A new charge-reset method for determining Auger-electron emission multiplicities

Dr Jacob Heery

UNIVERSITY OF SURREY

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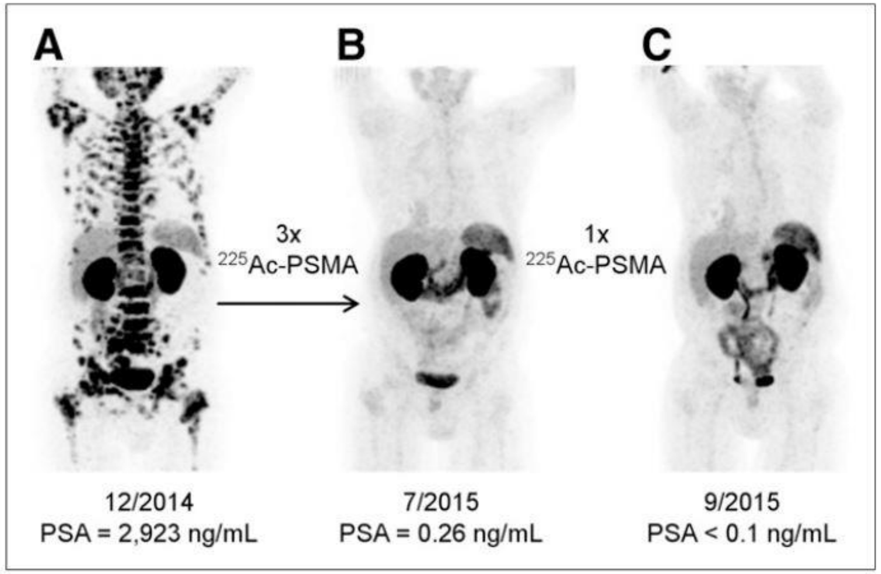
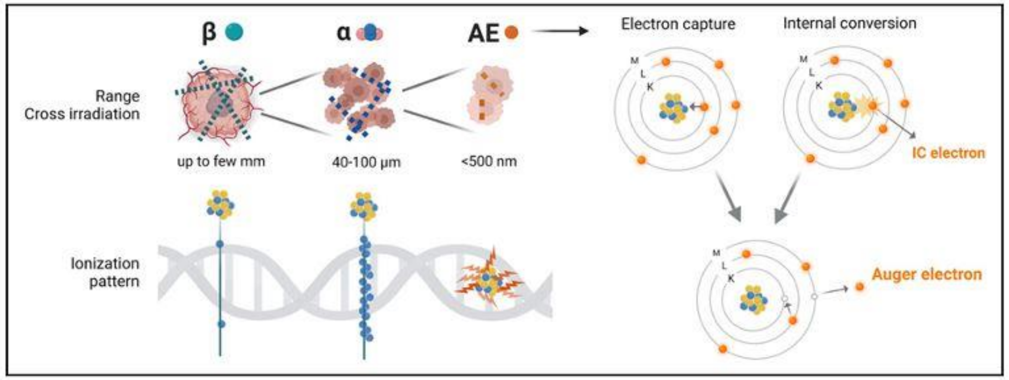
Background

Targeted radiotherapy

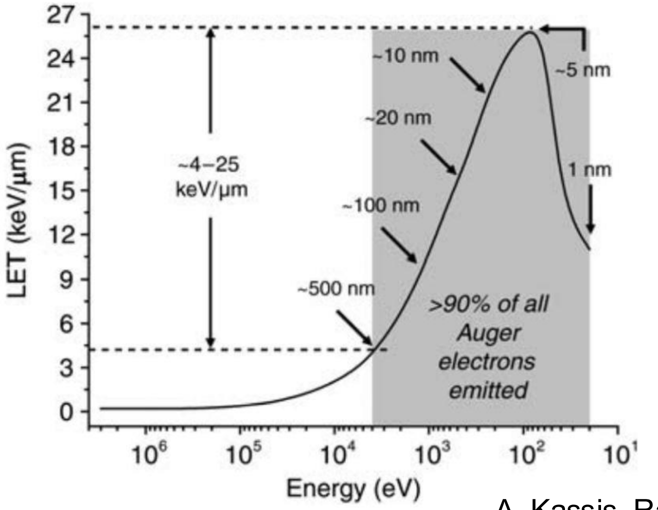


C. Kratochwil, et al. Journ. Nucl. Med., **57** 12 (2016)

Auger electron emission



J. Bolcaen, et al. Journ. Nucl. Med., **64** 9 (2023)

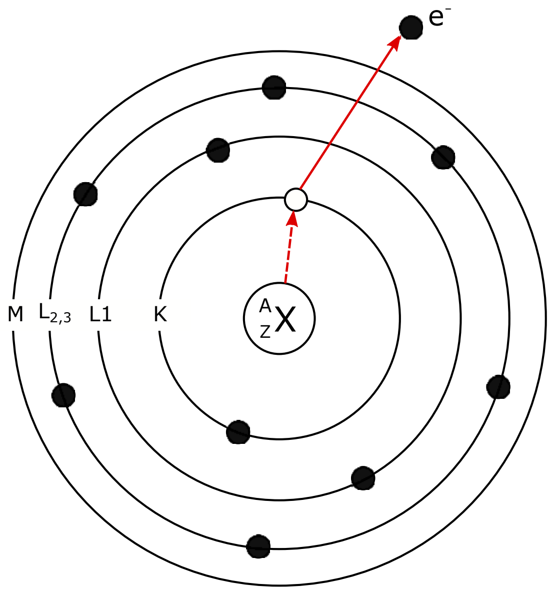


Particle	Linear Energy Transfer	Projected Range (NIST)
5-MeV alpha particle	95 keV μm^{-1}	40 μm
1-MeV electron	0.25 keV μm^{-1}	4.4 mm

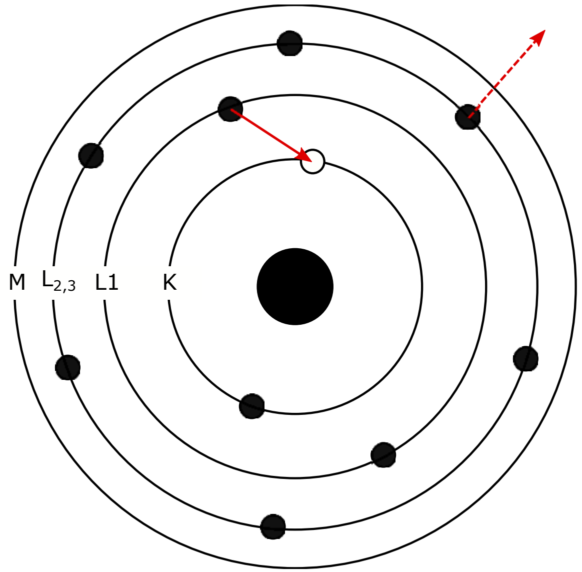
A. Kassis, Radiation Protection Dosimetry **143** 241 (2011)

What is an Auger electron?

Internal conversion



Auger emission



Notation: XYZ

X = (sub)shell of initial vacancy
Y = (sub)shell of de-exciting electron
Z = (sub)shell of emitted electron

$$E(X,YZ) = BE(X) - BE(Y) - BE(Z) + \varnothing$$

ø = Term related to hole-hole couplings

What makes a good Auger emitter?

From J. Bolcaen, et al. Journ. Nucl. Med., **64** 9 (2023)

Each category gets scored 1-5

Overall dosimetry score = $\langle \#AE \rangle + \langle T_{1/2} \rangle + \langle S_{all}^{self} \rangle + \left\langle \frac{S_{all}^{self}}{S_{all}^{self} + S_{all}^{cross}} \right\rangle^2 + \left\langle \frac{S_{particles}^{self}}{S_{all}^{self}} \right\rangle^2$

- $\langle \#AE \rangle$: Number of AEs emitted per decay
- $\langle T_{1/2} \rangle$: Physical half-life
- $\langle S_{all}^{self} \rangle$: Self-dose to the cell nucleus per decay in the cell nucleus
- $\left\langle \frac{S_{all}^{self}}{S_{all}^{self} + S_{all}^{cross}} \right\rangle^2$: Ratio of self-dose to the nucleus to total absorbed dose to the nucleus
- $\left\langle \frac{S_{particles}^{self}}{S_{all}^{self}} \right\rangle^2$: Ratio of self-dose from particles to self-dose from all radiations including photons for a 6.2-mm radius sphere of water

What makes a good Auger emitter?

From J. Bolcaen, et al. Journ. Nucl. Med., **64** 9 (

Overall dosimetry score = $\langle \#AE \rangle + \langle T_{1/2}$

Number of AEs emitted per decay

Physical half-life

Self-d
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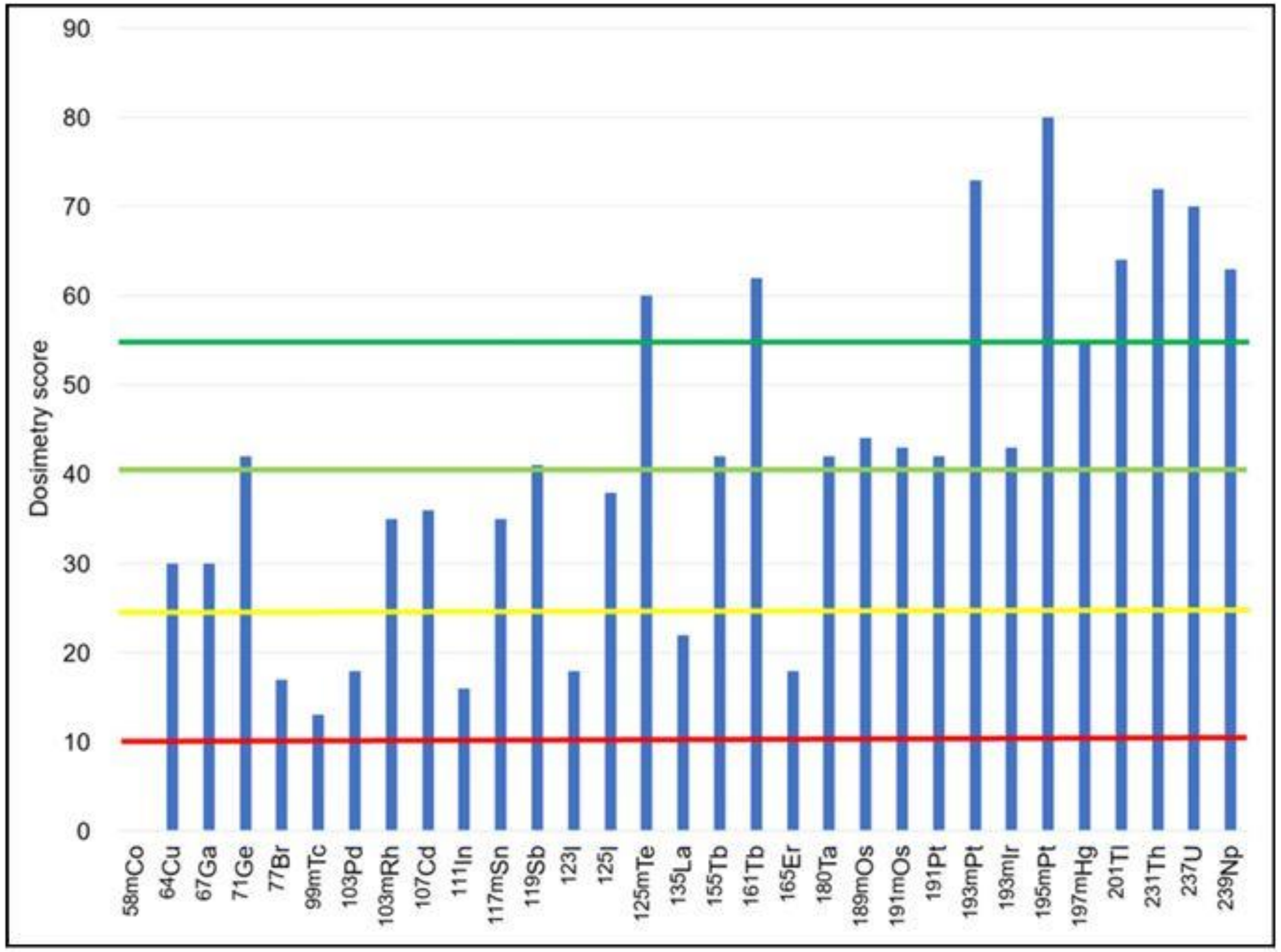

