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

Dr Jacob Heery

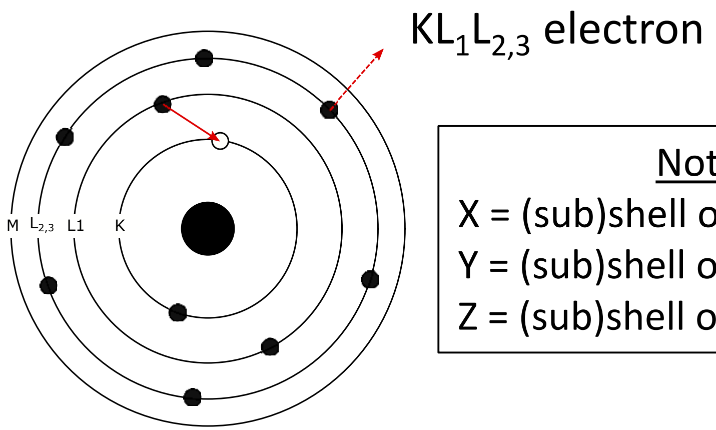
UNIVERSITY OF SURREY

The 29th International Nuclear Physics Conference

May 25-30, 2025
DCC, Daejeon, Korea

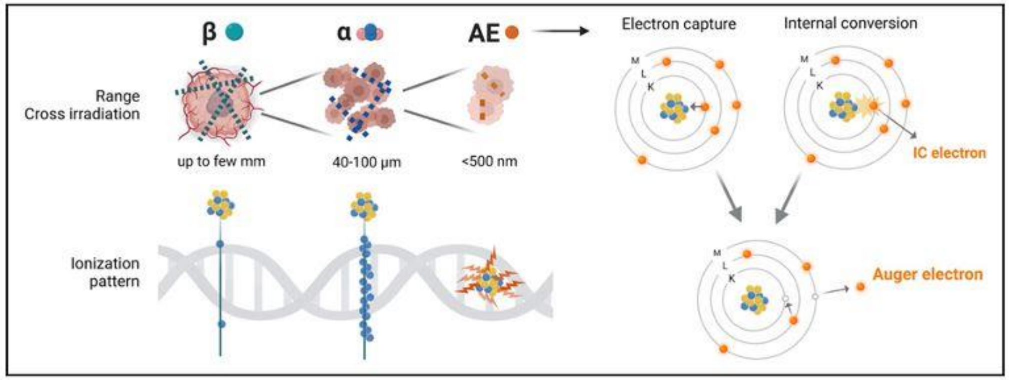
Background

What is an Auger electron



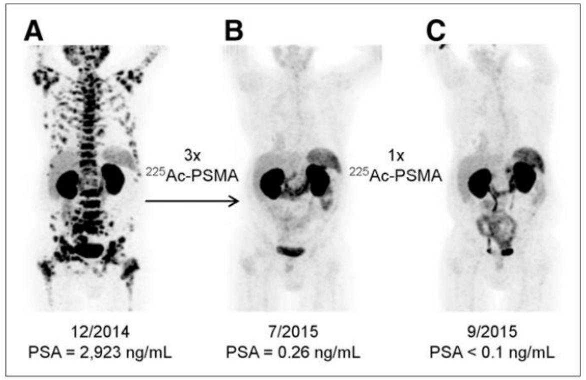
Notation: XYZ
X = (sub)shell of initial vacancy
Y = (sub)shell of de-exciting electron
Z = (sub)shell of emitted electron

Auger electron emission

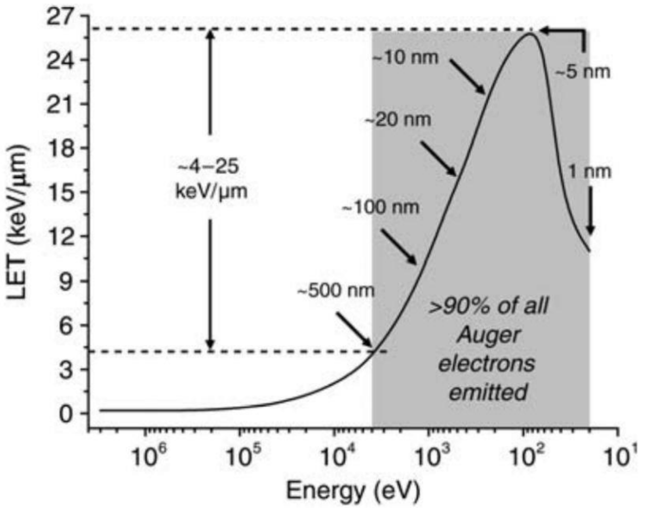


J. Bolcaen, et al. Journ. Nucl. Med., **64** 9 (2023)

Targeted radiotherapy



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



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

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
0.1-keV electron	27 keV μm^{-1}	3.7 nm

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

Number of AEs emitted per decay

Physical half-life

Self-dose to the cell nucleus per decay in the cell nucleus

Ratio of self-dose to the nucleus to total absorbed dose to the nucleus

Ratio of self-dose from Auger particles to self-dose from all radiations including photons for a 6.2-mm radius sphere of water

What makes a good Auger emitter?

