Realistic modelling for in-flight gas-filled recoil separators

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Working principle of a gas-filled separator in short

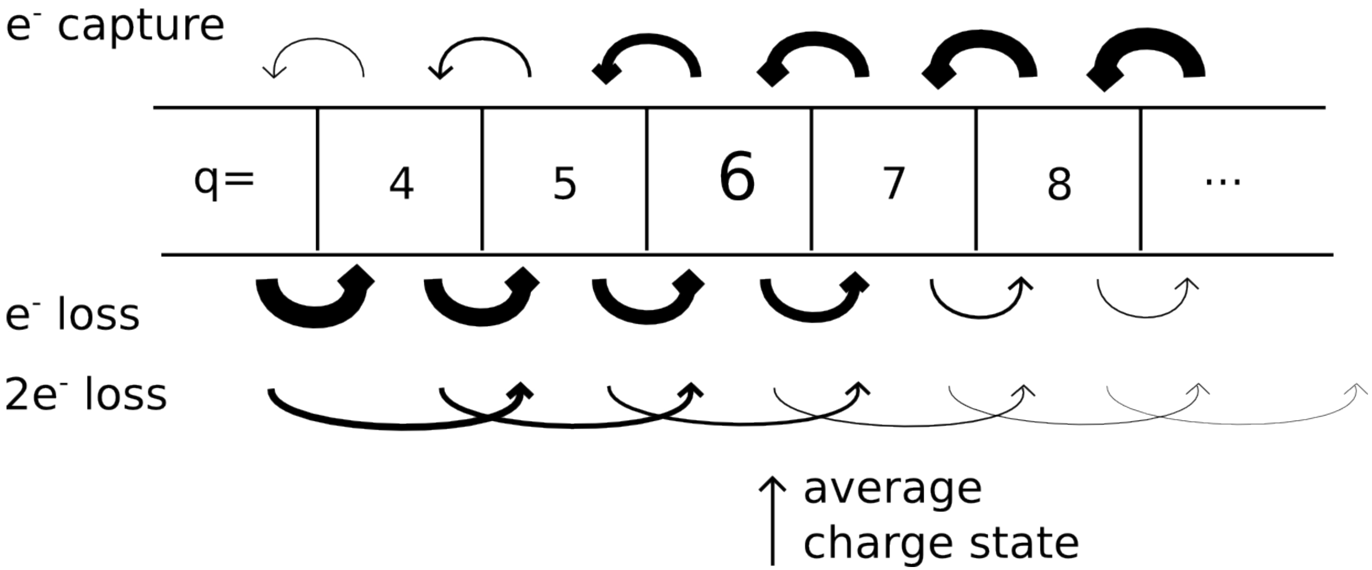
Due to the dense
charge exchange collisions
with the filling gas,
the heavy ion follows a trajectory defined by
a average charge state
and momentum.

The trajectory is
independent on initial charge state after target
which makes gas filled separators efficient.

Additionally, the charge state increases as velocity
increases which enhances also the
energy acceptance.

Working principle of a gas-filled separator

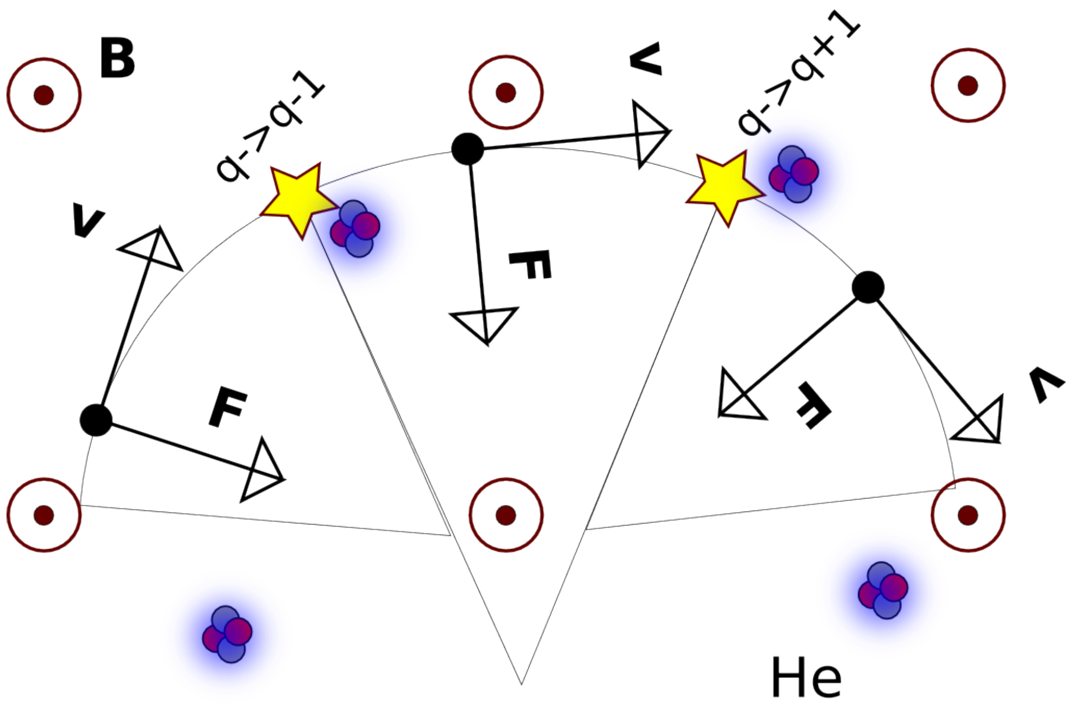
How do the gas-filled separators work?



The heavy ion travels in a low pressure (~1 mbar) gas (He) volume and interacts with the gas molecules. This interaction can change the charge:

q->q-1 : electron capture process
q->q-1 : electron loss process
q->q-2 : two electron loss process

Working principle of a gas-filled separator



Mean free path:

$$l_{qq'} = \frac{1}{n(\sigma_c + \sigma_l)} = \frac{p}{kT(\sigma_c + \sigma_l)}$$

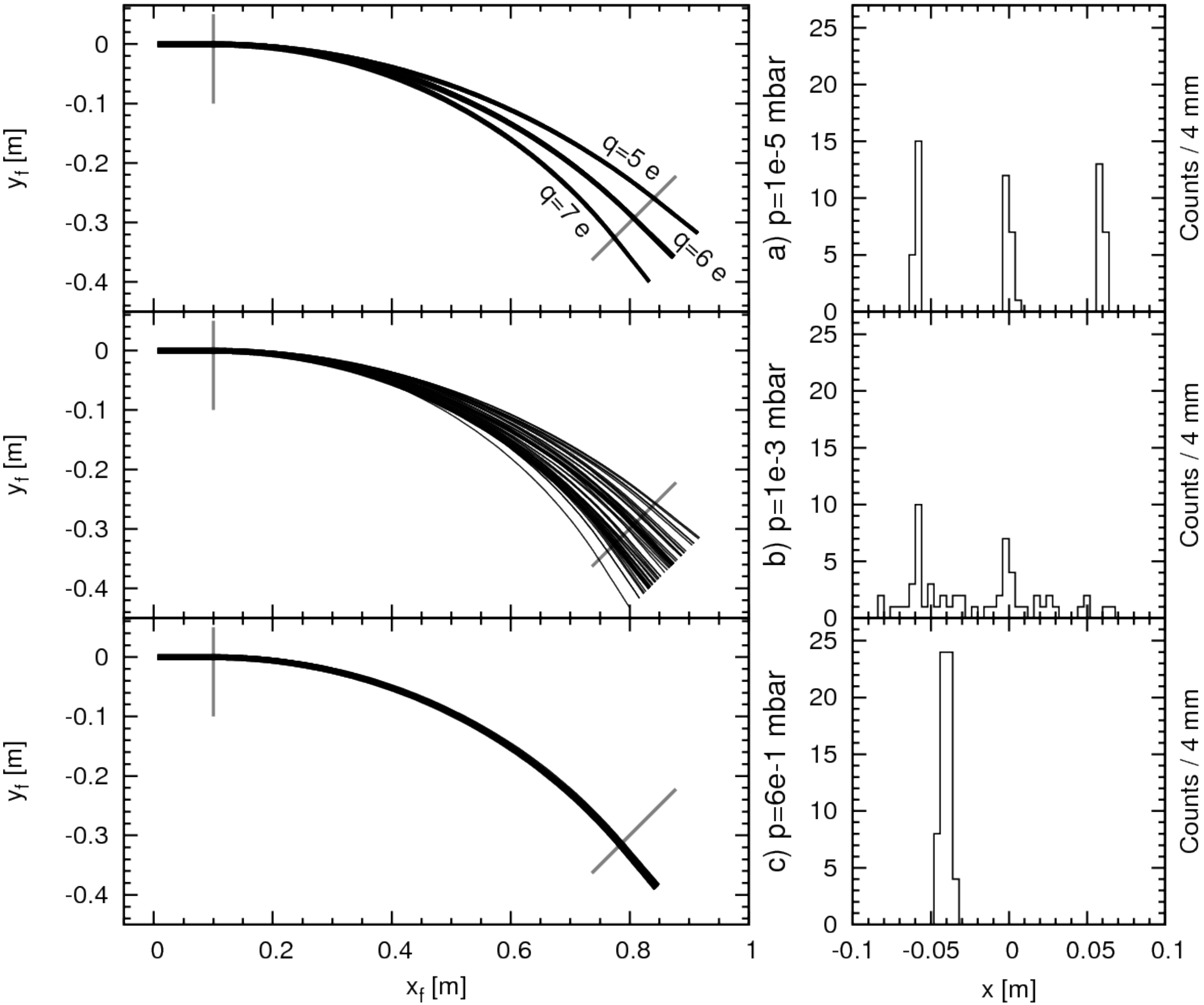
If the *mean free path* between subsequent *charge exchange collisions* is small compared to the bending radius of a dipole magnet then the ion will behave as it had an *effective charge state* and its trajectory is well defined.