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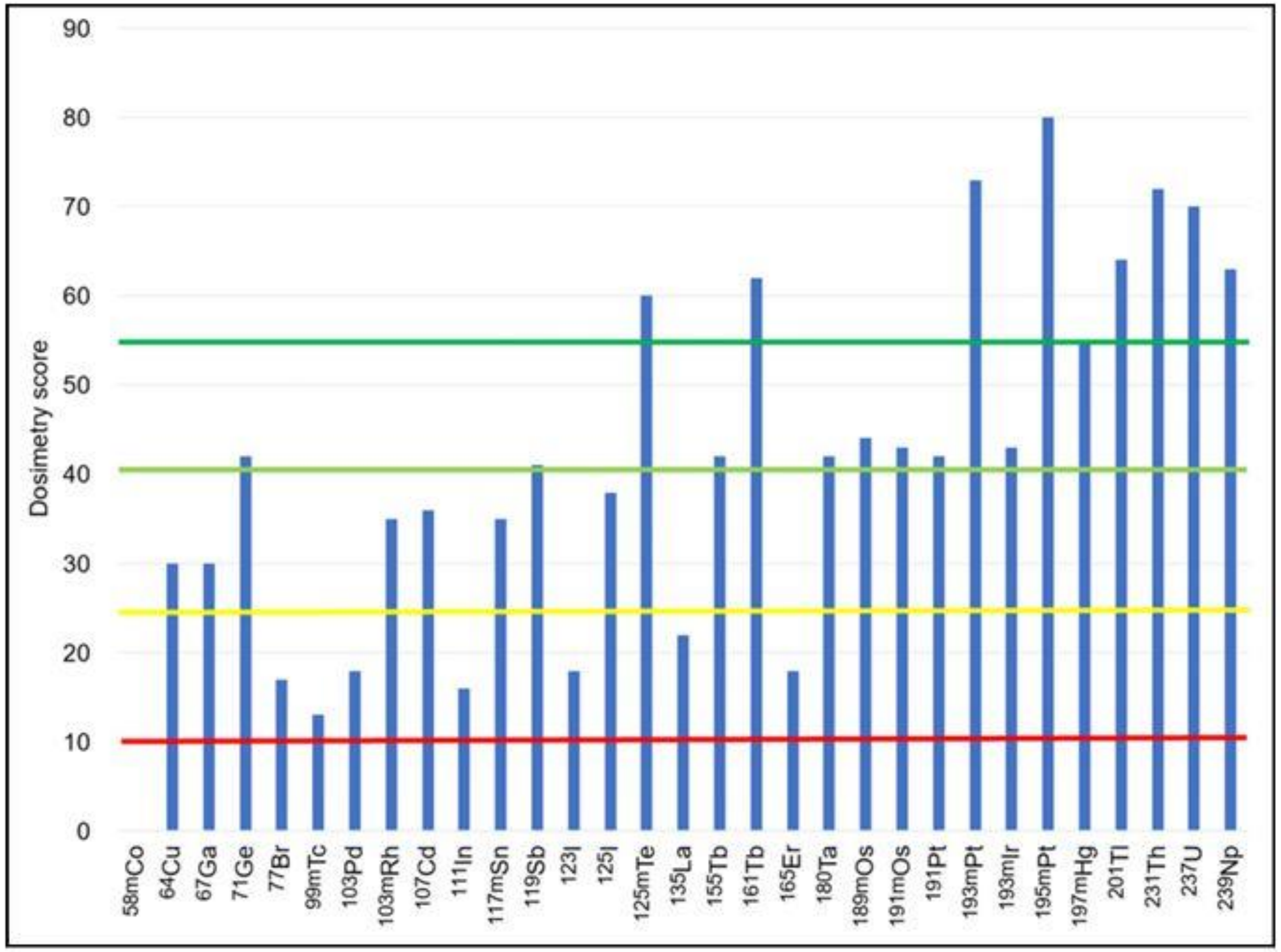

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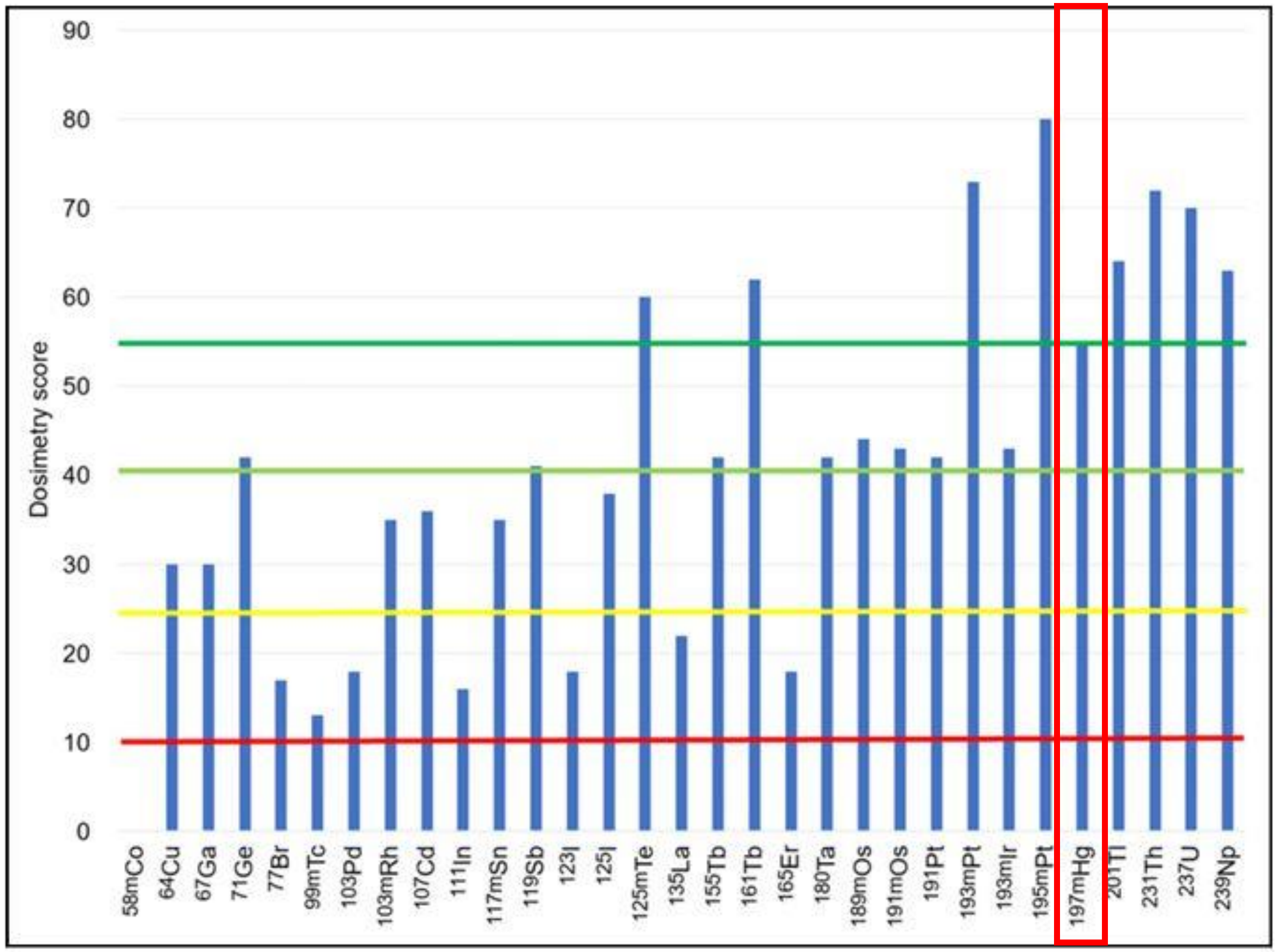
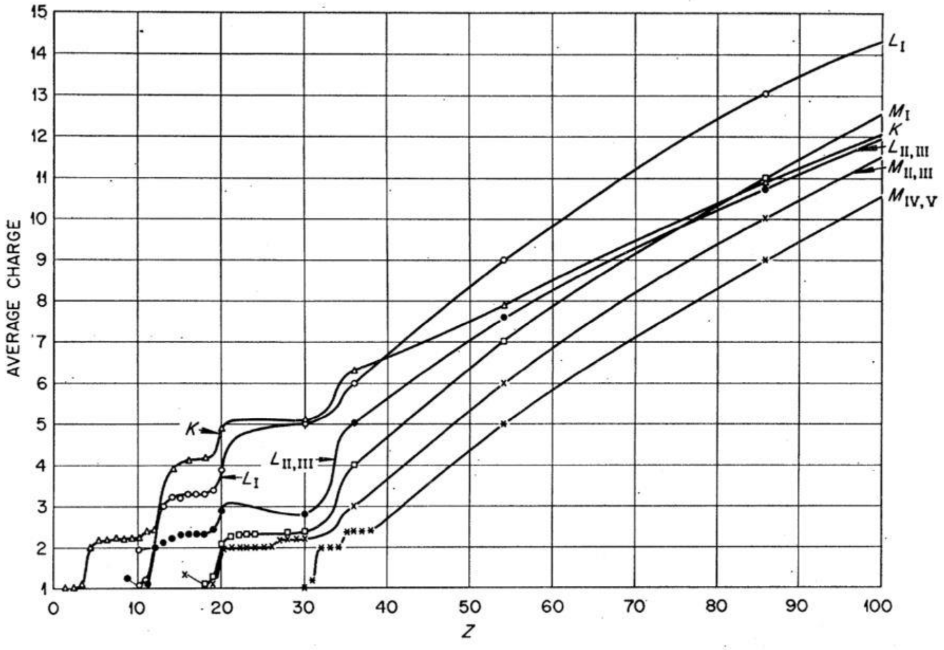
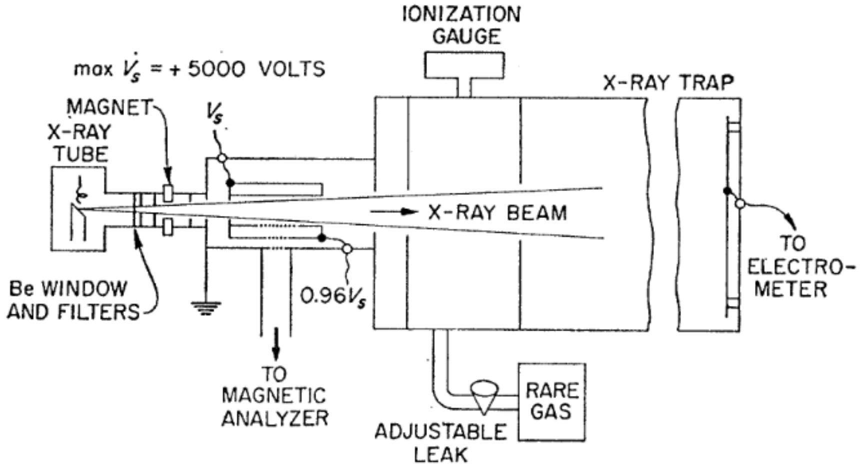


Existing data on number of AEs emitted

From the International Commission on Radiological Protection publication 107:
“A method, based on the RELAX computer code of Cullen (1992), for calculating detailed atomic radiations has been introduced into EDISTR04 in order to treat transitions from outer shells.”

