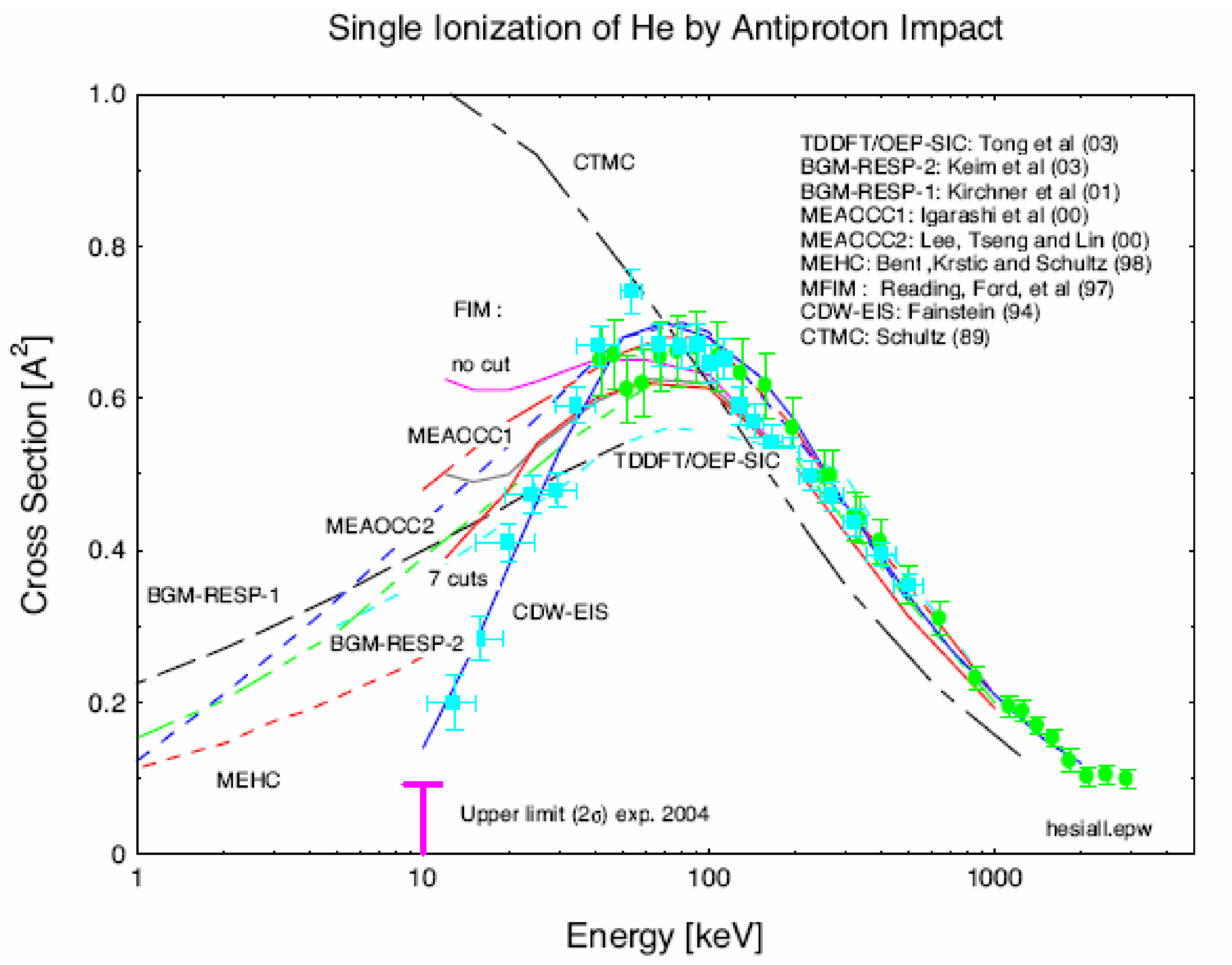
He$^+$ ions

10 keV, raw