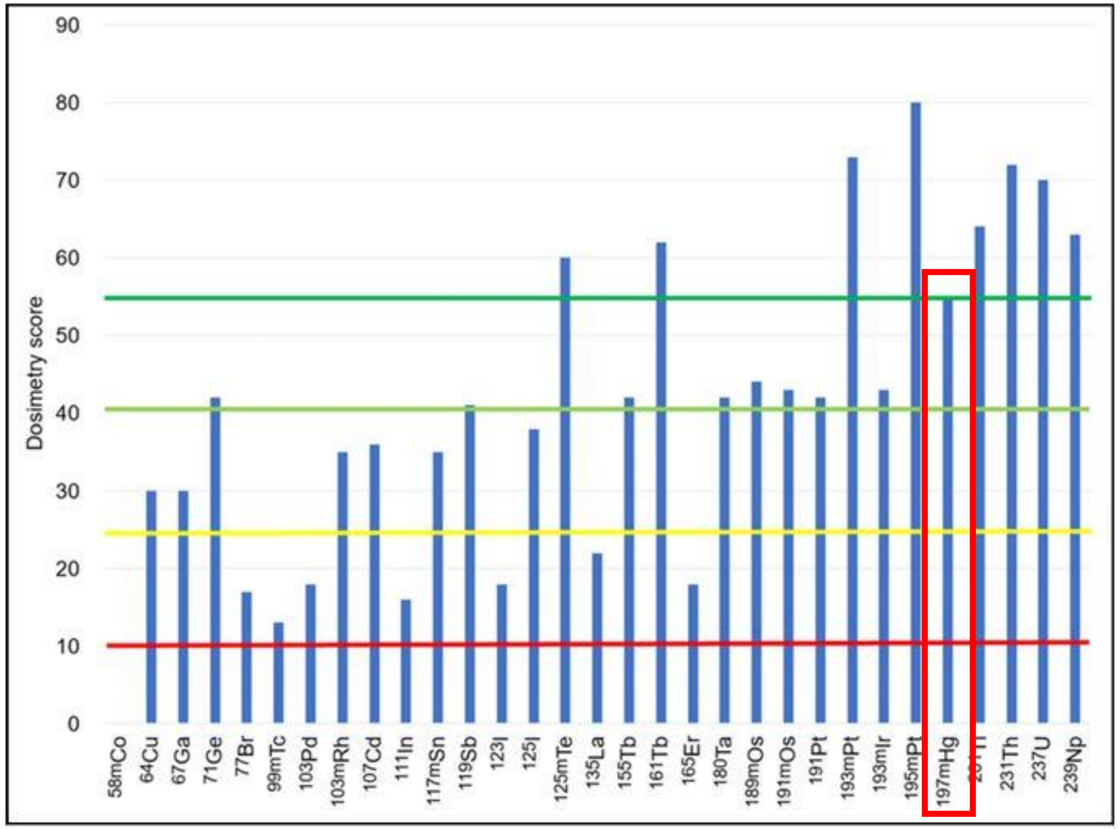
From J. Bolcaen, et al. Journ. Nucl. Med., **64** 9 (202

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

Number of AEs emitted per decay

Self-dose
decay in t

Physical half-life



articles to
ons
.2-mm

Ratio of self-dose to the nucleus to total absorbed dose to the nucleus

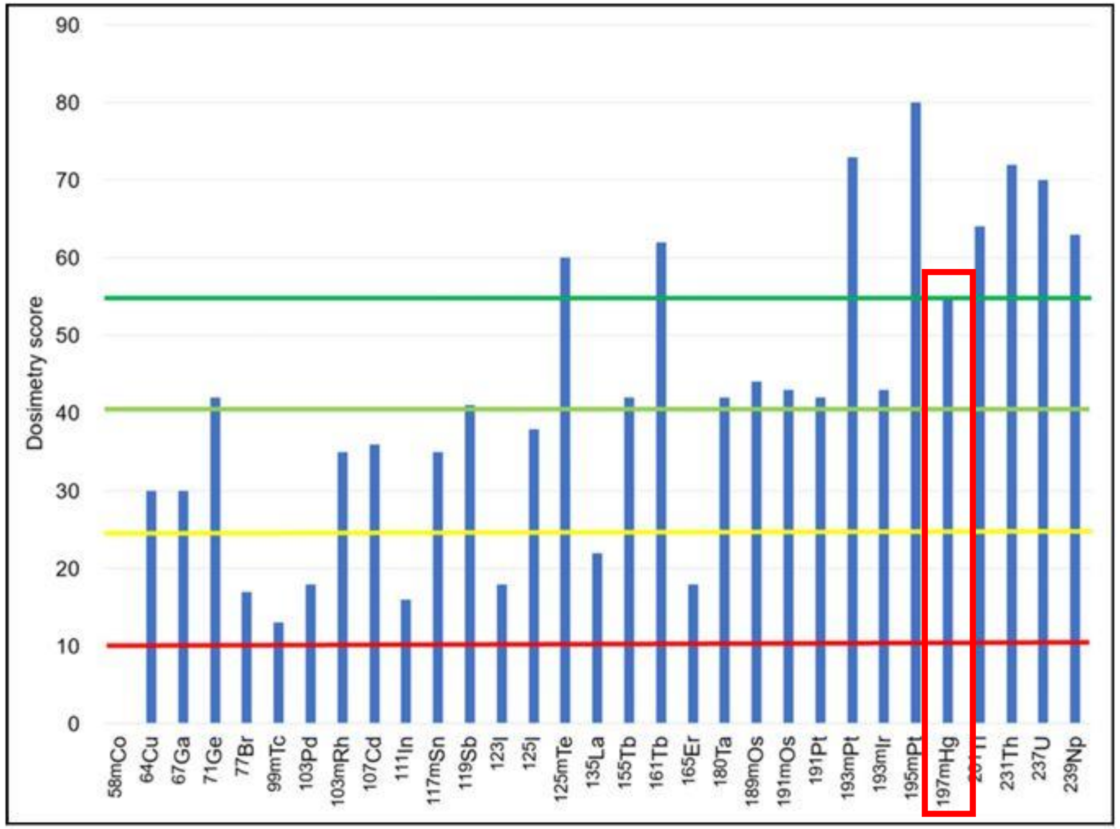
What makes a good Auger emitter?