Eckerman K, Endo A. ICRP publication 107. Nuclear decay data for dosimetric calculations. Ann ICRP. 2008;38:7–96

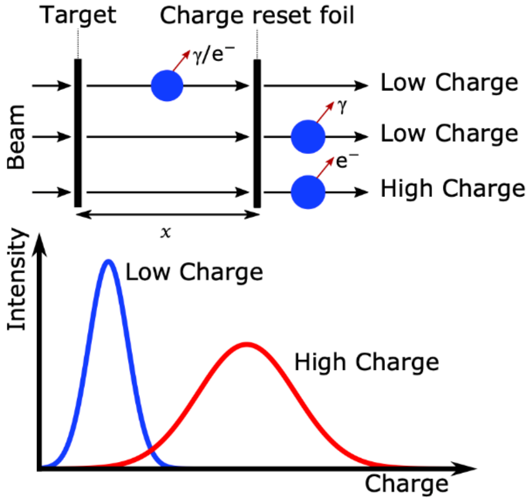


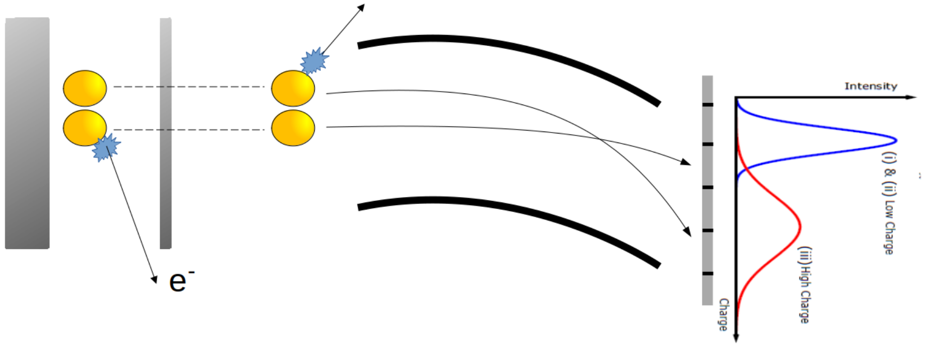


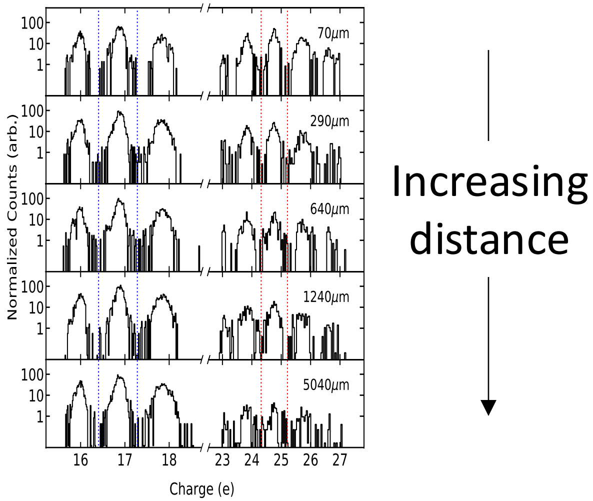
T. A. Carlson, W. E. Hunt, M. O. Krause. Relative Abundances of Ions Formed as the Result of Inner-Shell Vacancies in Atoms, Phys. Rev., 151:41–47, (1966)

The charge plunger method

Collaboration between:
University of Jyväskylä (J. Uusitalo, J. Sarén)
University of Manchester (D.M. Cullen, L. Barber)
University of Liverpool (R.-D. Herzberg)
University of the West of Scotland (B.S. Nara Singh)
University of Surrey (J. Heery)







Relative intensities depends on:
- Target-reset foil distance
- Recoil velocity
- Internal conversion coefficient,
- Lifetime of excited state,

L. Barber, J. Heery, et al. Nucl. Instr. and Meth. in Phys. Res. Sec. A, **979**, 164454, (2020)
J. Heery, L. Barber, et al. EPJA, **57**, 132, (2021)

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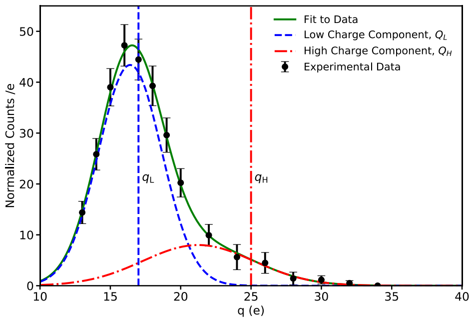

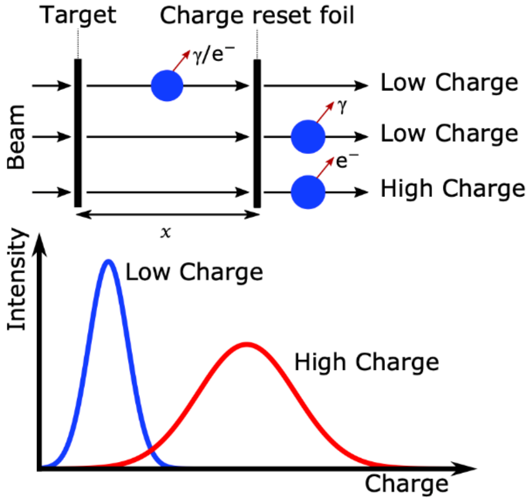

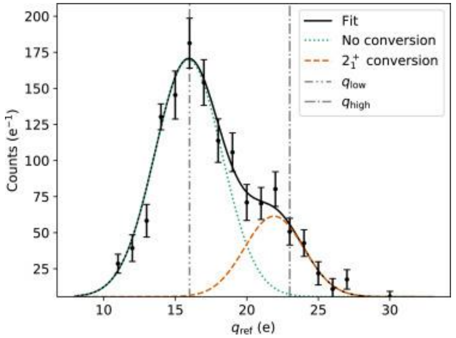

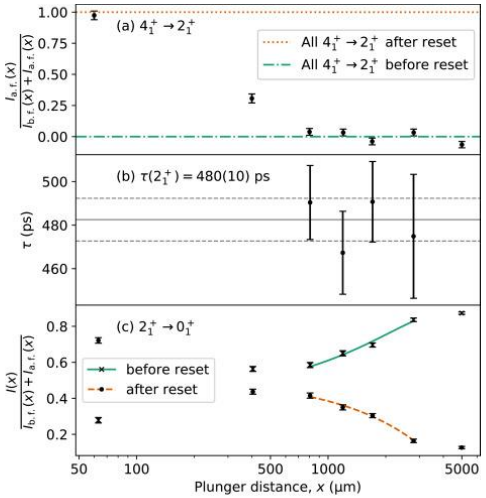

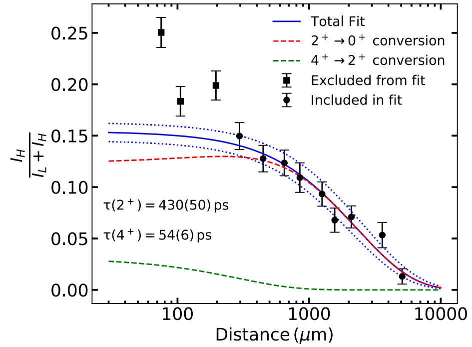

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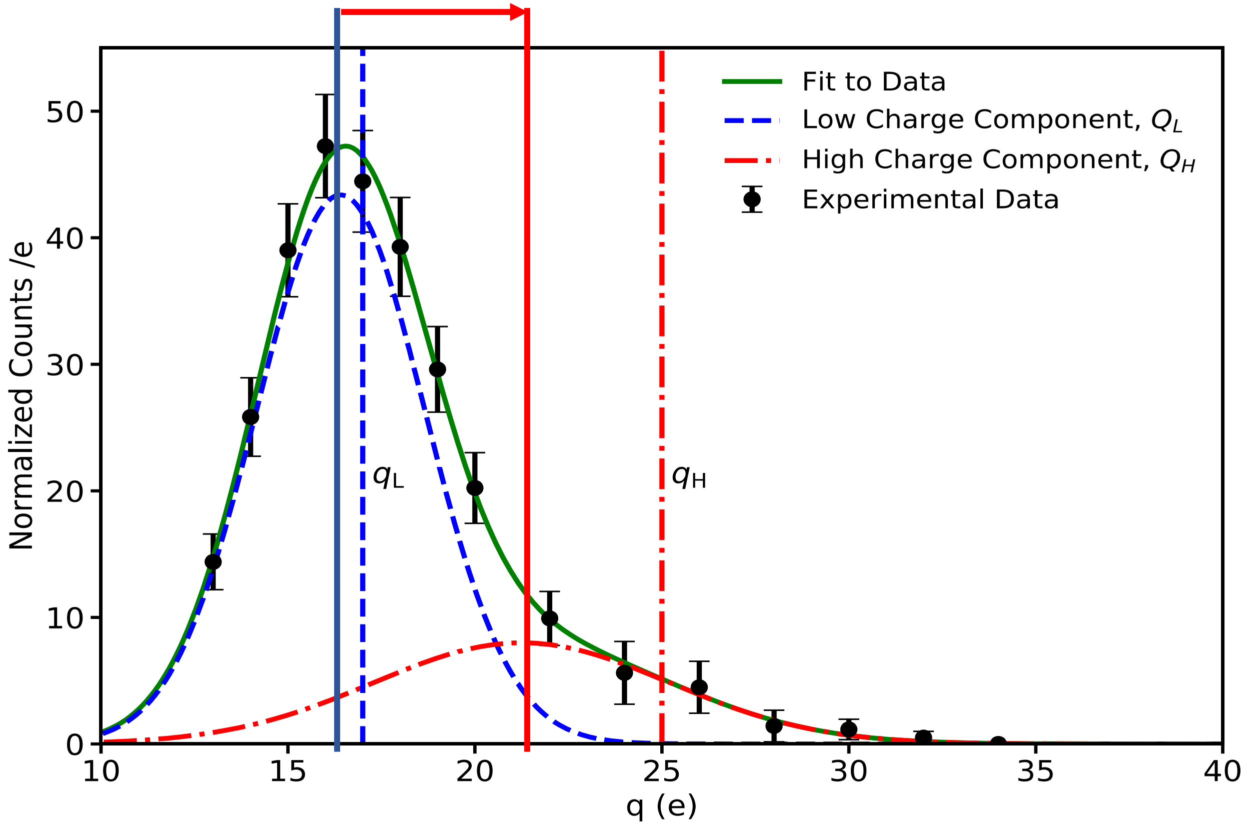
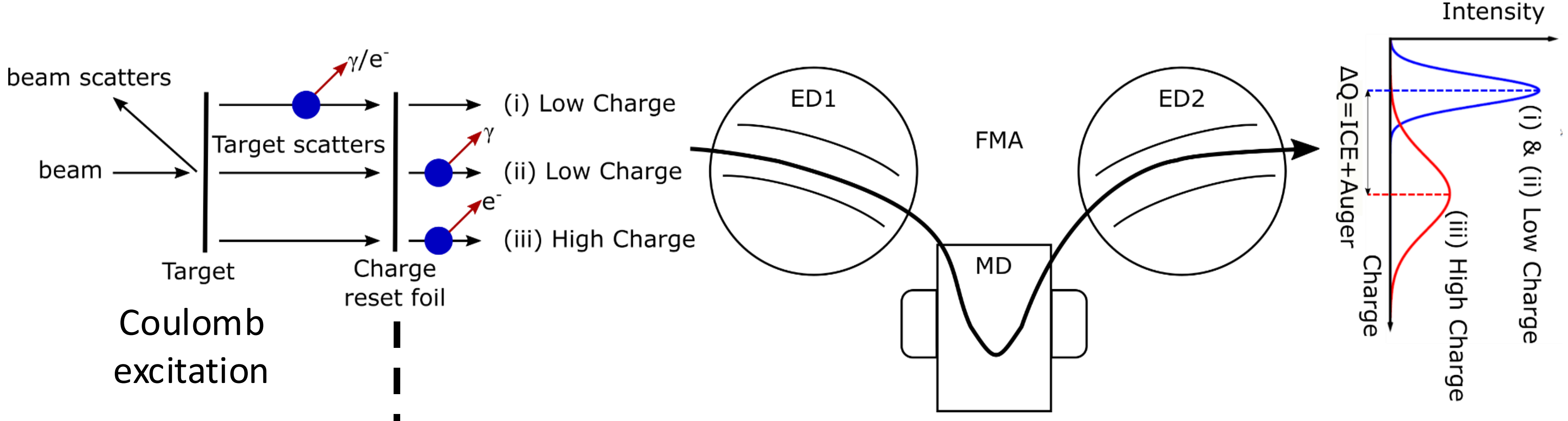
The charge plunger method