Mean free path can be controlled with the gas pressure.

Working principle of a gas-filled separator

An example:

A monoenergetic needle beam through a simple magnetic dipole with different pressures without energy loss and scattering.

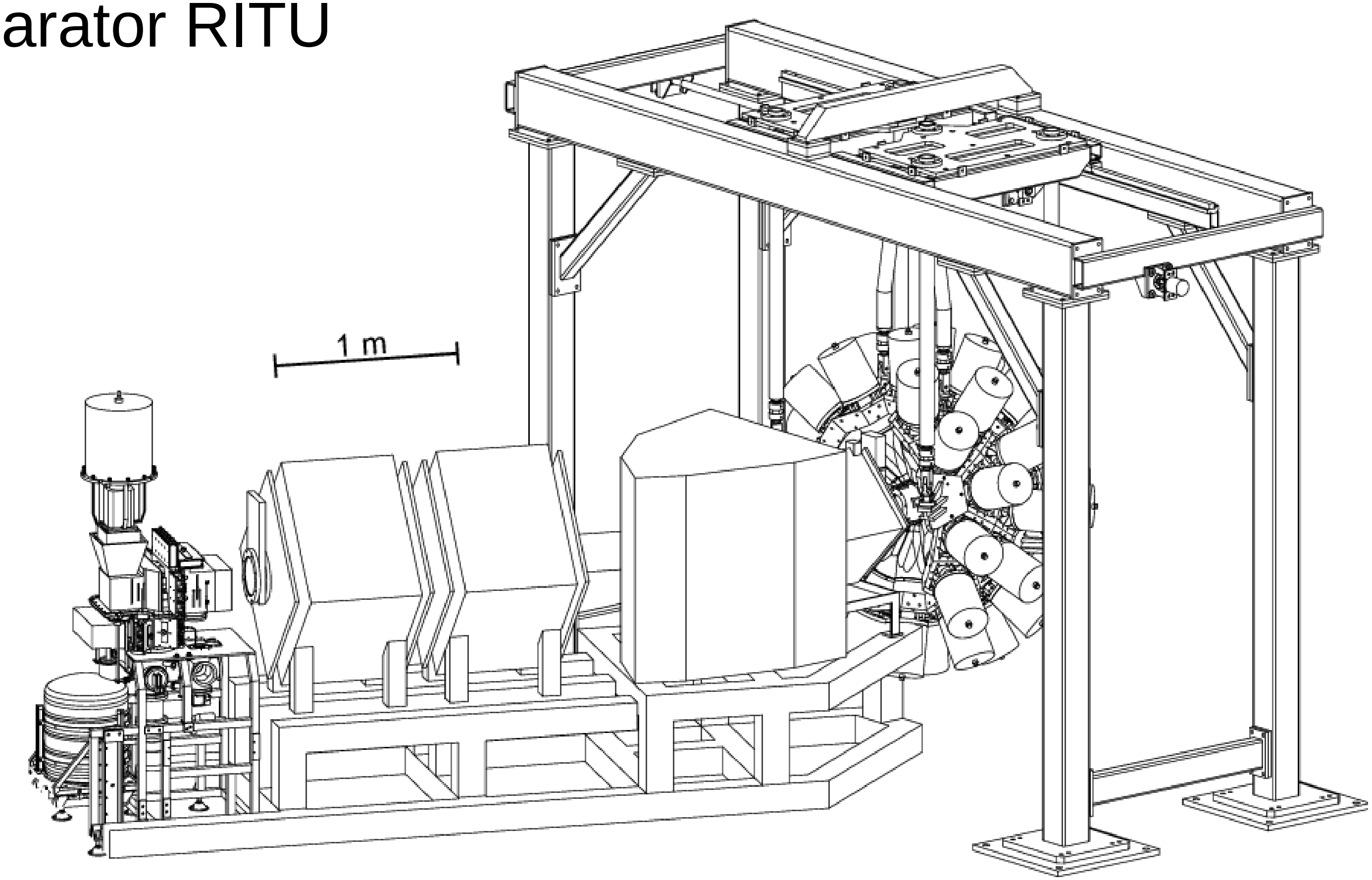


Tests with RITU gas-filled separator

NIM A 654 (2011) 508-521:

J. Sarén, J. Uusitalo, M. Leino, J. Sorri

Absolute transmission and separation properties of the gas-filled recoil separator RITU



Average charge state estimation vs. experiment

The average charge states were calculated with six formulas and compared to the observed one.

Best results are given by Oganessian old and new formulas:

$$q_4 = \begin{cases} 0.394(v/v_0)Z^{1/3} + 1.65 & \text{if } v/v_0 < 9.13Z^{-1/3} \\ 0.723(v/v_0)Z^{1/3} - 1.18 & \text{if } v/v_0 > 9.13Z^{-1/3} \end{cases}$$

$$q_5 = 0.00871(v/v_0)^{1.54}Z^{1.10} + 2.05$$

Also the formula by Gregorich (PRC72(2005)014605) gives good results (m=0.641, b=-0.235, d=0.517, f=74.647):

$$\bar{q}_7 = mx + b + d\sin\left\{\frac{2\pi}{32}\left[Z - (mx+b) - f\right]\right\}$$

$$x = \frac{v}{v_0}Z^{1/3} \quad (\text{valid for } Z \gtrsim 45)$$

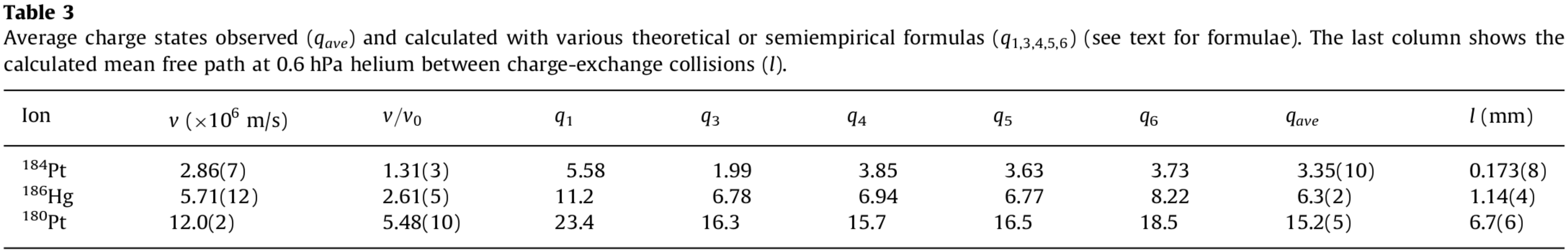


Table 3

Average charge states observed (q_{ave}) and calculated with various theoretical or semiempirical formulas ($q_{1,3,4,5,6}$) (see text for formulae). The last column shows the calculated mean free path at 0.6 hPa helium between charge-exchange collisions (l).