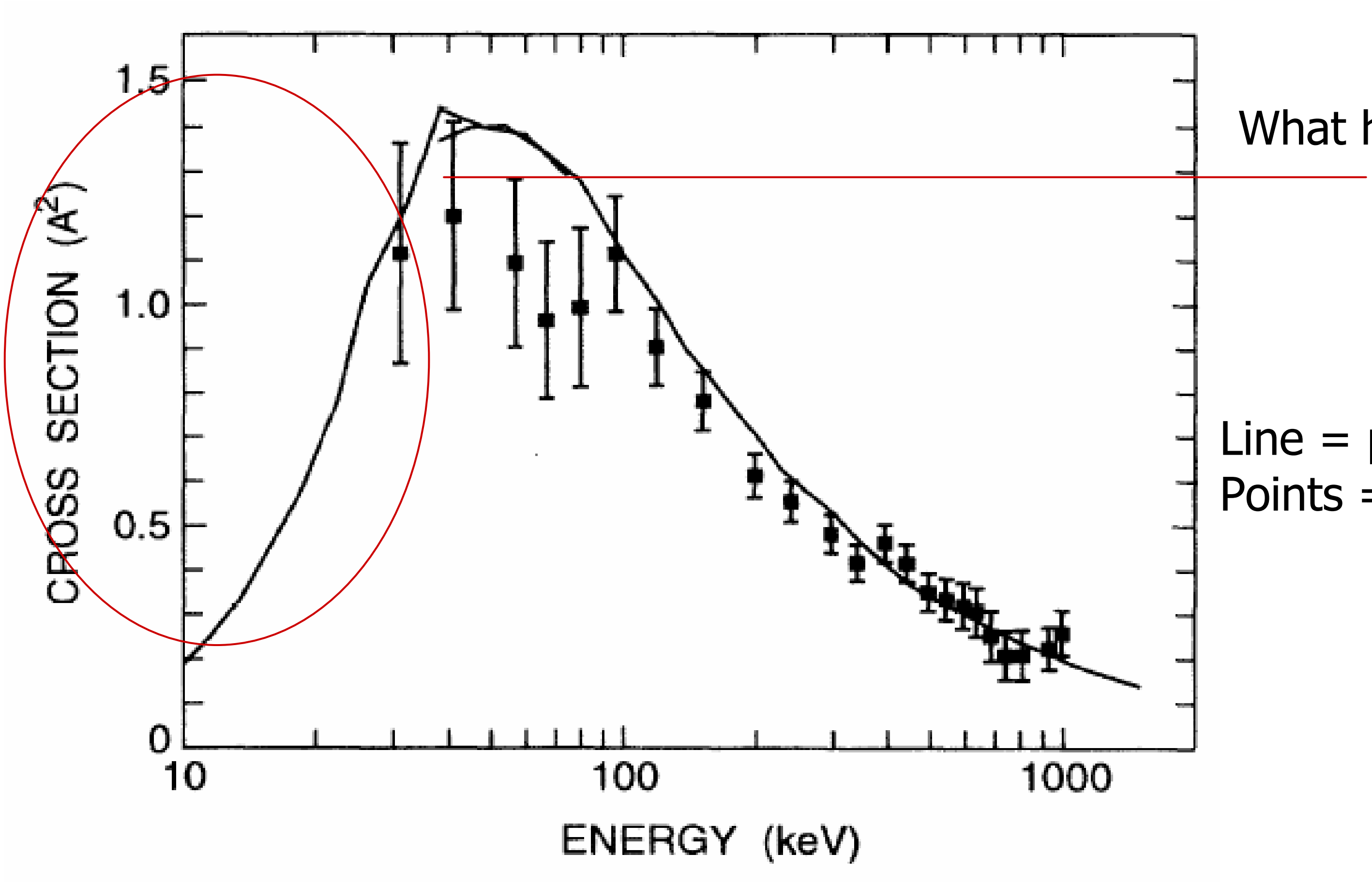


No He$^+$ ions

Single ionization of He (preliminary)