Average increase in charge due to ICE + Auger electron emission

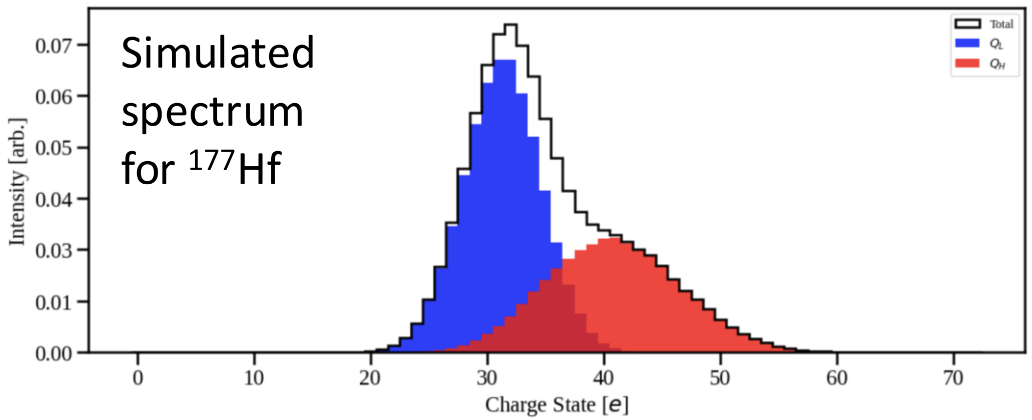


If we take a case where we know the nuclear structure information (e.g. ICC, lifetime) we can investigate the effect of the Auger emissions

Idea: Charge reset method



$$N_A = \Delta Q - 1$$



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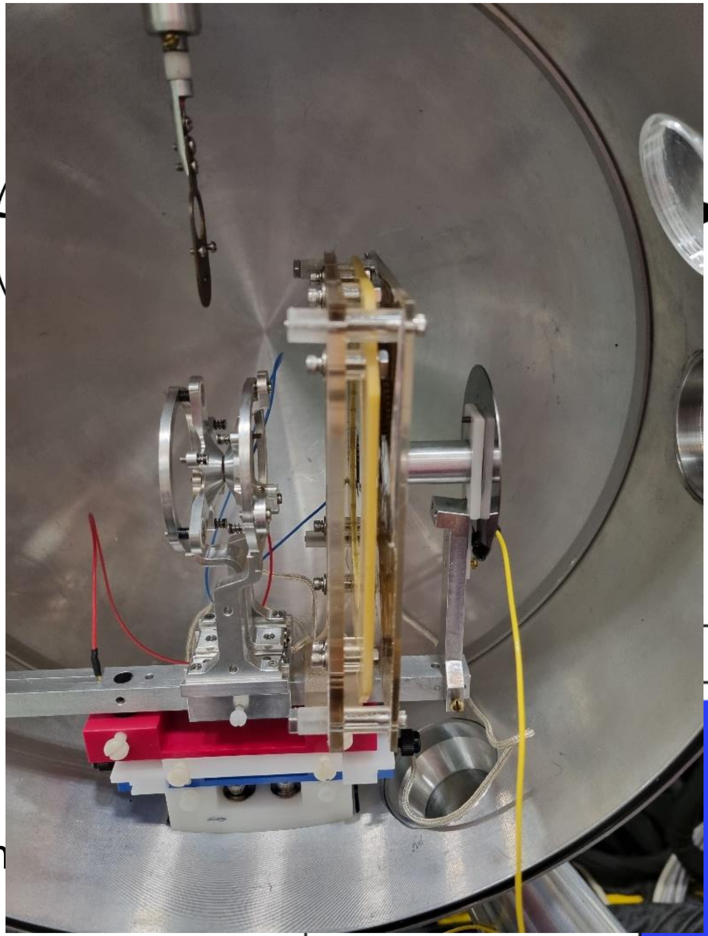

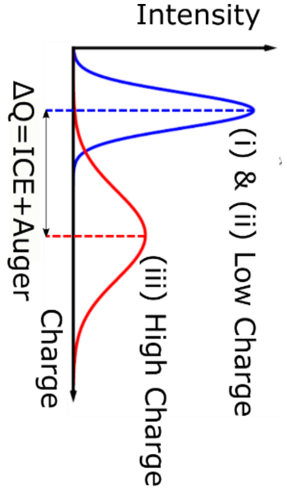

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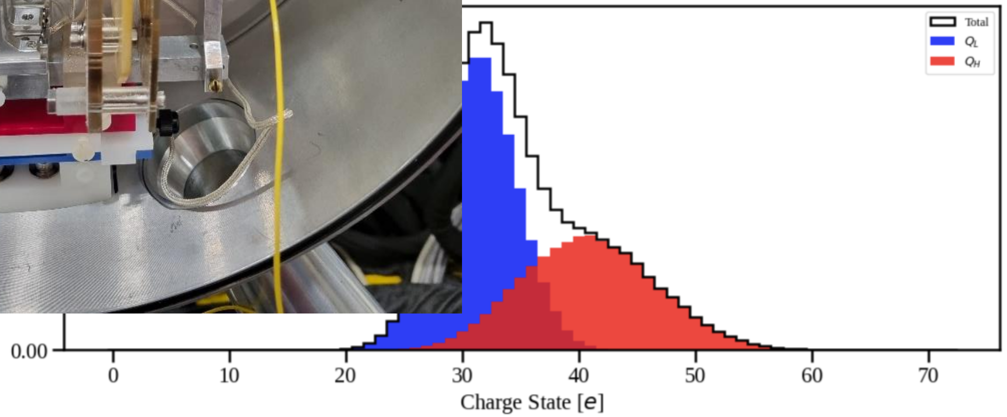
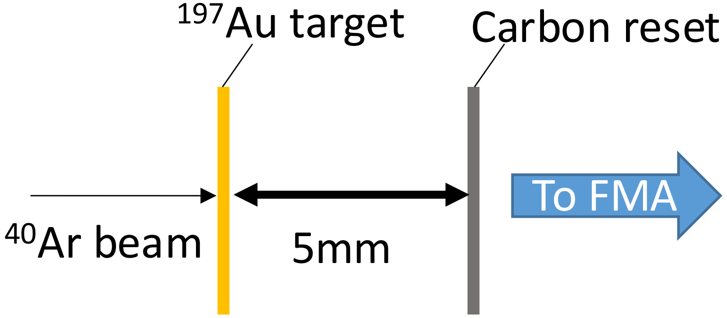
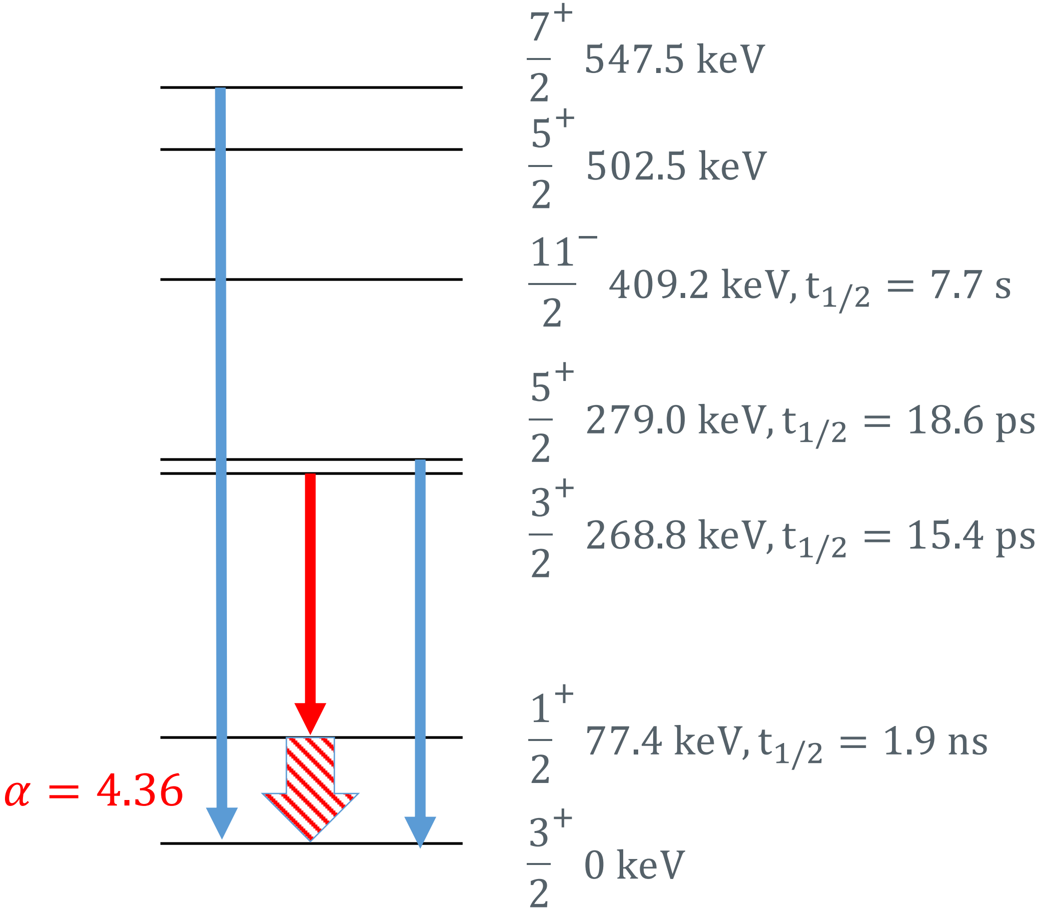