From J. Bolcaen, et al. Journ. Nucl. Med., **64** 9 (202

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

Number of AEs emitted per decay

Self-dose
decay in t



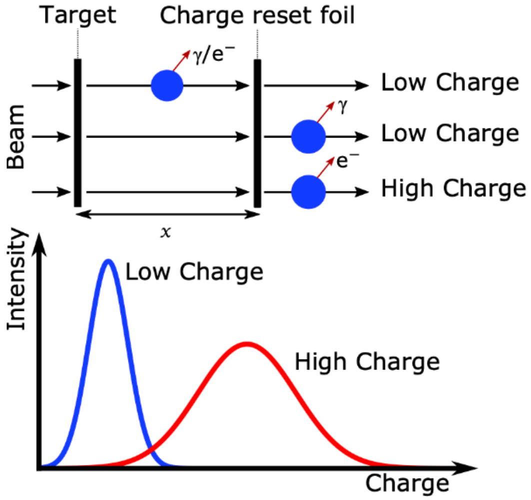
articles to
ons
.2-mm

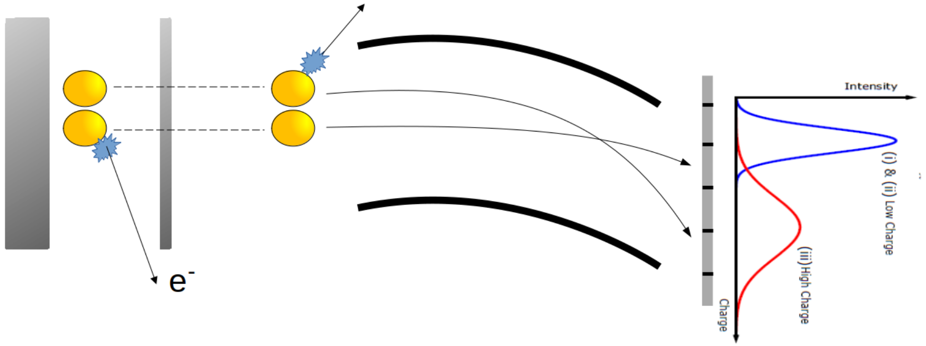
From the International Commission on Radiological Protection publication 107:
"A method, based on the RELAX computer code of Cullen (1992), for calculating detailed atomic radiations has been introduced into EDISTR04 in order to treat transitions from outer shells."

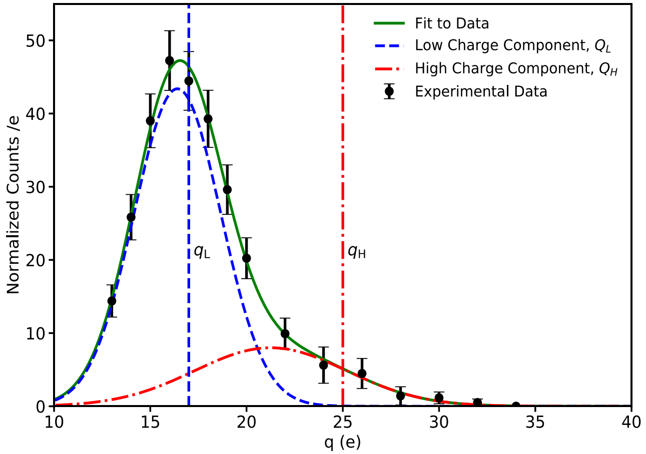
Eckerman K, Endo A. ICRP publication 107. Nuclear decay data for dosimetric calculations. Ann ICRP. 2008;38:7–96

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)