Ion	v ($\times 10^6$ m/s)	v/v_0	q_1	q_3	q_4	q_5	q_6	q_{ave}	l (mm)
^{184}Pt	2.86(7)	1.31(3)	5.58	1.99	3.85	3.63	3.73	3.35(10)	0.173(8)
^{186}Hg	5.71(12)	2.61(5)	11.2	6.78	6.94	6.77	8.22	6.3(2)	1.14(4)
^{180}Pt	12.0(2)	5.48(10)	23.4	16.3	15.7	16.5	18.5	15.2(5)	6.7(6)

Density effect

It has been observed, also in our tests, that higher density i.e. shorter mean free time between collisions leads to a higher average charge state!

One should note that the energy loss in gas drives charge state down when pressure is increased!

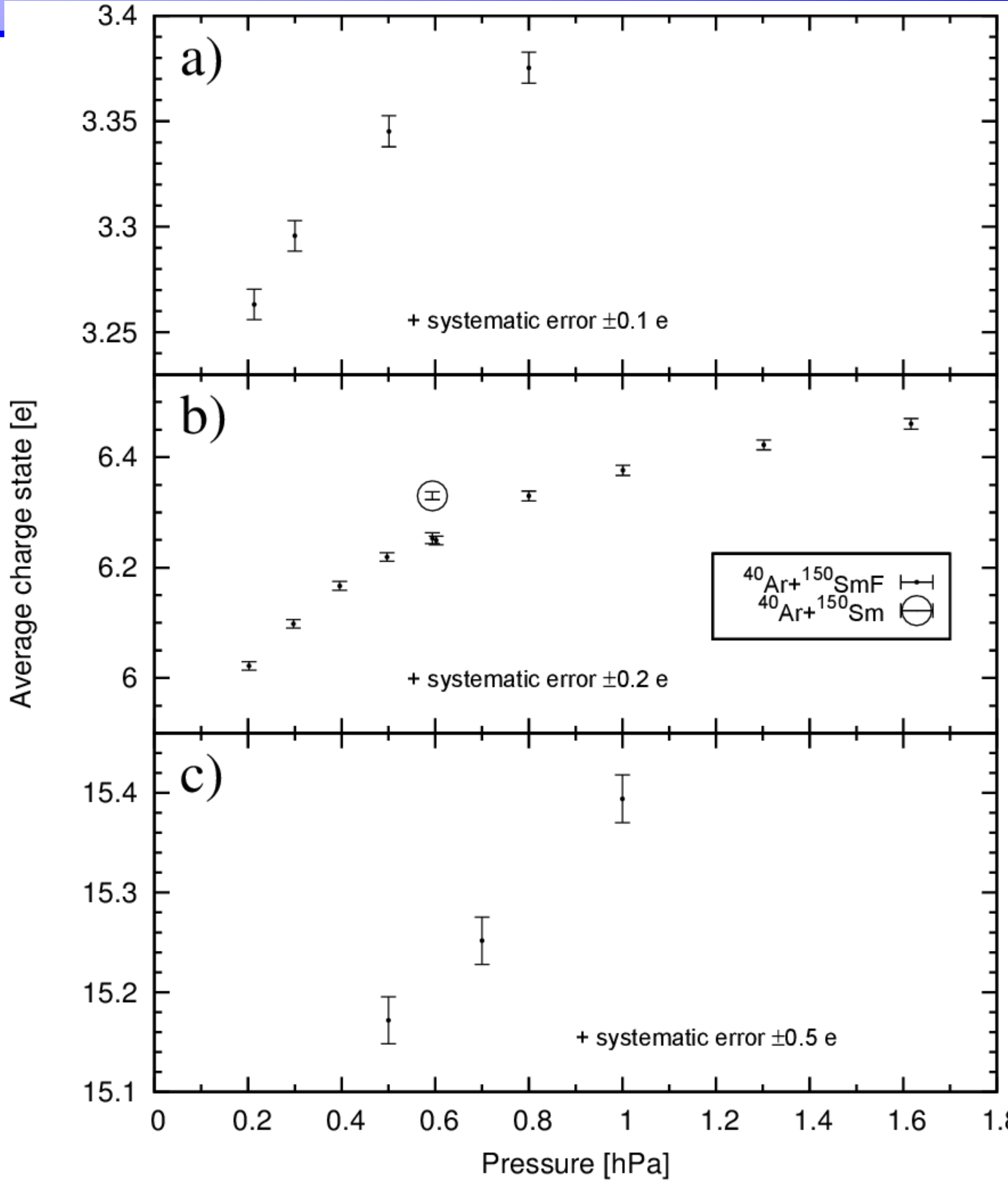


Figure: Development of the average charge state of an evaporation residue as a function of pressure in reactions:

(a) 168Er(20Ne,4n)184Pt,

(b) 150SmF(40Ar,4n)186Hg and

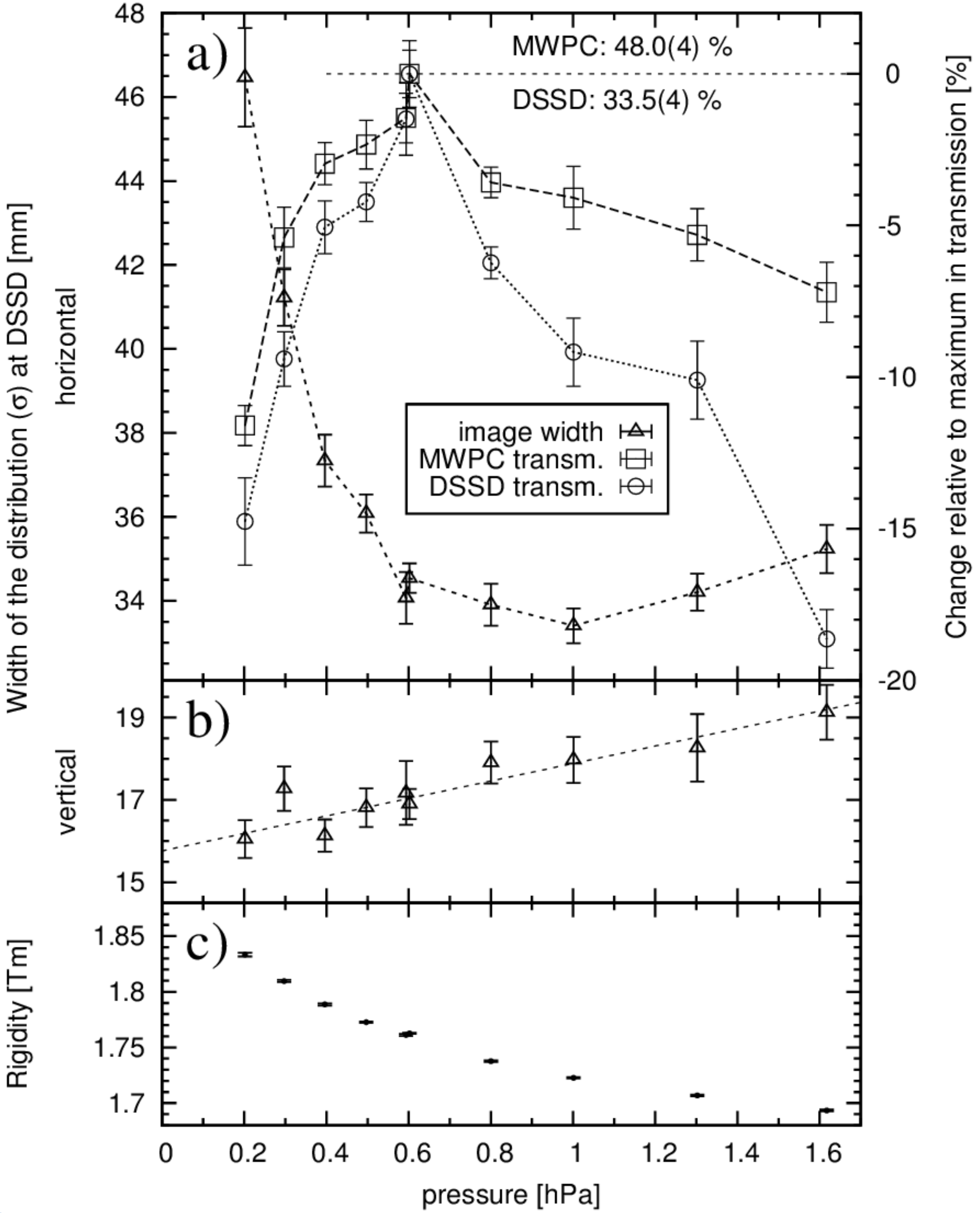
(c) natMo(84Kr,4n)180Pt

Balance between mean free path and scattering

There is always an optimal pressure(s) where image size is minimized – this is due to processes: charge exchange statistics and scattering in gas.