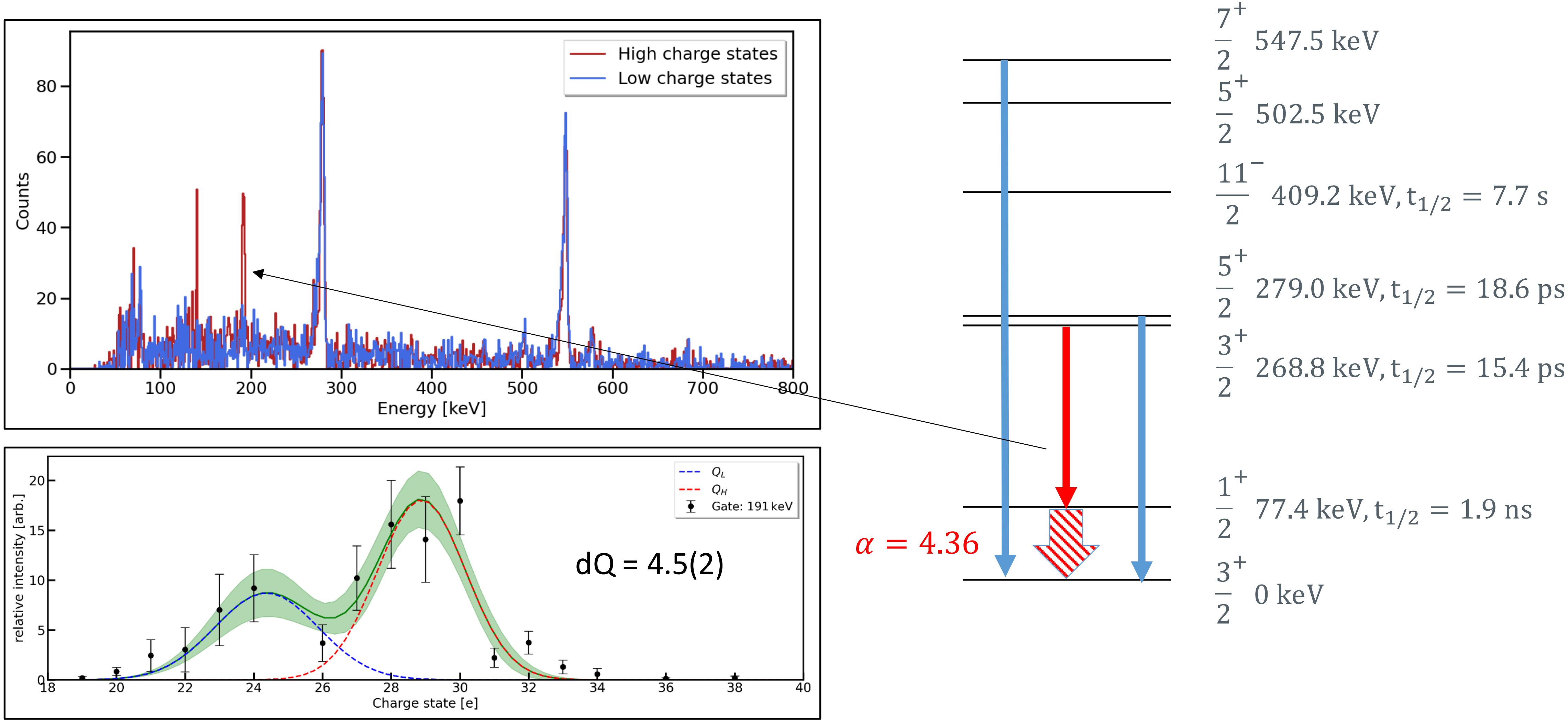
Experiment at Argonne National Laboratory



- Two beam energies investigated: **150** MeV and **101** MeV.
- Recoiling Au ions at ~80 MeV (~0.9 cm/ns) and ~50 MeV (~0.7 cm/ns) separated by A/q using FMA
- All states above 77 keV have half-lives ~10 ps or lower
- Gate on 191-keV gamma-ray populating 77-keV state
- Will have low-charge (gamma-decay and IC before reset) and high-charge (IC after foil) component
- Centroid difference between HC and LC gives mean Auger-electron multiplicity
- Fusion-evaporation reactions on C-foil used for normalisation of gamma-ray intensities (no FMA condition)



^{40}Ar on ^{197}Au at 150MeV



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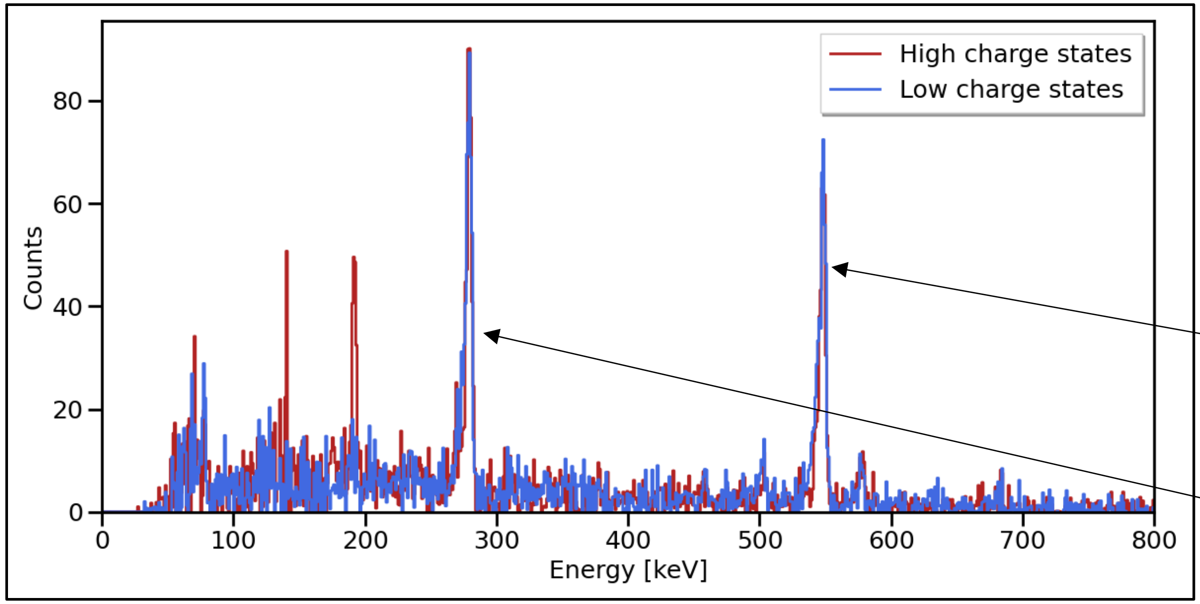