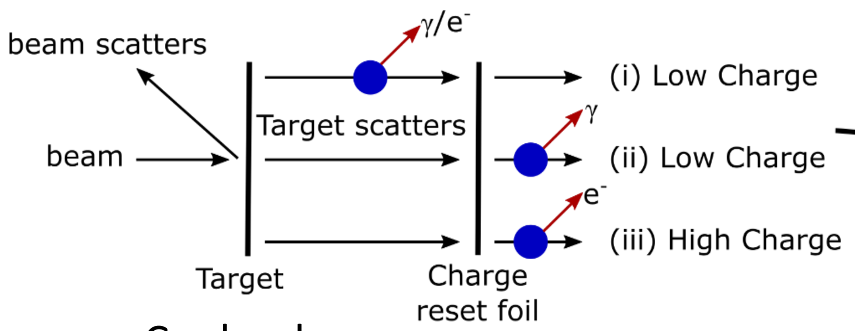


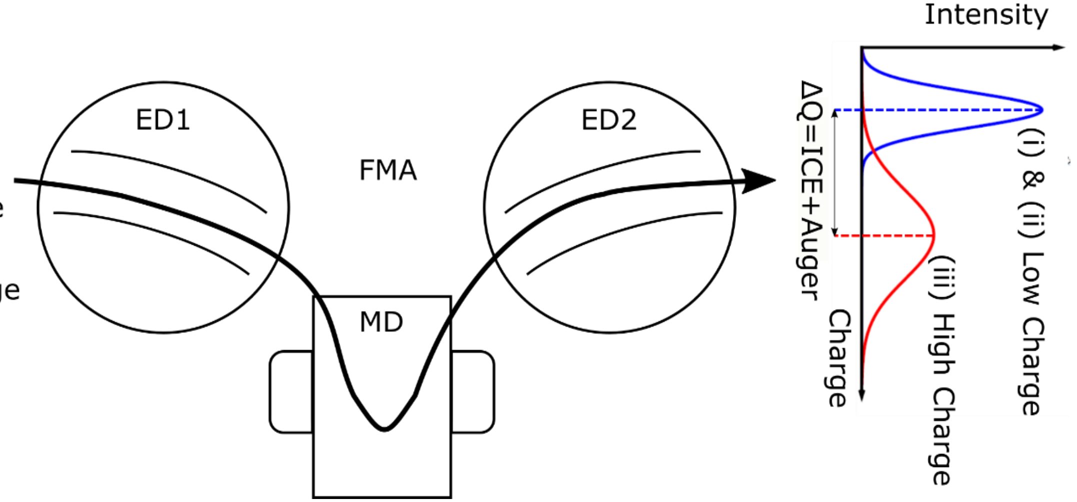




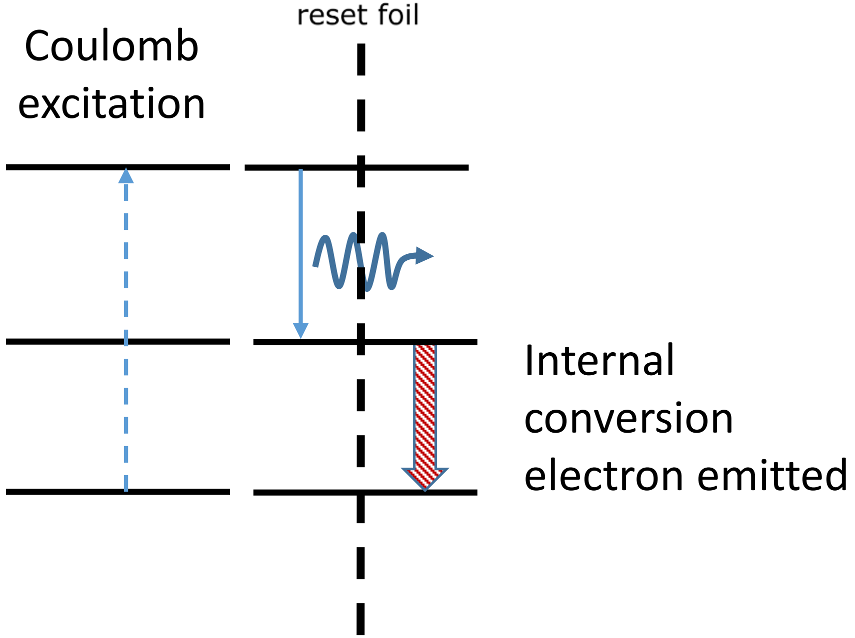
L. Barber, J. Heery, et al. Nucl. Instr. and Meth. in Phys. Res. Sec. A, **979**, 164454, (2020)
J. Heery, L. Barber, et al. EPJA, **57**, 132, (2021)