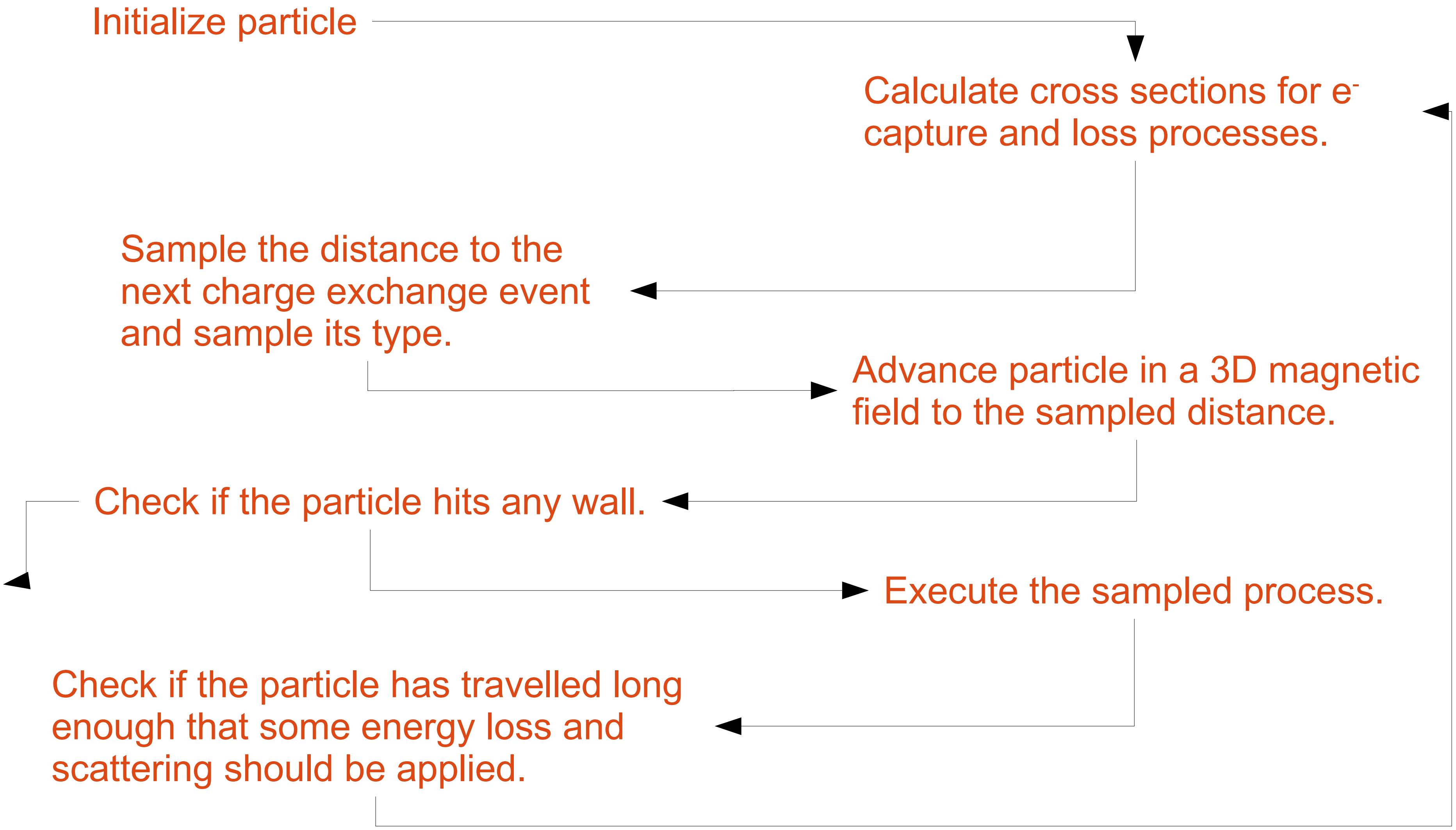
Optimal pressure is device dependant!

Nondispersive (here vertical) direction gives information about scattering.



Simulation of a gas-filled separator

How to implement the simulation of a gas-filled separator in practice:



Initialize particle

Calculate cross sections for e^- capture and loss processes.

Sample the distance to the next charge exchange event and sample its type.

Advance particle in a 3D magnetic field to the sampled distance.

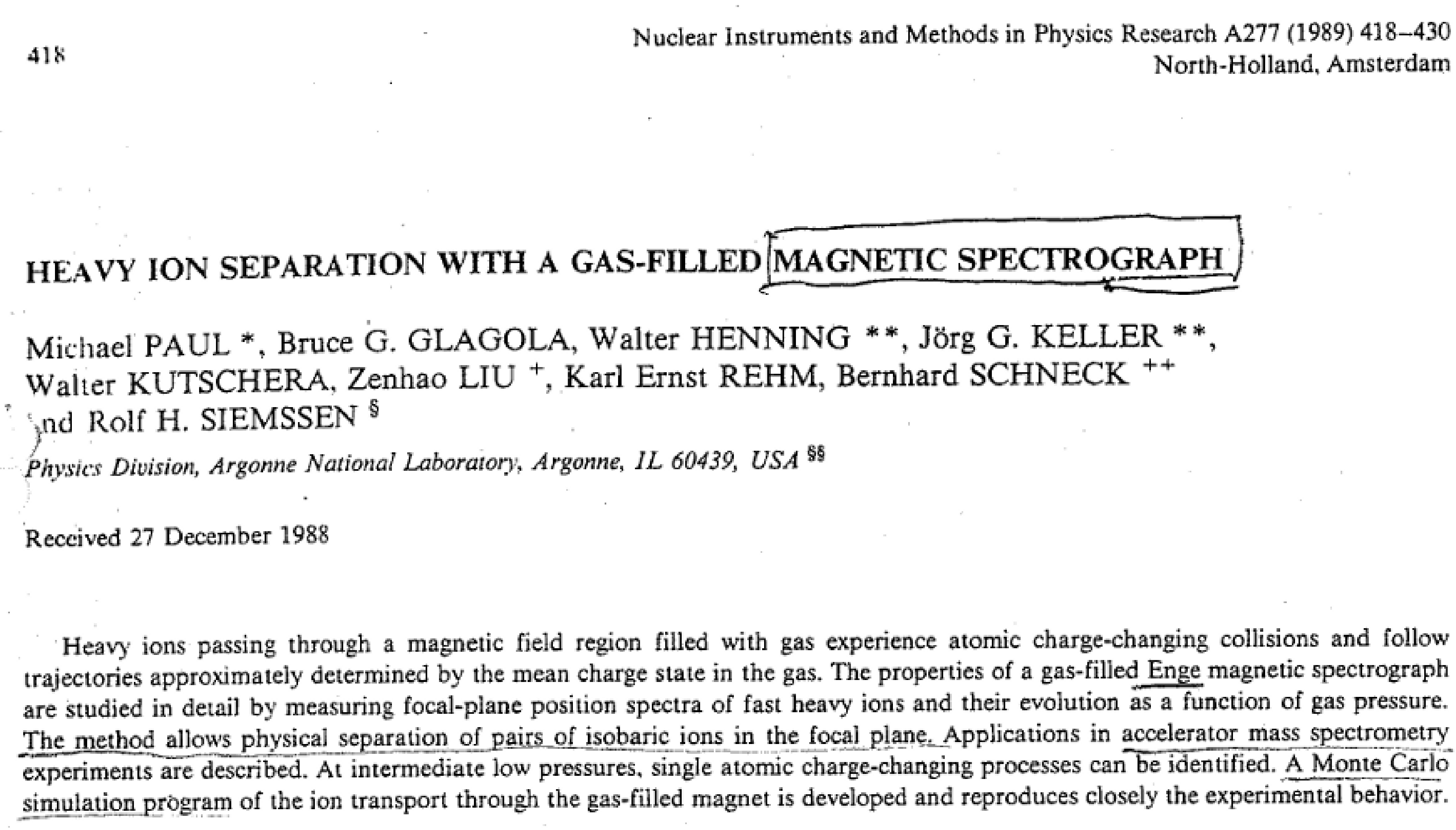
Check if the particle hits any wall.

Execute the sampled process.