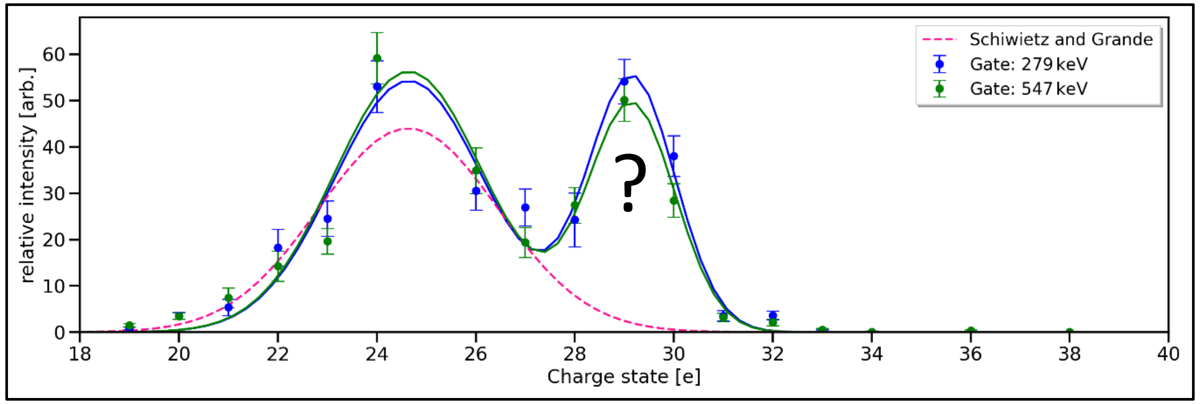

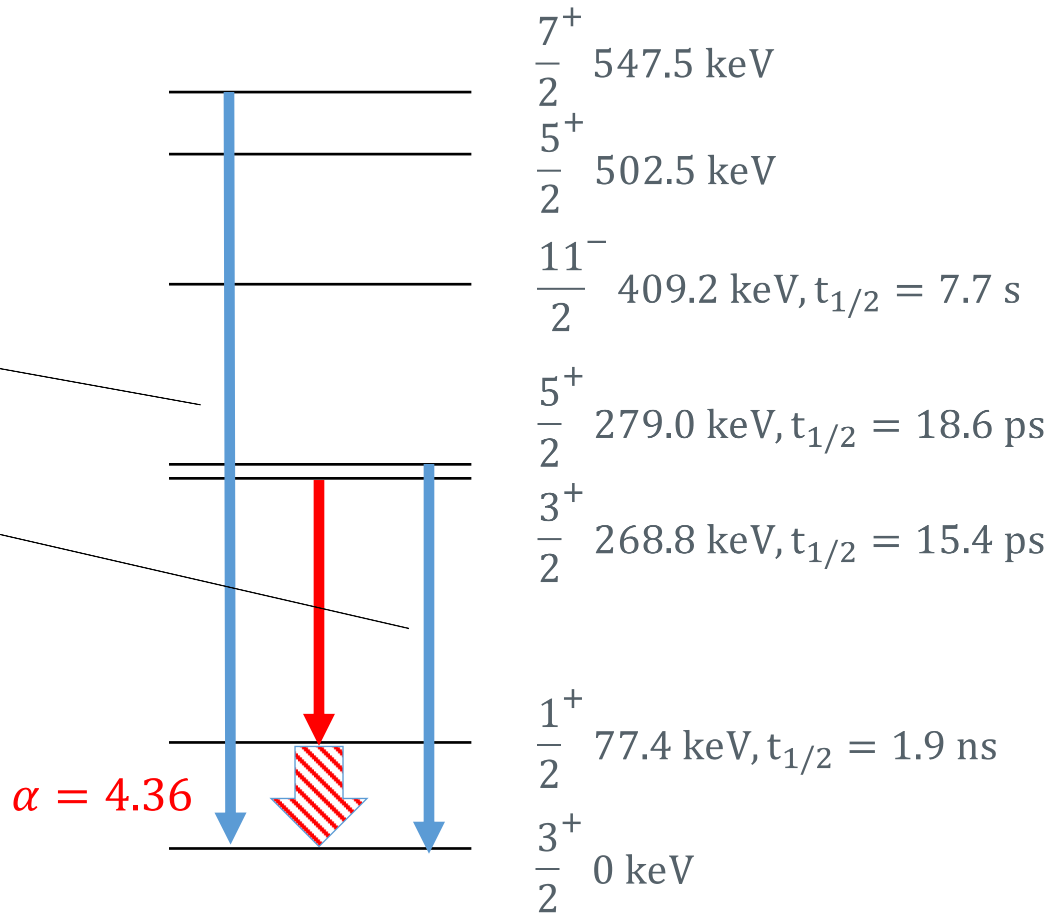

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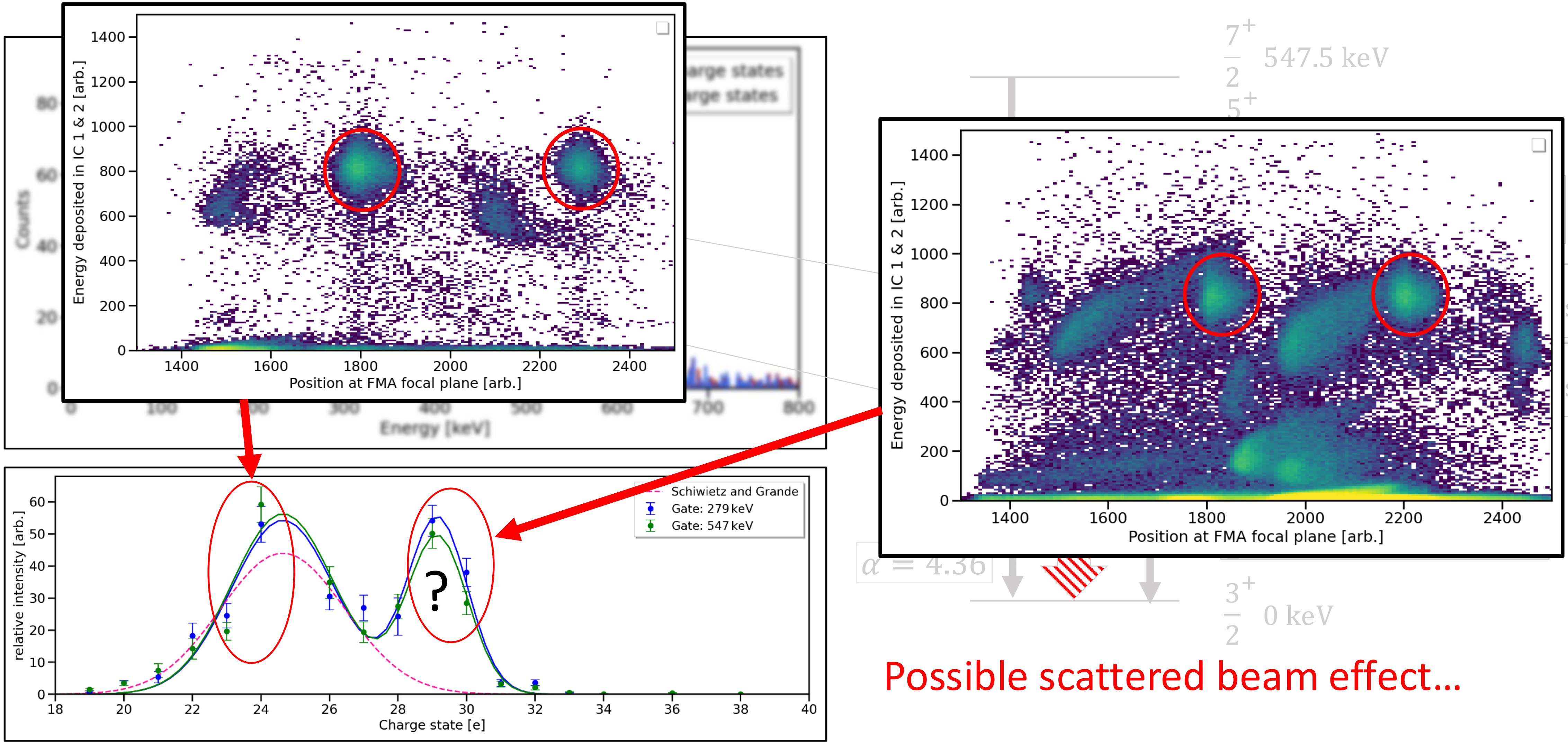
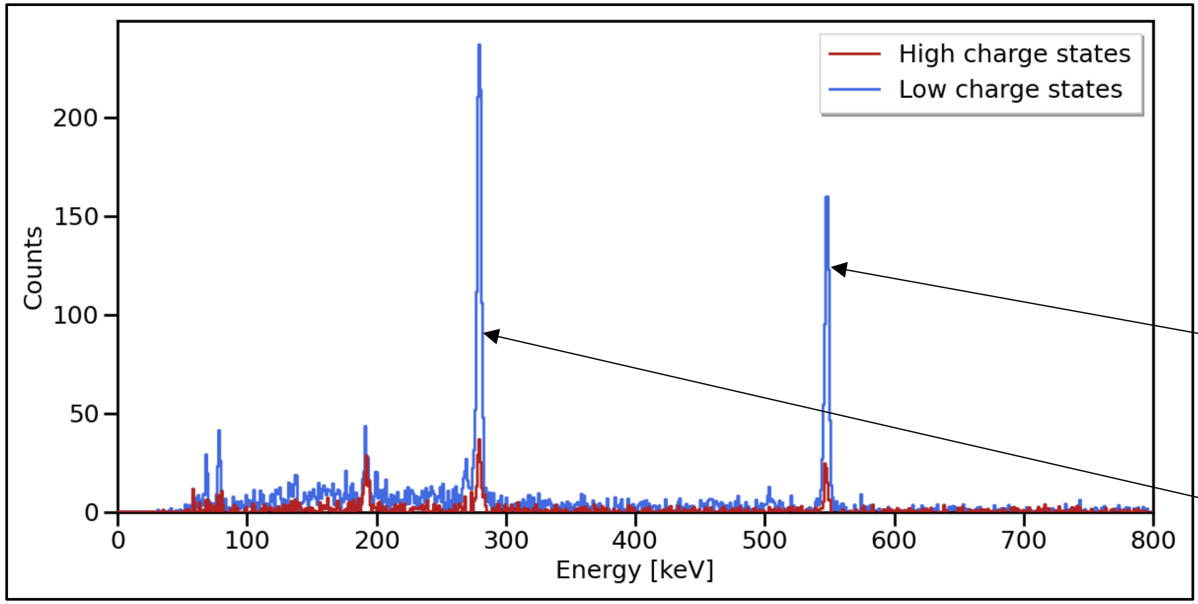
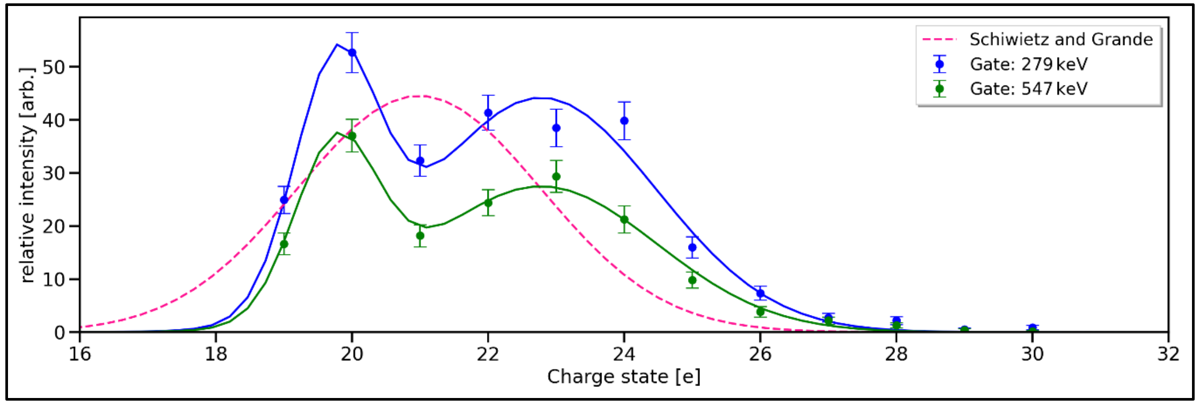
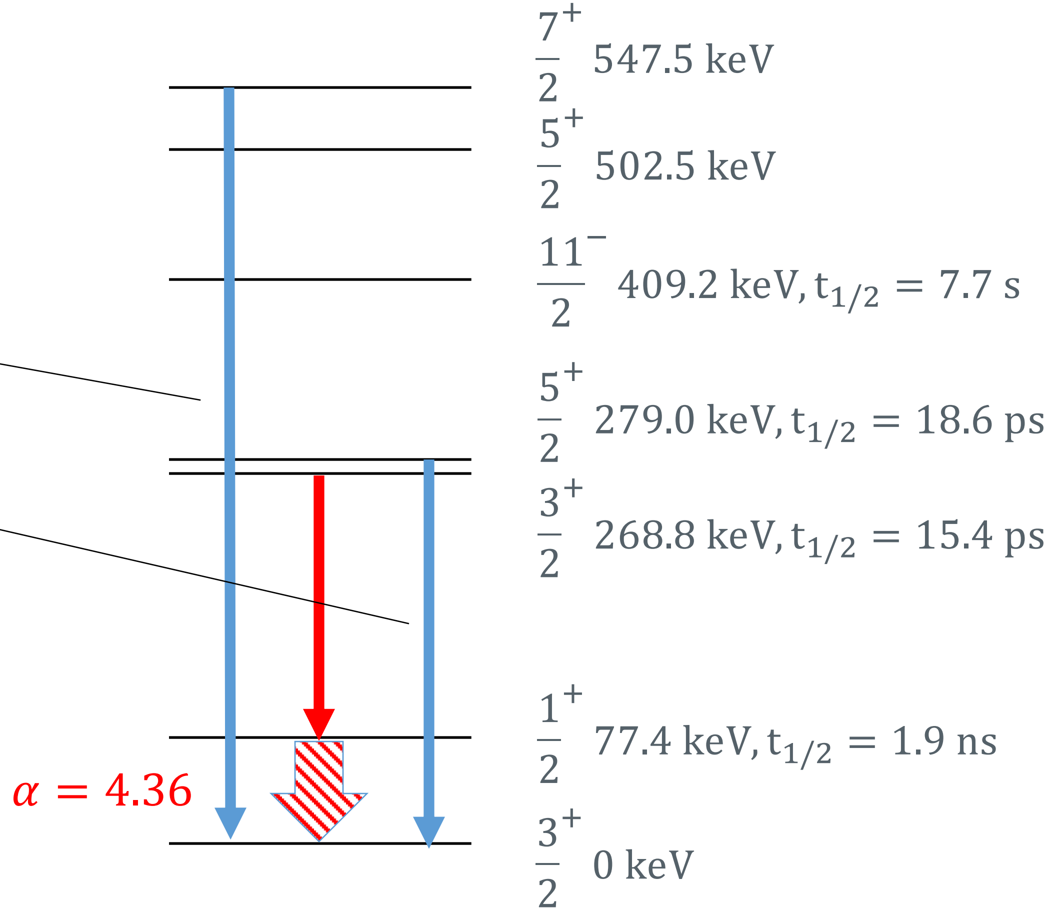