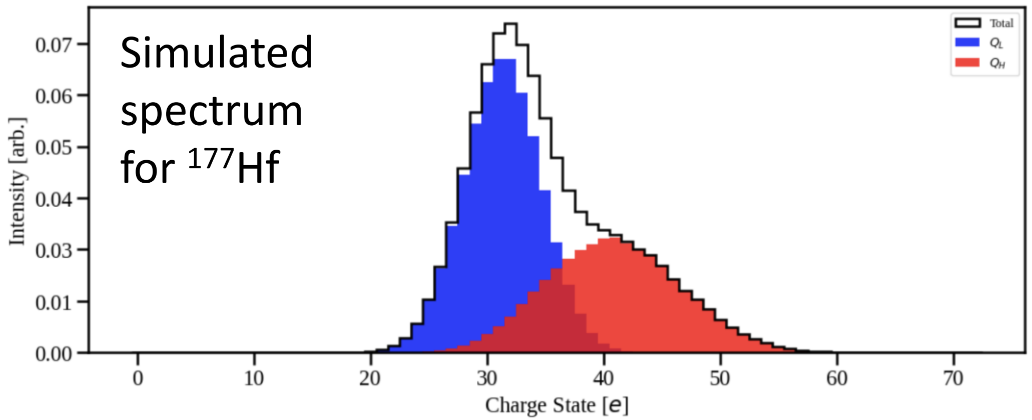
Idea: Charge reset method



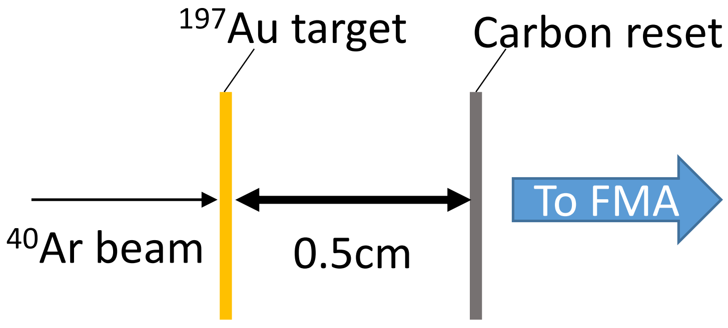


$$N_A = \Delta Q - 1$$

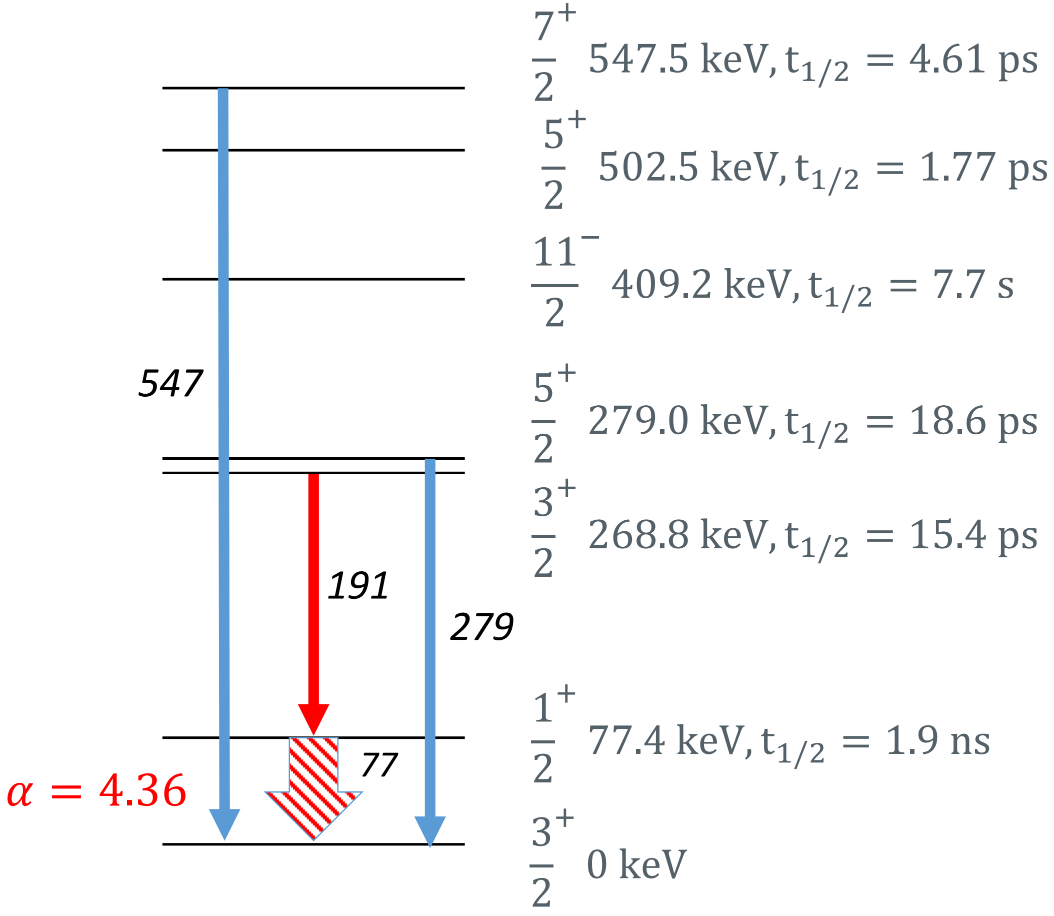




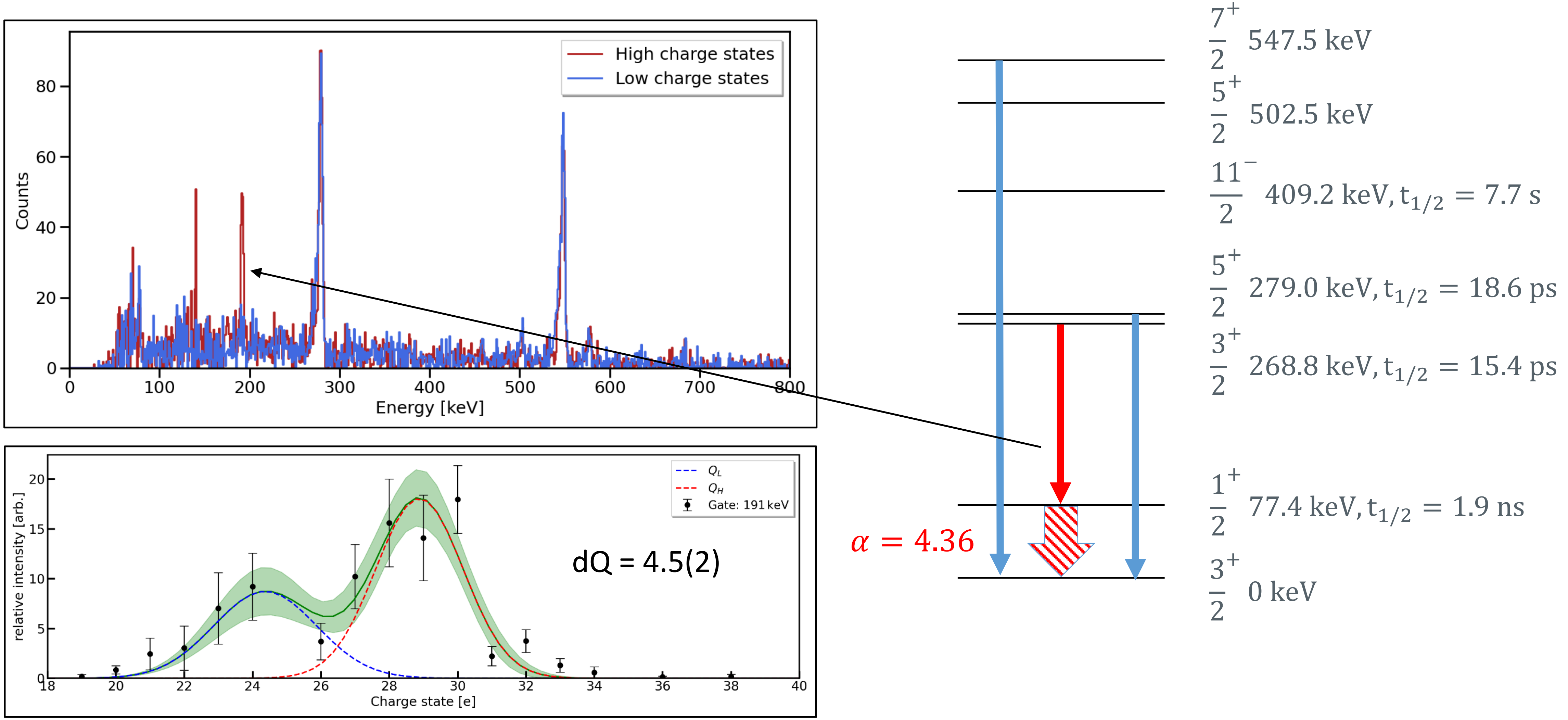
Experiment at Argonne National Laboratory