Check if the particle has travelled long enough that some energy loss and scattering should be applied.

Simulation of a gas-filled separator

A first realistic Monte Carlo simulation. All others use similar methods.



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Nuclear Instruments and Methods in Physics Research A277 (1989) 418–430
North-Holland, Amsterdam

HEAVY ION SEPARATION WITH A GAS-FILLED MAGNETIC SPECTROGRAPH

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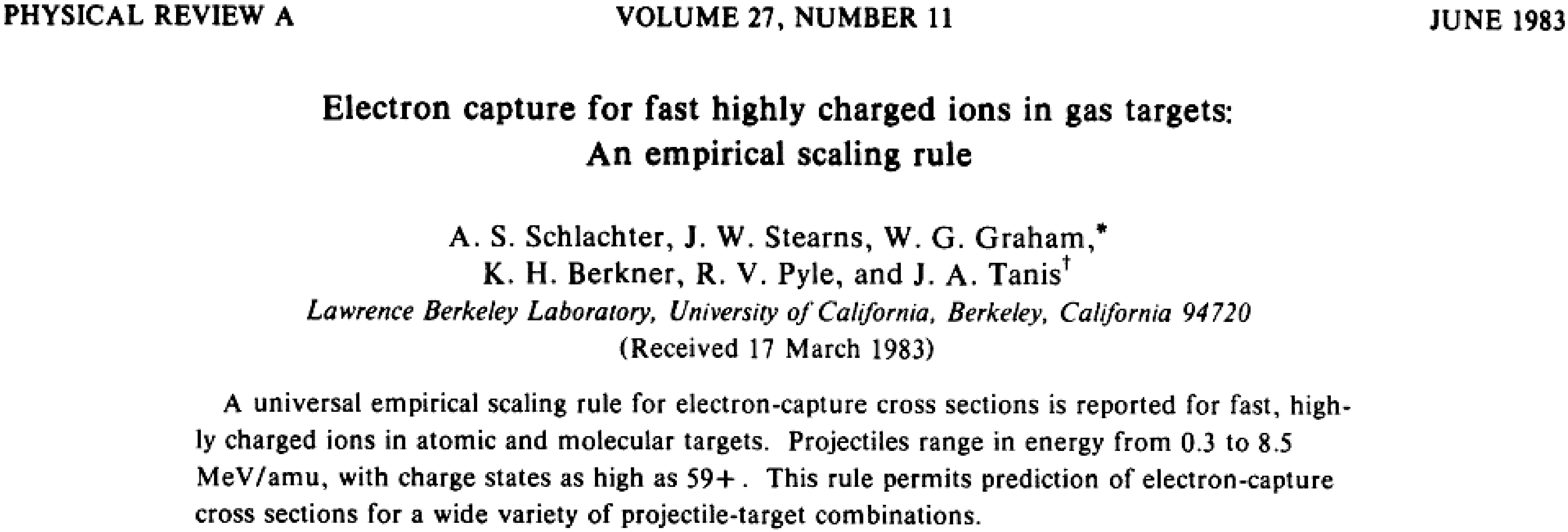
Received 27 December 1988

Heavy ions passing through a magnetic field region filled with gas experience atomic charge-changing collisions and follow trajectories approximately determined by the mean charge state in the gas. The properties of a gas-filled Enge magnetic spectrograph are studied in detail by measuring focal-plane position spectra of fast heavy ions and their evolution as a function of gas pressure. The method allows physical separation of pairs of isobaric ions in the focal plane. Applications in accelerator mass spectrometry experiments are described. At intermediate low pressures, single atomic charge-changing processes can be identified. A Monte Carlo simulation program of the ion transport through the gas-filled magnet is developed and reproduces closely the experimental behavior.

Electron capture and loss cross sections



PHYSICAL REVIEW A VOLUME 27, NUMBER 11 JUNE 1983

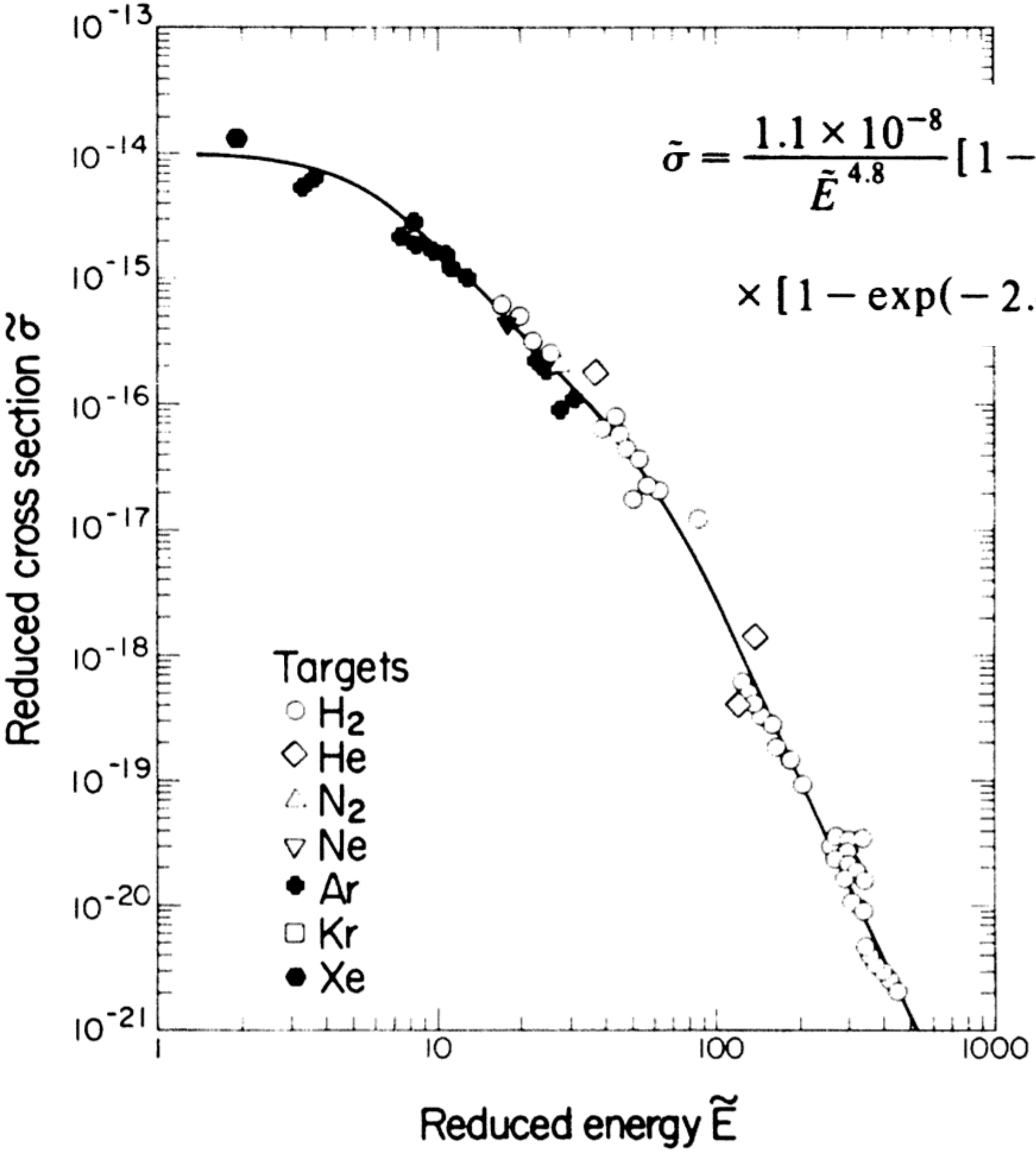
Electron capture for fast highly charged ions in gas targets: An empirical scaling rule

A. S. Schlachter, J. W. Stearns, W. G. Graham,*
K. H. Berkner, R. V. Pyle, and J. A. Tanis†
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

(Received 17 March 1983)

A universal empirical scaling rule for electron-capture cross sections is reported for fast, highly charged ions in atomic and molecular targets. Projectiles range in energy from 0.3 to 8.5 MeV/amu, with charge states as high as 59+. This rule permits prediction of electron-capture cross sections for a wide variety of projectile-target combinations.