Possible scattered beam effect…

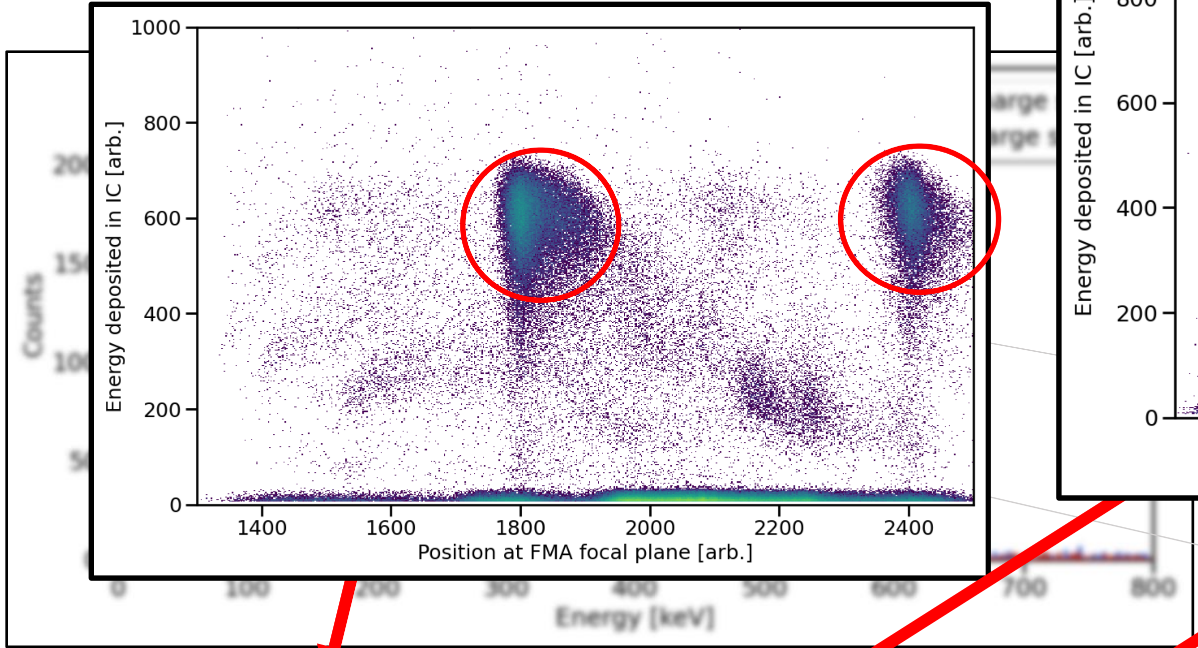
^{40}Ar on ^{197}Au at 101MeV

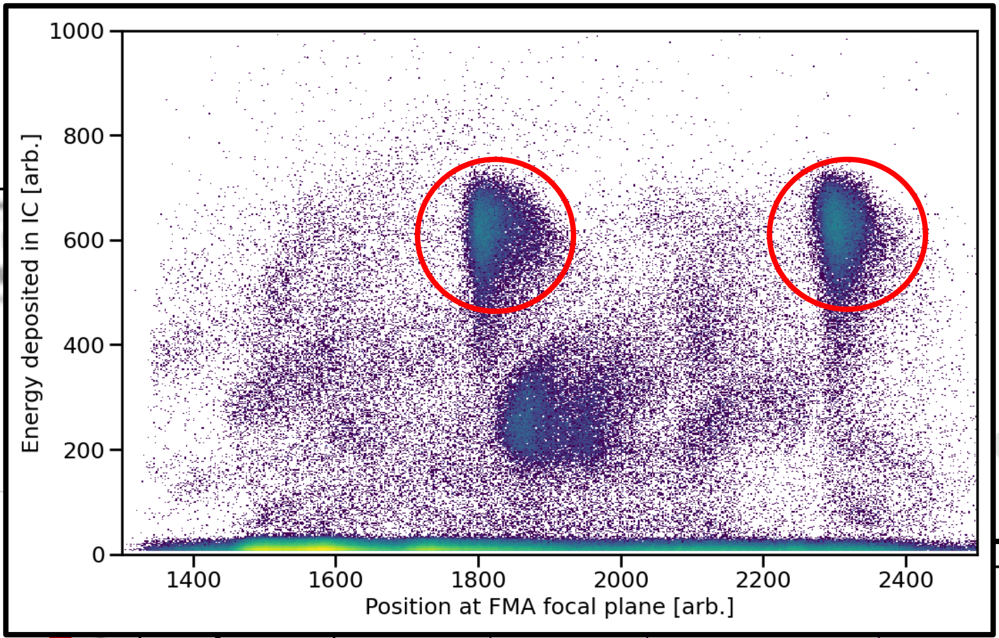


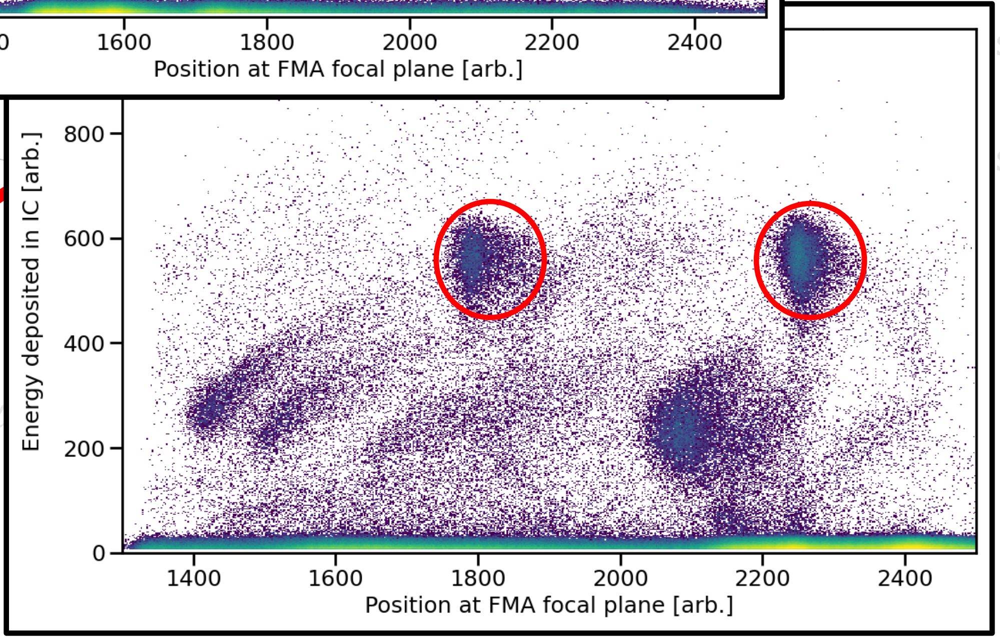


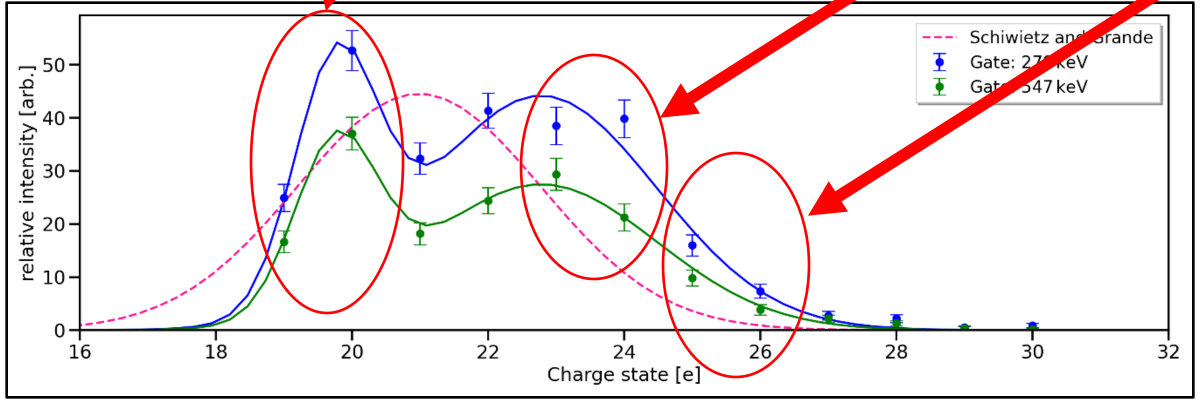


^{40}Ar on ^{197}Au at 101MeV









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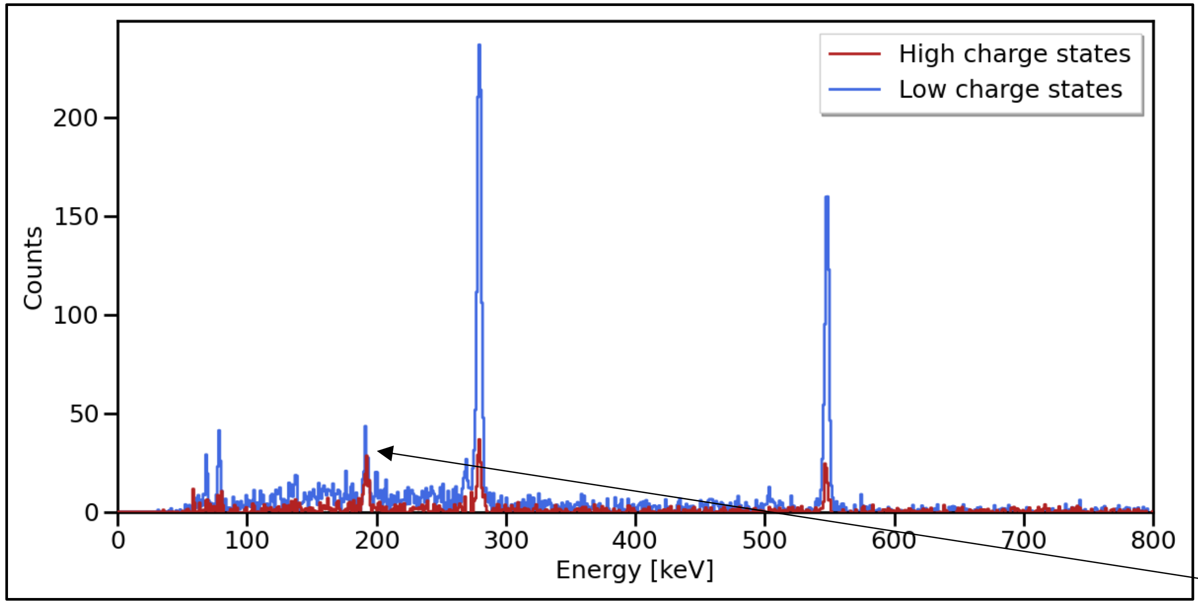