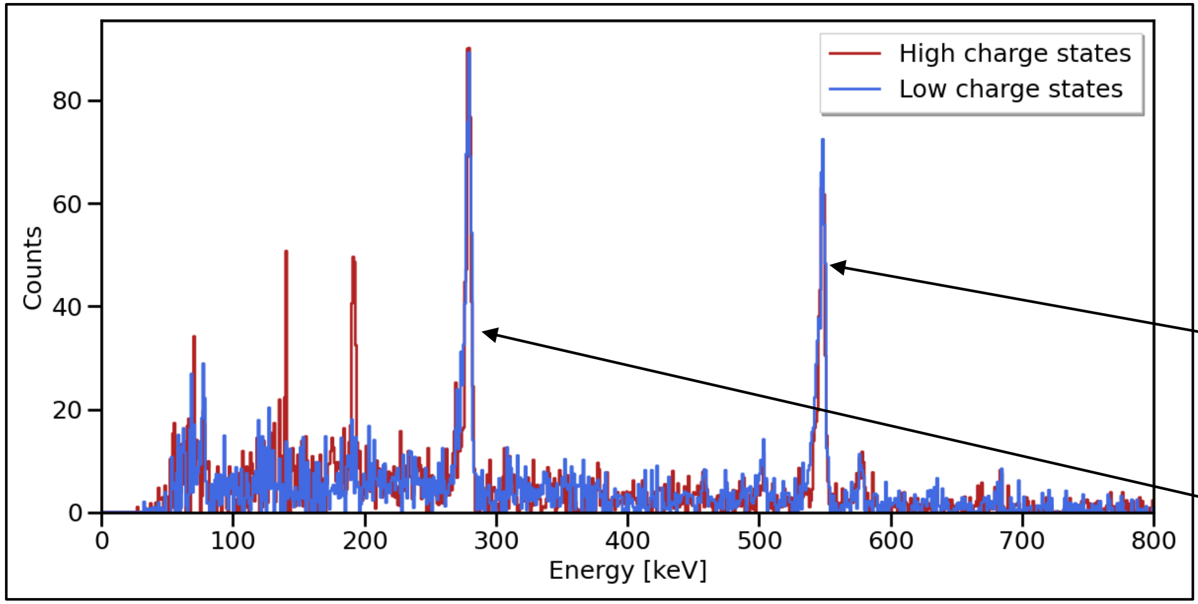
- Two beam energies investigated: **150** MeV and **101** MeV.
- Recoiling Au ions at ~80 MeV (~0.9 cm/ns) and ~50 MeV (~0.7 cm/ns) separated by A/q using FMA
- All states above 77 keV have half-lives ~10 ps or lower
- Fusion-evaporation reactions on C-foil used for normalisation of gamma-ray intensities (no FMA condition)