Electron capture and loss cross sections



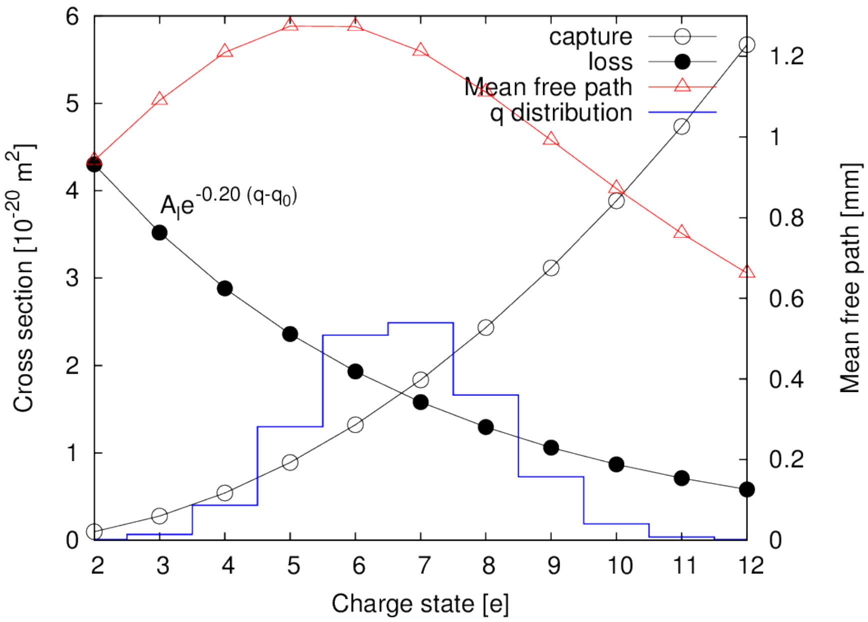
$$\tilde{\sigma} = \frac{1.1 \times 10^{-8}}{\tilde{E}^{4.8}}\left[1 - \exp(-0.037\tilde{E}^{2.2})\right] \times \left[1 - \exp(-2.44 \times 10^{-5}\tilde{E}^{2.6})\right] \, .$$

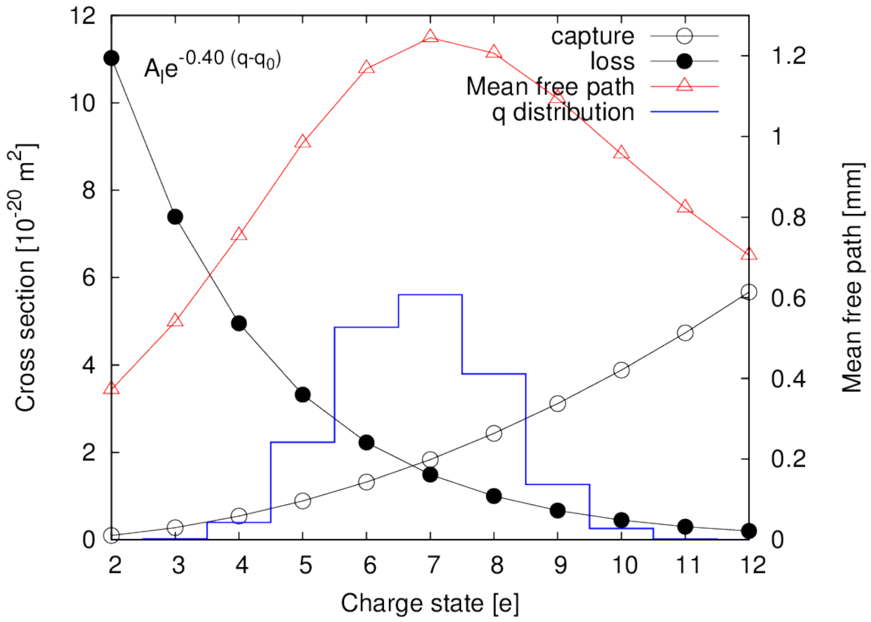
Conclusion this far:

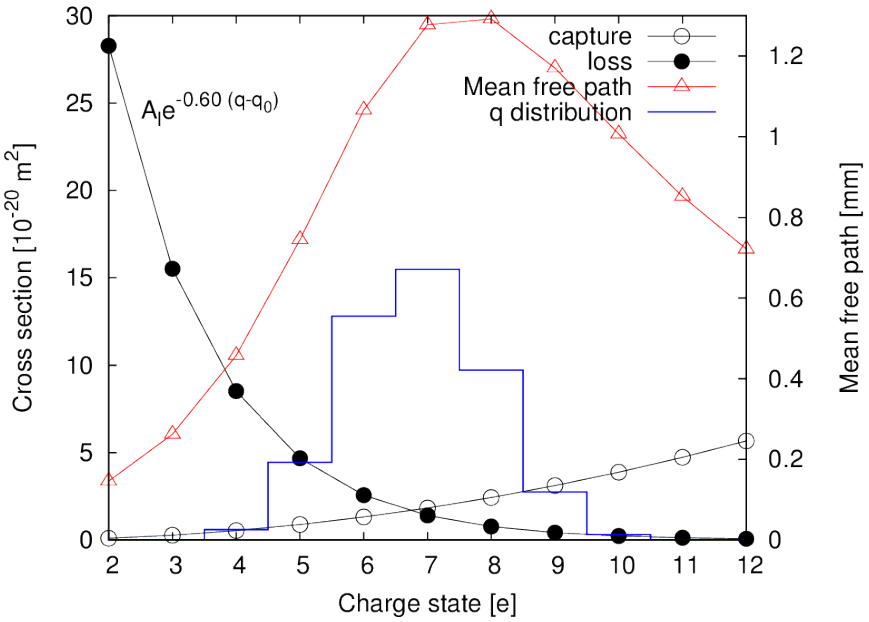
Cross sections for the electron capture process can be calculated with a reasonable accuracy.

How about the electron loss process...

Electron capture and loss cross sections





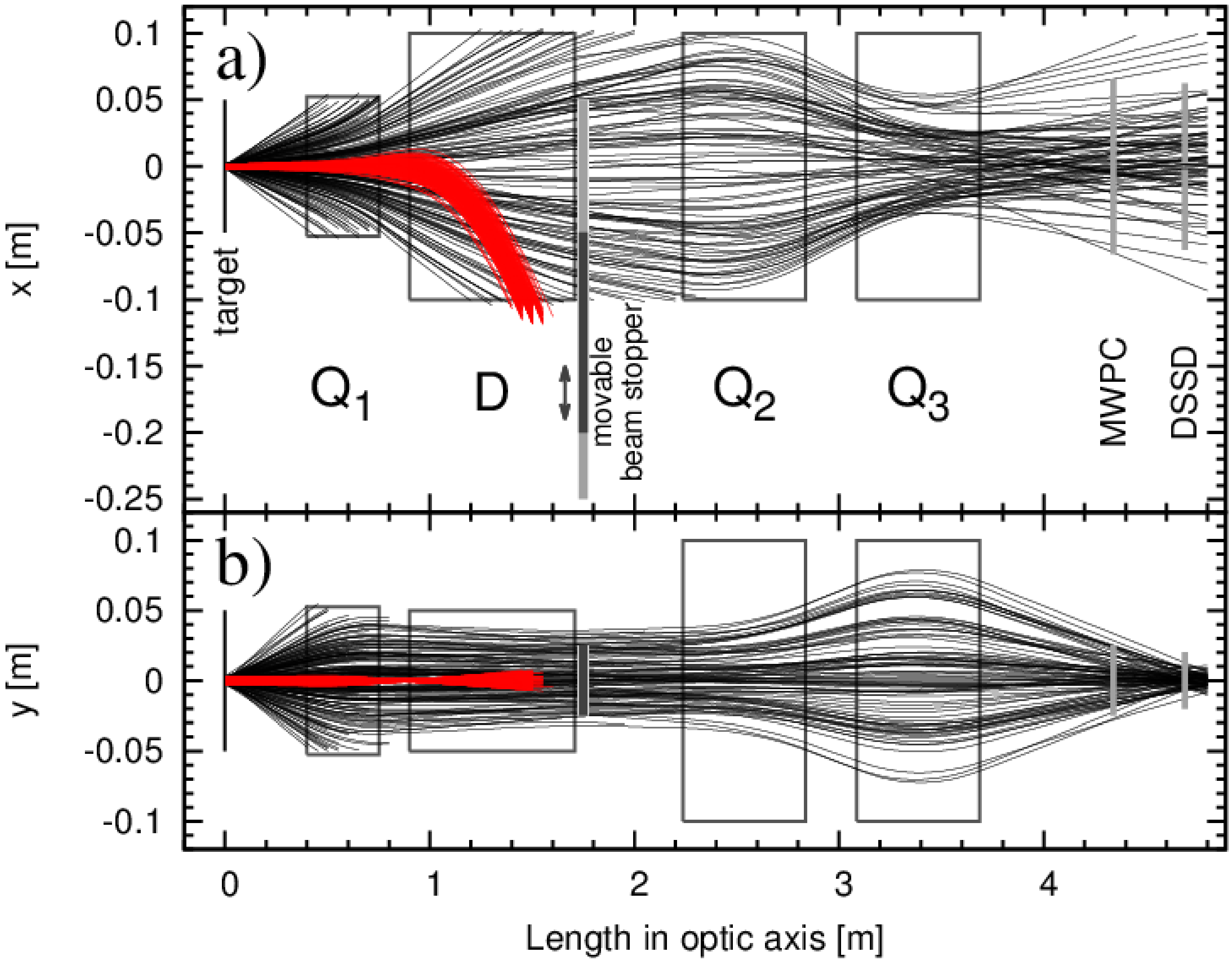


Strategy to obtain the electron loss cross section:

- Use exponential model for the electron loss cross section.
- At *average charge state*, q_0, the electron loss and capture cross sections must be equal.
- Guess the factor in exponential function. Here values 0.2, 0.4 and 0.6 are shown for 31 MeV 186Hg. This factor affects on q-distribution width.

Simulating RITU separator

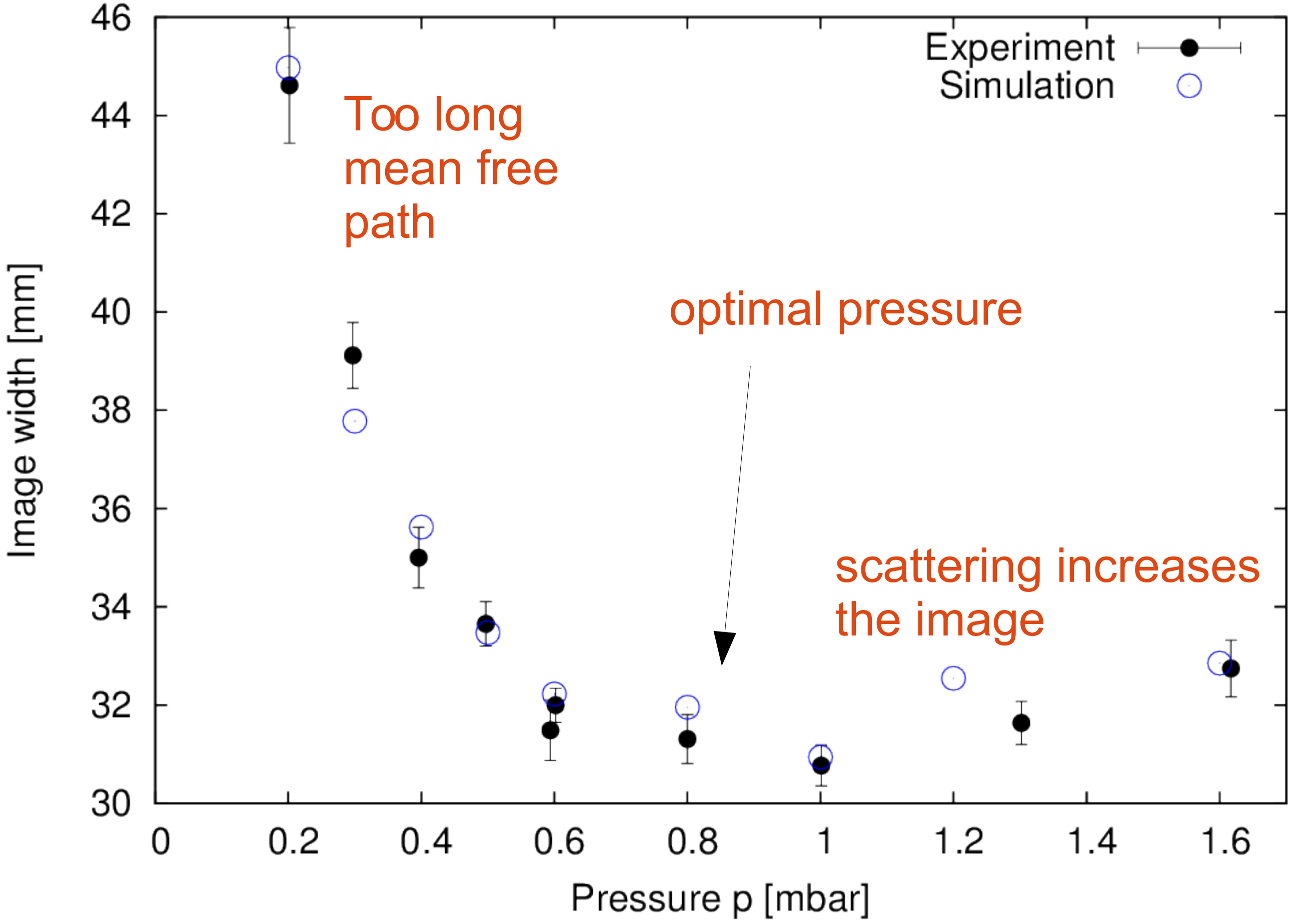
Some simulated 186Hg trajectories in RITU (0.6 mbar):



Simulating RITU separator

A new simulation code applied to the 40Ar + 150SmF run in RITU

In dispersive, horizontal direction:



Too long mean free path

optimal pressure

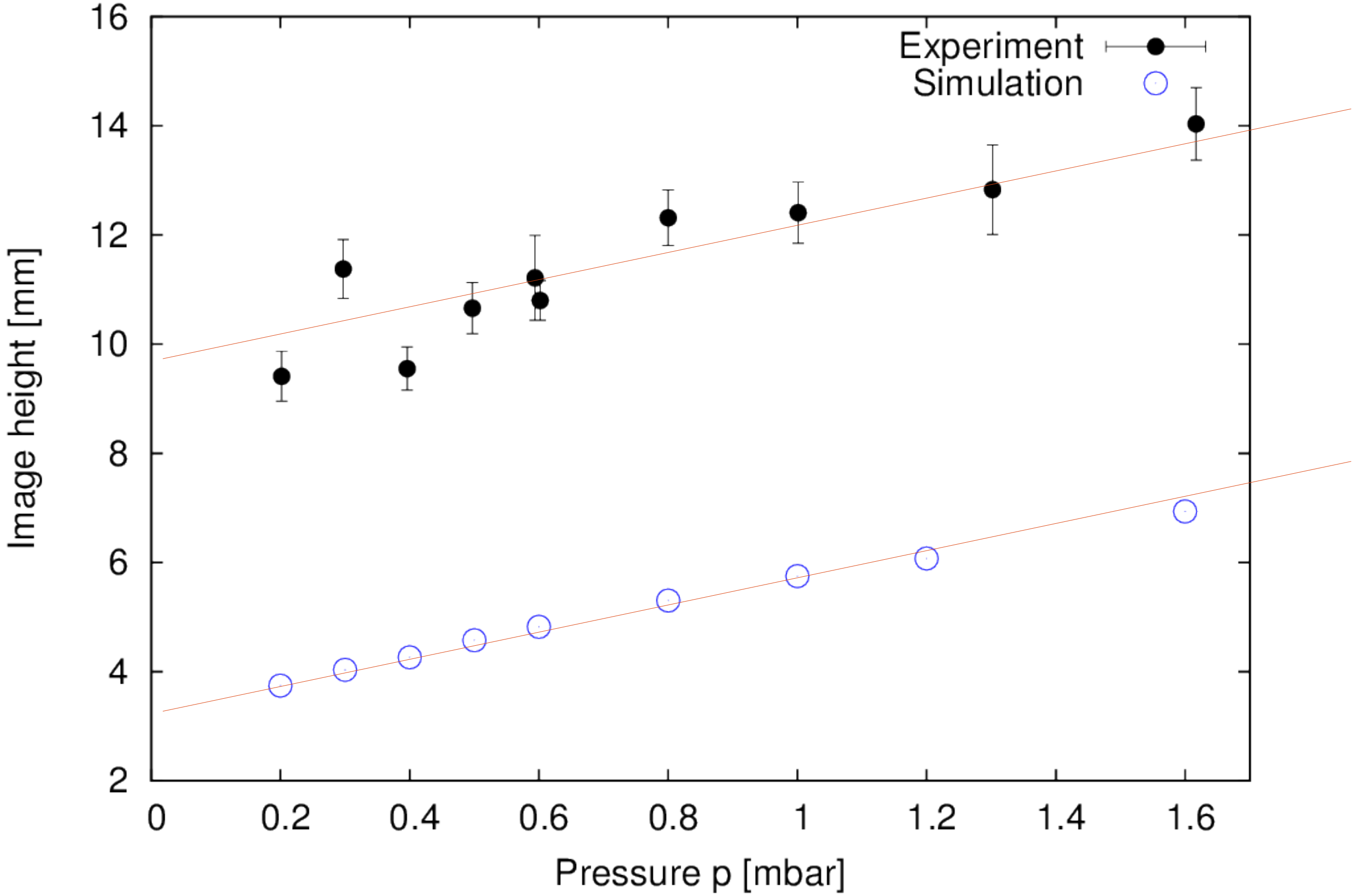
scattering increases the image

The shape of the width as a function of pressure is given mainly by the initial energy distribution and the capture and loss cross sections.