Ionization of atomic (heavy) hydrogen

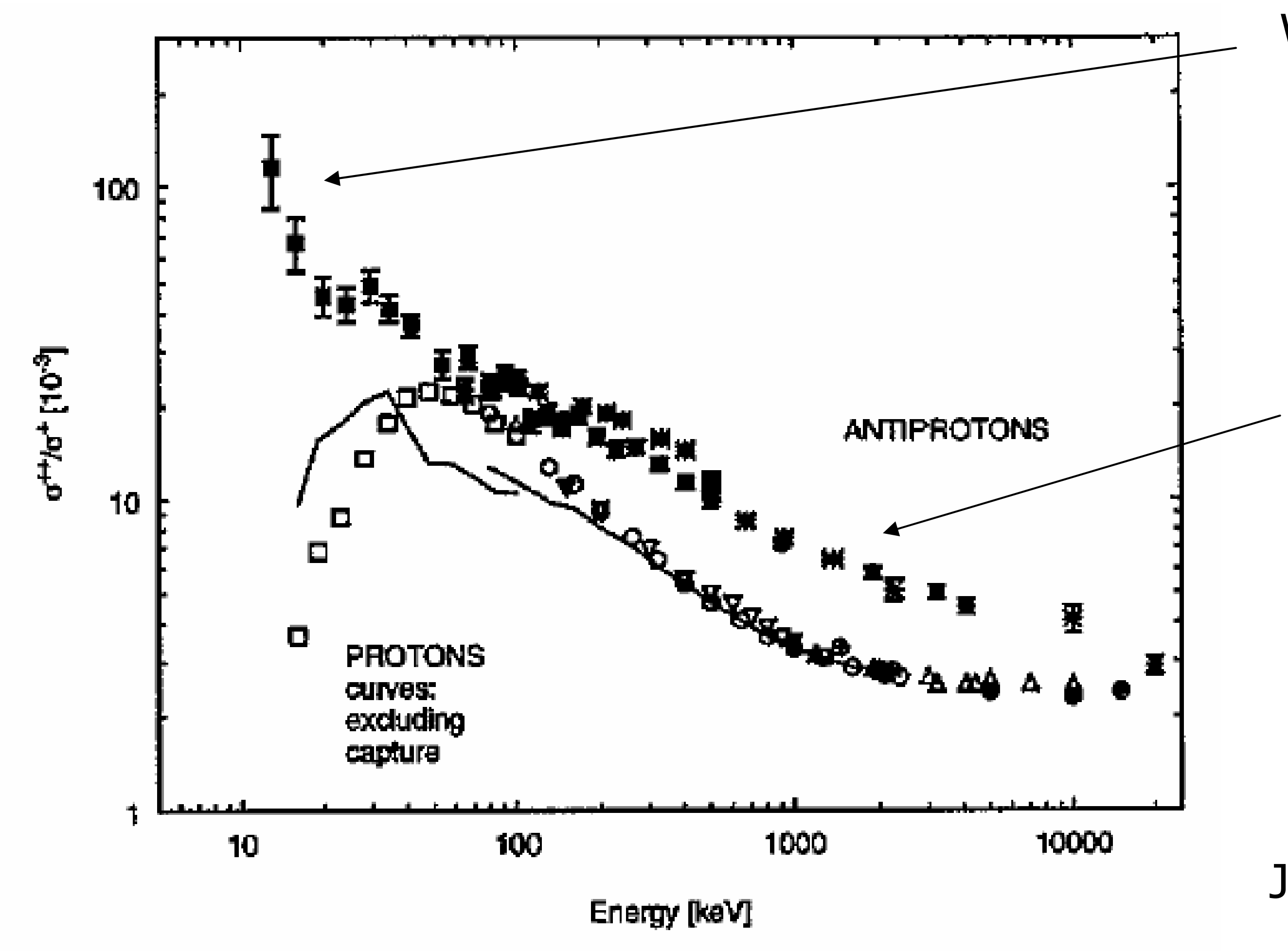


What happens here?