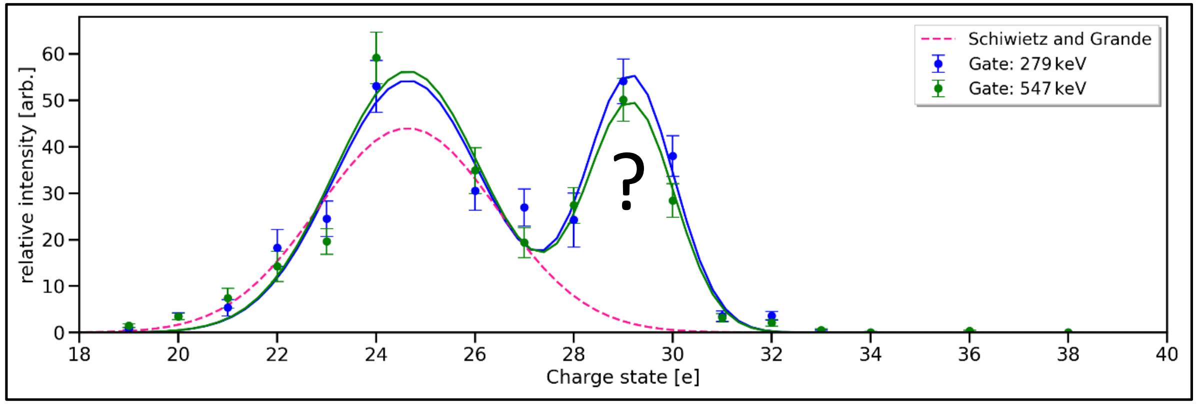


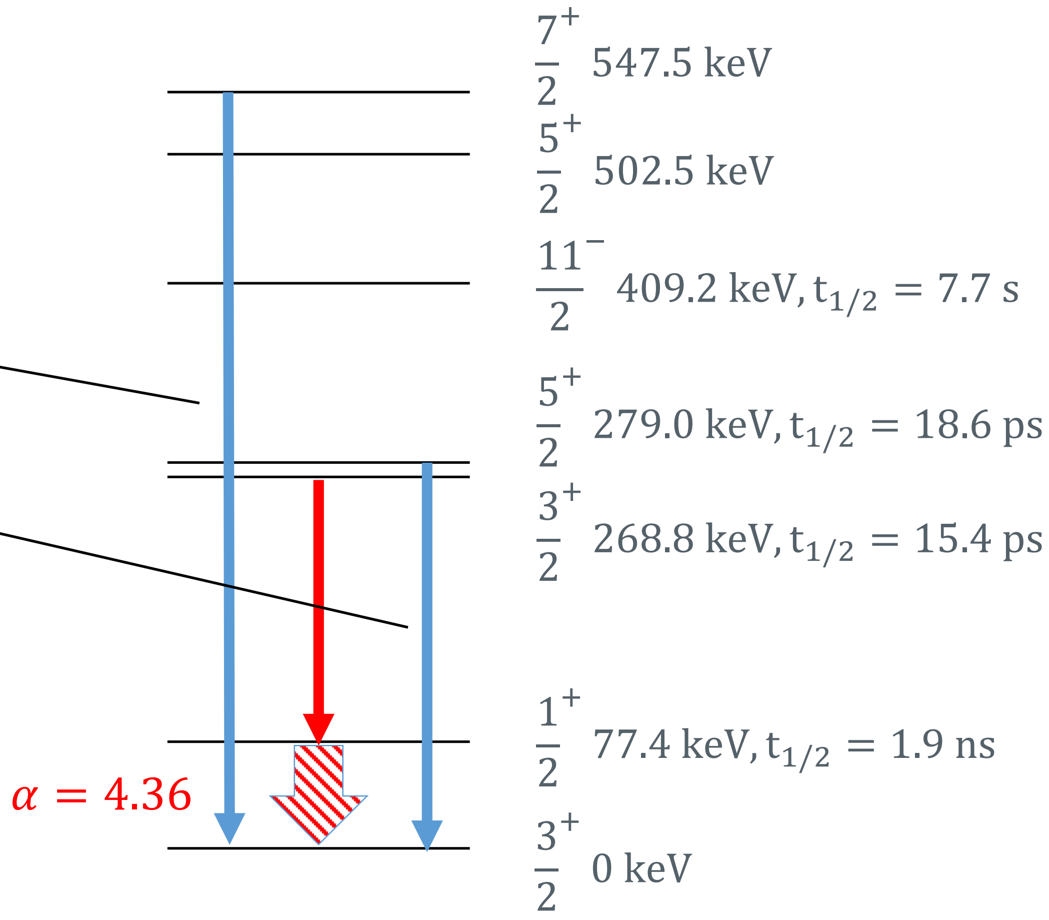
^{40}Ar on ^{197}Au at 150MeV