Simulating RITU separator

A new simulation code applied to the 40Ar + 150SmF run in RITU

In nondispersive, vertical, direction:



Here the slope is most important. It is used to adjust the scattering in gas.

Simulating RITU separator

The density effect

The density effect was found to be reproduced quite nicely with two parameter model. Parameters are:

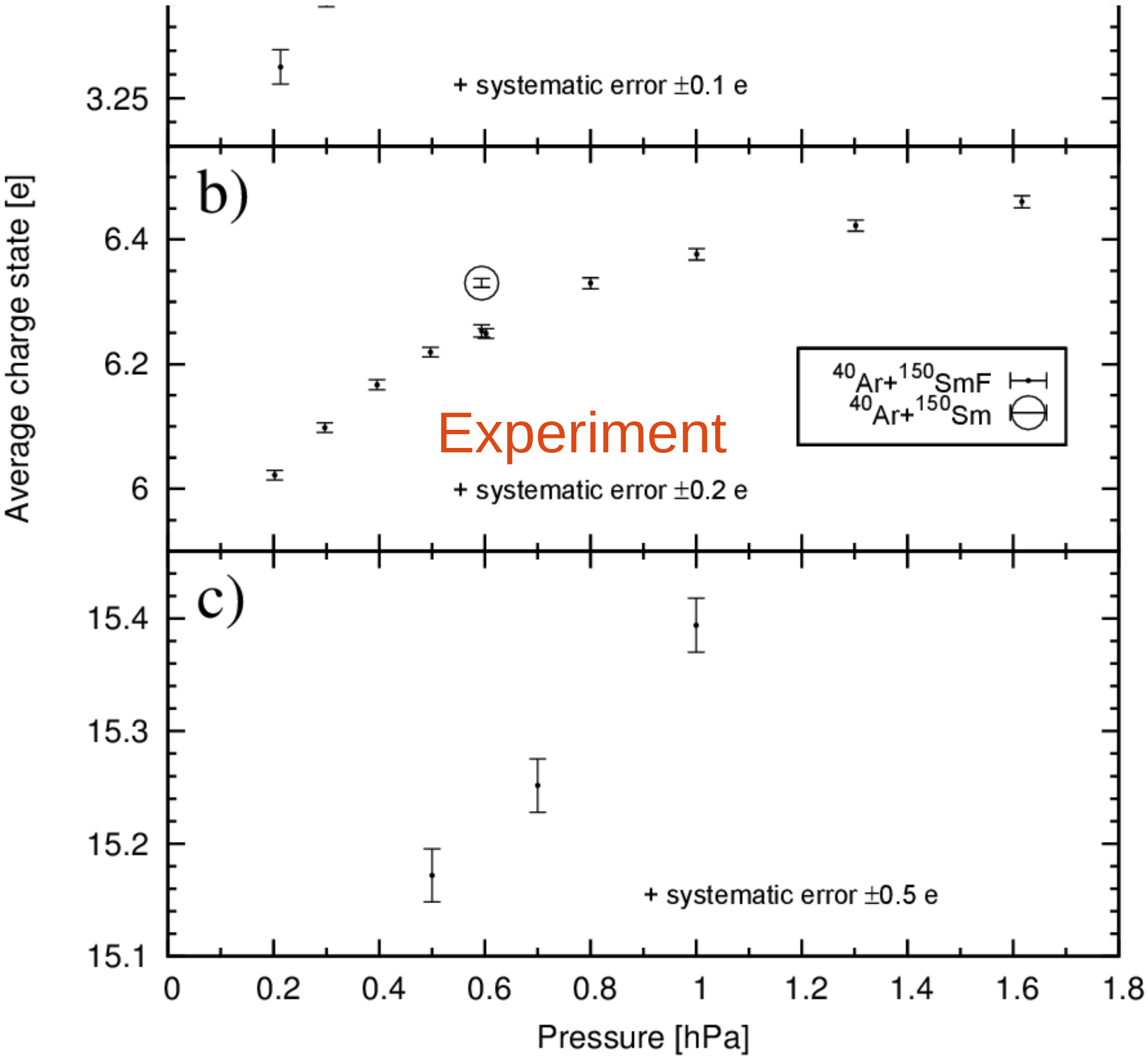
1) a lifetime of the atomic exitation after an charge exchange collision and
2) a hindrance factor which is used to decrease the electron capture cross section while the atom is exited.

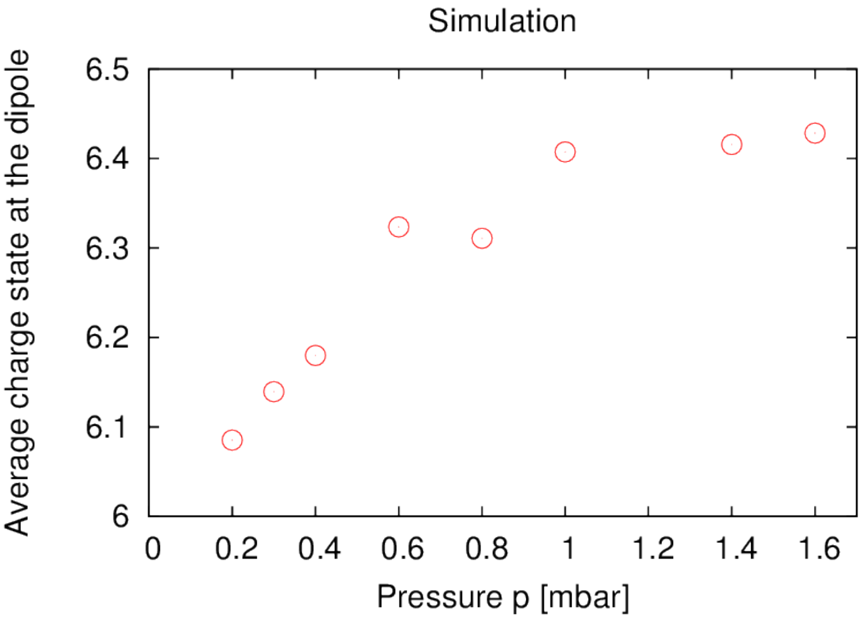
Values around 0.5 – 1 ns for the half life and value of 1.5 – 2.0 for the hindrance factor reproduces the observed change in average charge state as a function of pressure for the 186Hg. Other cases needs to be studied.

Simulating RITU separator

A new simulation code applied to the 40Ar + 150SmF run in RITU

Density effect:





Simulation parameters and their sources

- Particles from the fusion kinematics code or angular distribution and energy distribution
- Energy losses and scattering in the gas from 1) an external model, 2) experiment or 3) TRIM
- Density effect parameters (life time and hindrance factor for capture) from experiment. To be studied how these change for different reactions!
- Factor in the exponential model for electron loss from experiment. To be studied how this changes for different reactions.
- Average charge state from an empirical formula.

Conclusions about simulations

- The used set of parameters in the simulation model seems to be adequate to reproduce the observed phenomena.
- Interplay between parameters is not straightforward and needs to be studied carefully.
- The model developed can enable us to design slightly better experiments and to understand the observed distributions.

What next?

- To analyse the effect of the parameters in a systematic way.
- Analyse the transmission as a function of pressure.
- Compare the other reactions and future RITU reaction to simulations.
- Add ”large angle” collisions with helium.
- Add target like products.
- Add weights to code in order to simulate beam rejection.
- Simulate the alphas scattered by beam.
- Publish the code as open source.

Thank you