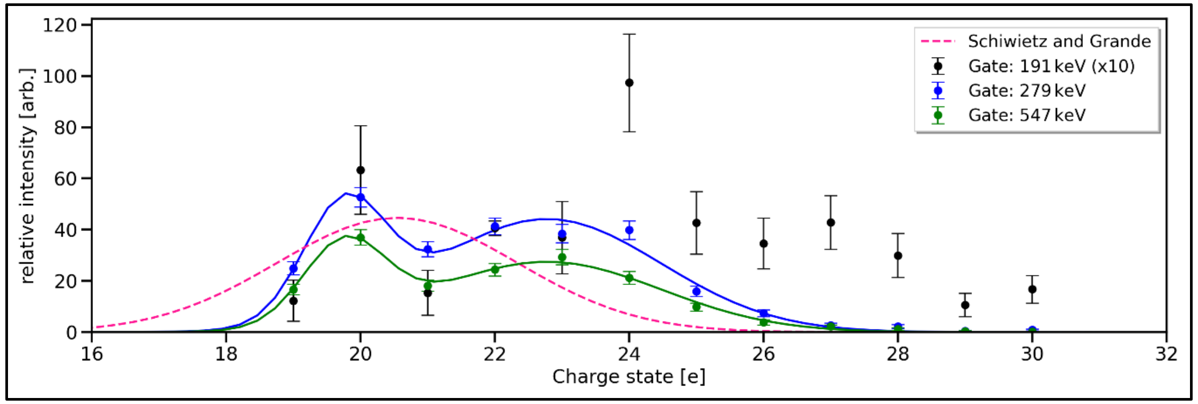

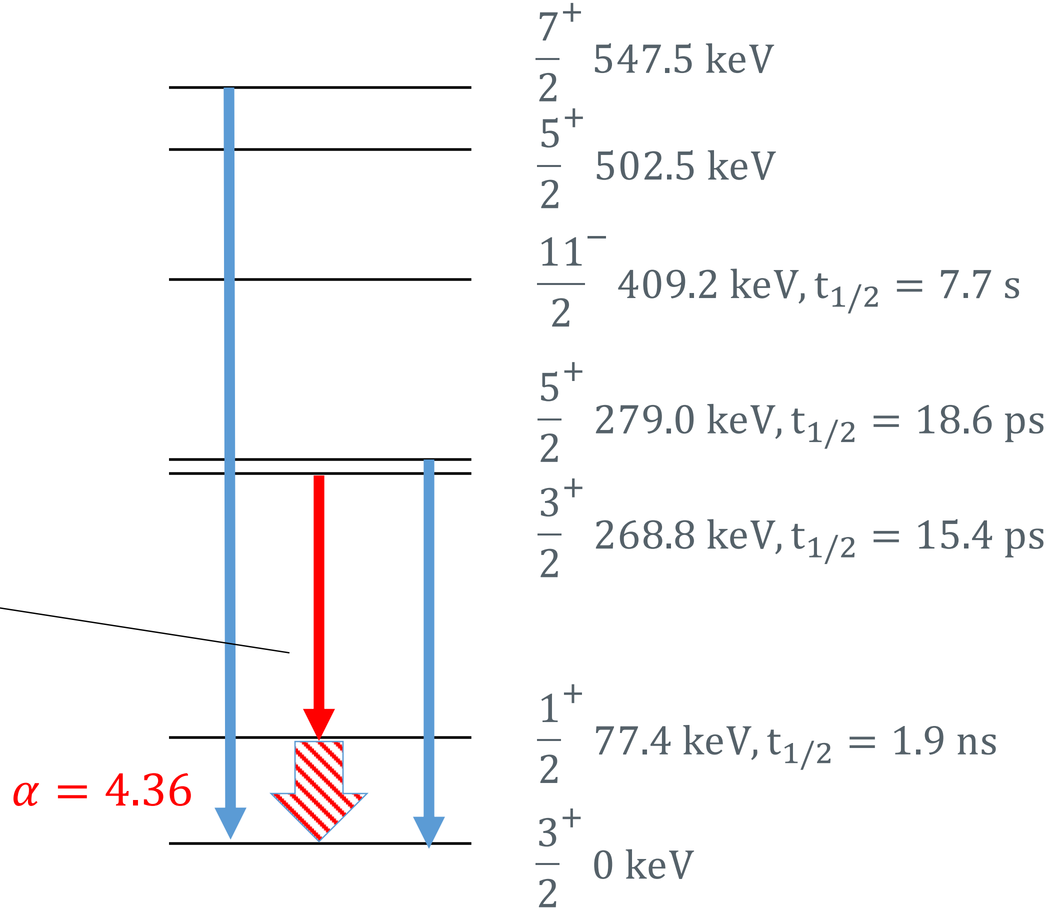

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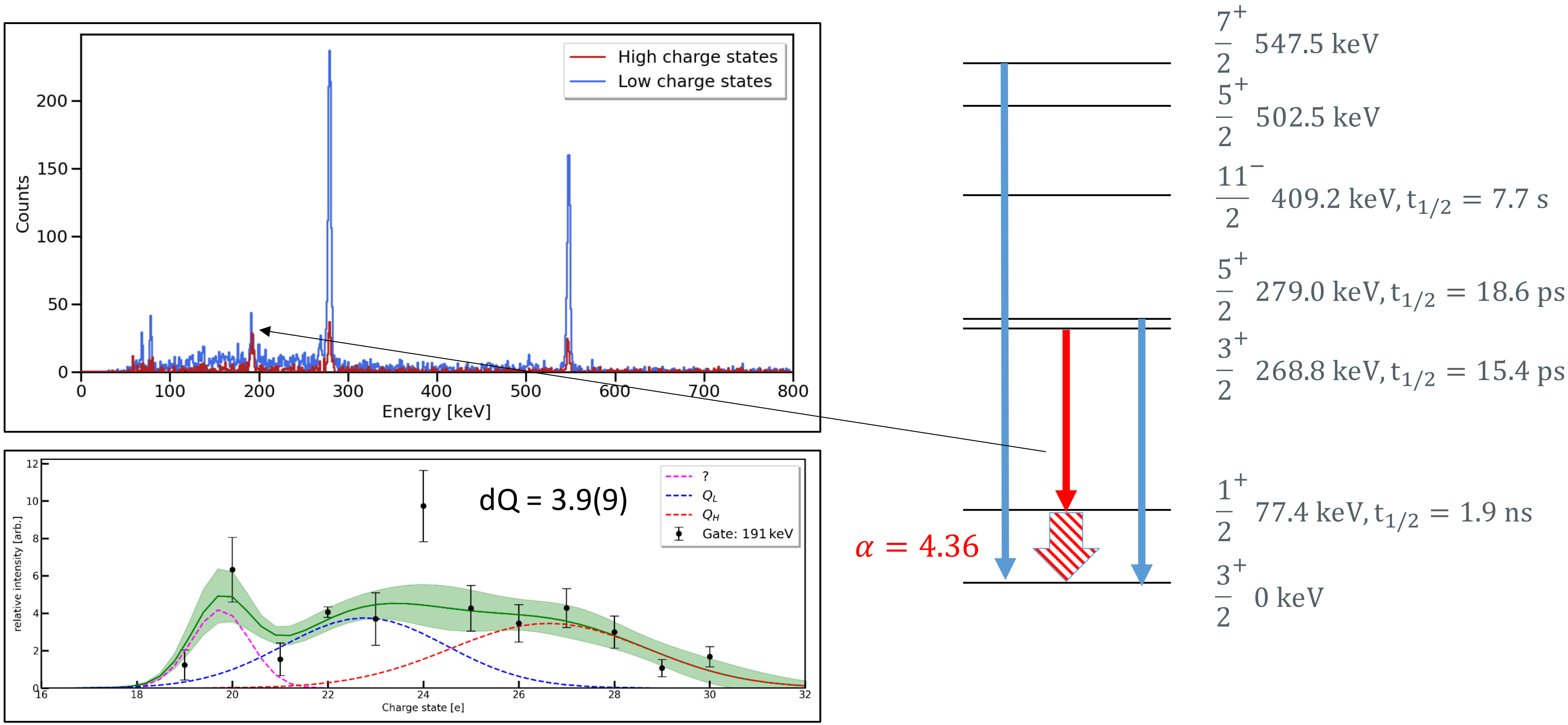
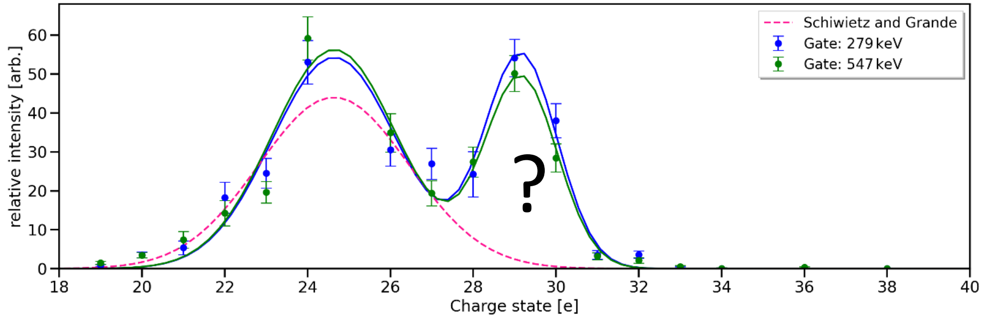
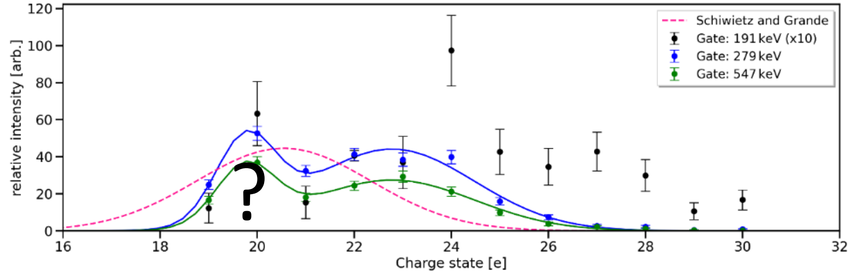


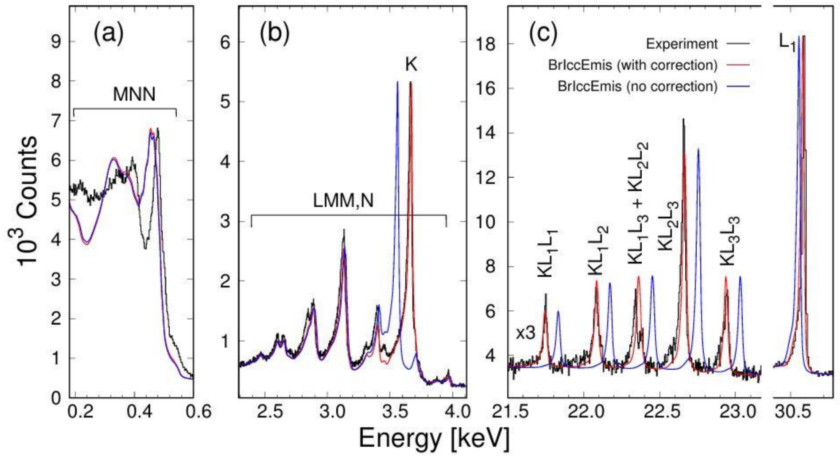
Future steps

- Work out what's going on:
    - ➢ Possible scattered beam compone



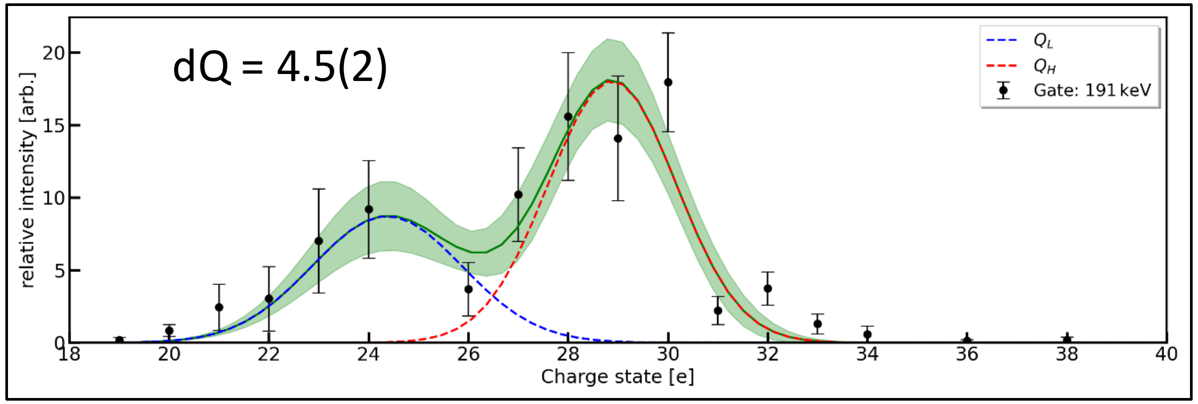


- Comparison to theoretical calculations
    - ➢ BrIccEmis



Summary

- Determining the number of electrons emitted during an Auger cascade is important for targeted radiotherapy.
- A method has been developed to determine the average number of Auger electrons emitted following a vacancy based on resetting the charge state of an ion following an inelastic scattering reaction.
- An experiment was performed at Argonne National Laboratory combining GRETINA and the FMA spectrometer.
- Preliminary results are encouraging but still some questions to be answered!
- Waiting for theoretical results using BrIccEmis



THANKS TO COLLABORATORS

J. Henderson, C. Müller-Gatermann, C. Cassells, D. Doherty, A. Ertoprak, J. Fuller, H. Jayatissa, D. Jenkins, V. Karayonchev, F. Kondev, A. Korichi, T. Lauritsen, G. Lotay, B.S. Nara Singh, E. O'Sullivan, W. Reviol, N. Sensharma, M. Siciliano, R.S. Sidhu

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