Line = protons
Points = antiprotons

PRL 74, 4627 (1995)

Double ionization of He (ratio)



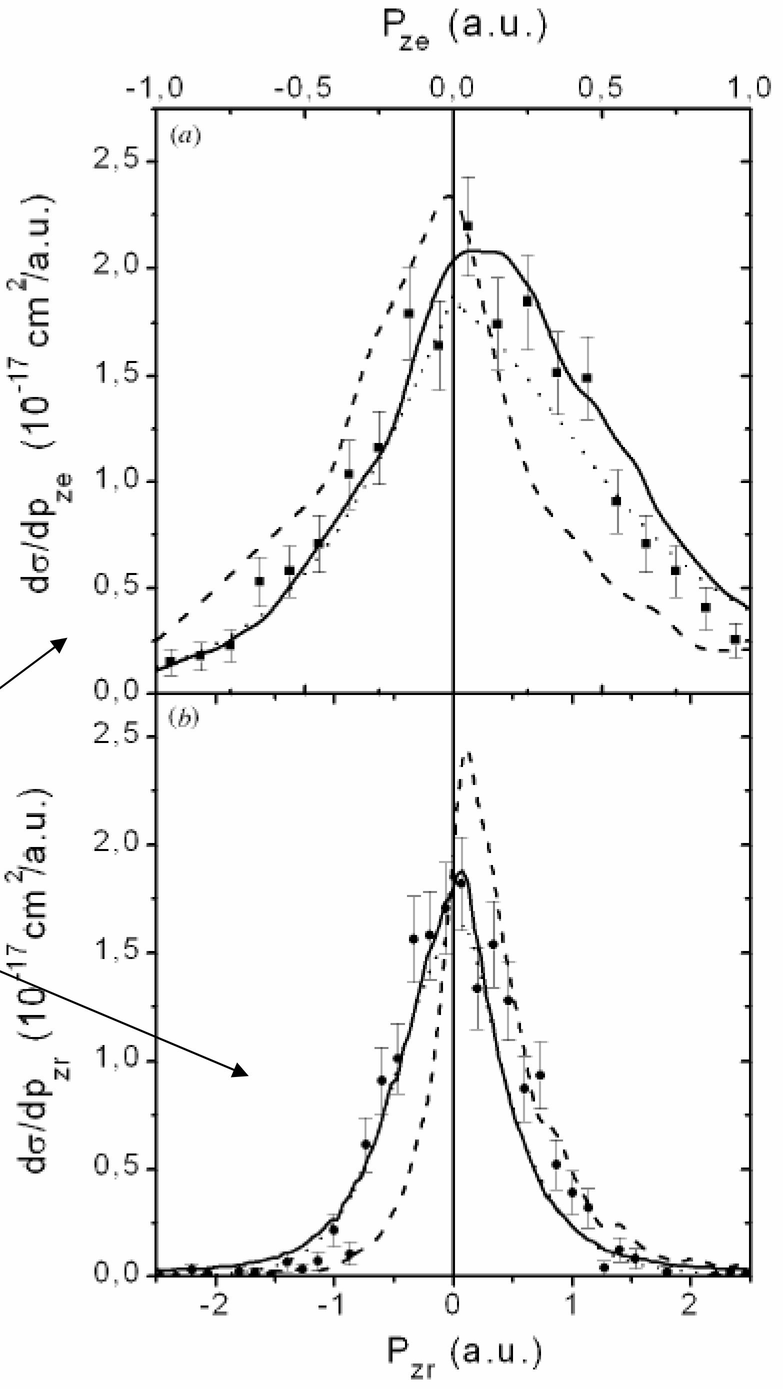
Where does this go?

TS-1 (SO) and TS-2 interference

JPB 27, 925 (1994)

Differential

- Single ionization of He by 945 keV pbars



Longitudinal electron momentum

Longitudinal recoil ion momentum

■ Pbars
—— Protons
- - - - - - - CTMC
············ CDW

Conclusions

- We have measured the stopping powers in a number of targets down to appr. 1 keV for both protons and antiprotons
- Very good agreement between Sigmund's binary theory, the electron gas model and our data for metals – some discrepancy for LiF
- For an insulator (LiF) there is a clear conclusion: There is no "threshold effect" and the absence cannot be explained by "molecular orbitals"
- Previous measurements of the He single cross section at >13 keV are supported by new measurements that indicate a very small ionization at 10 keV.