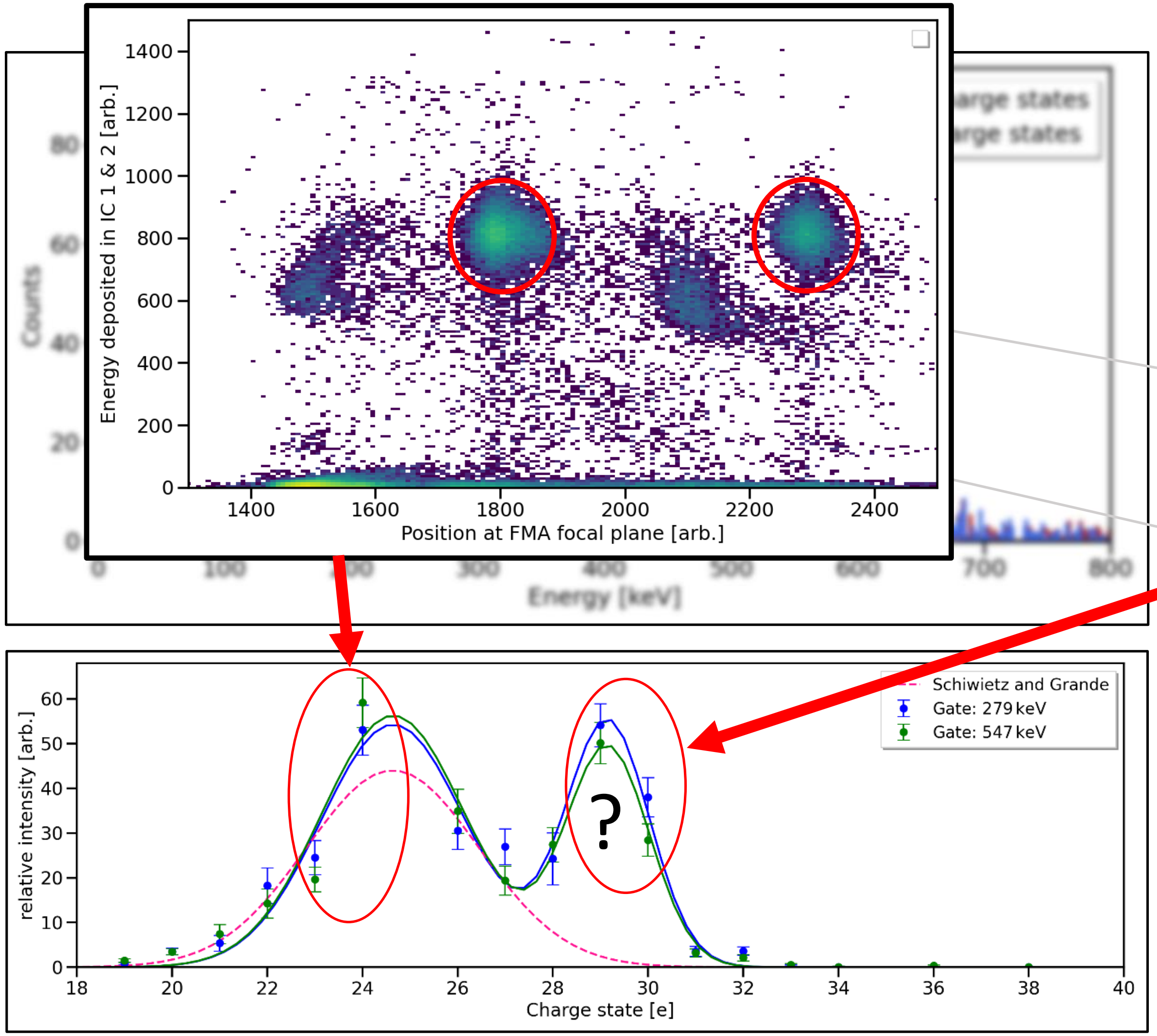
^{40}Ar on ^{197}Au at 150MeV

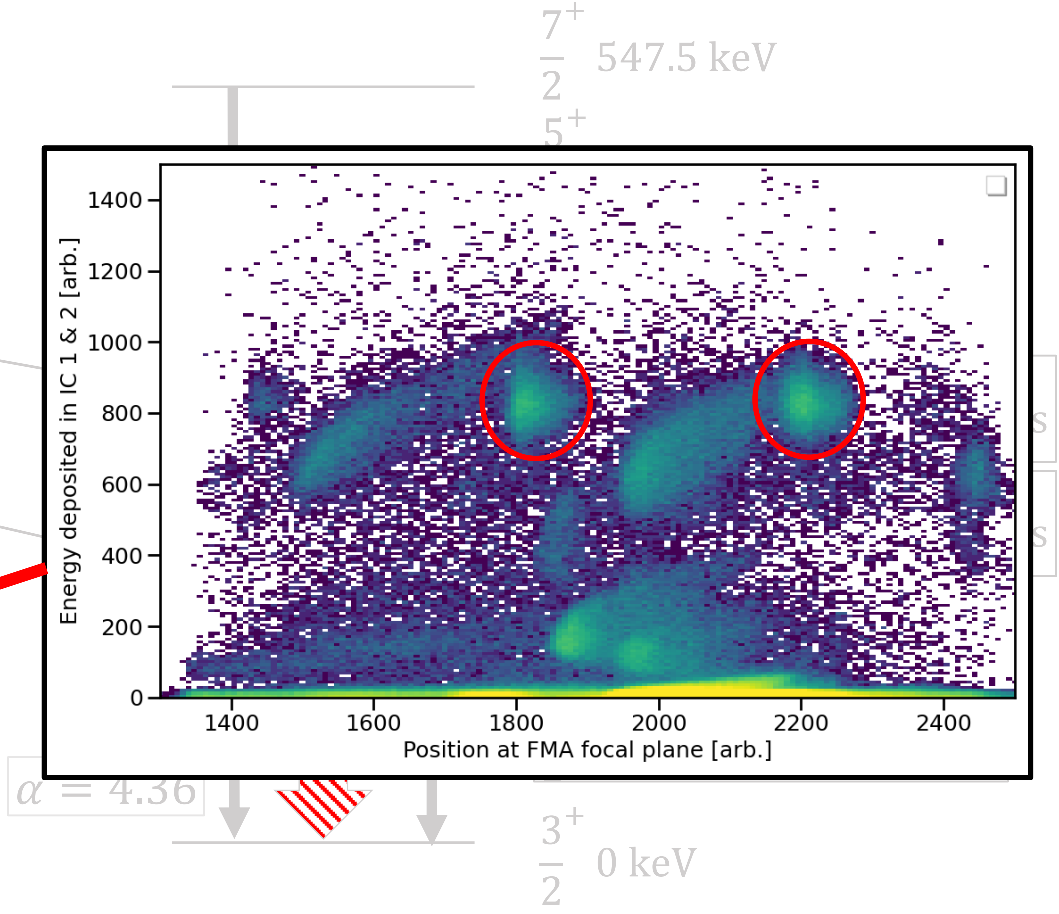






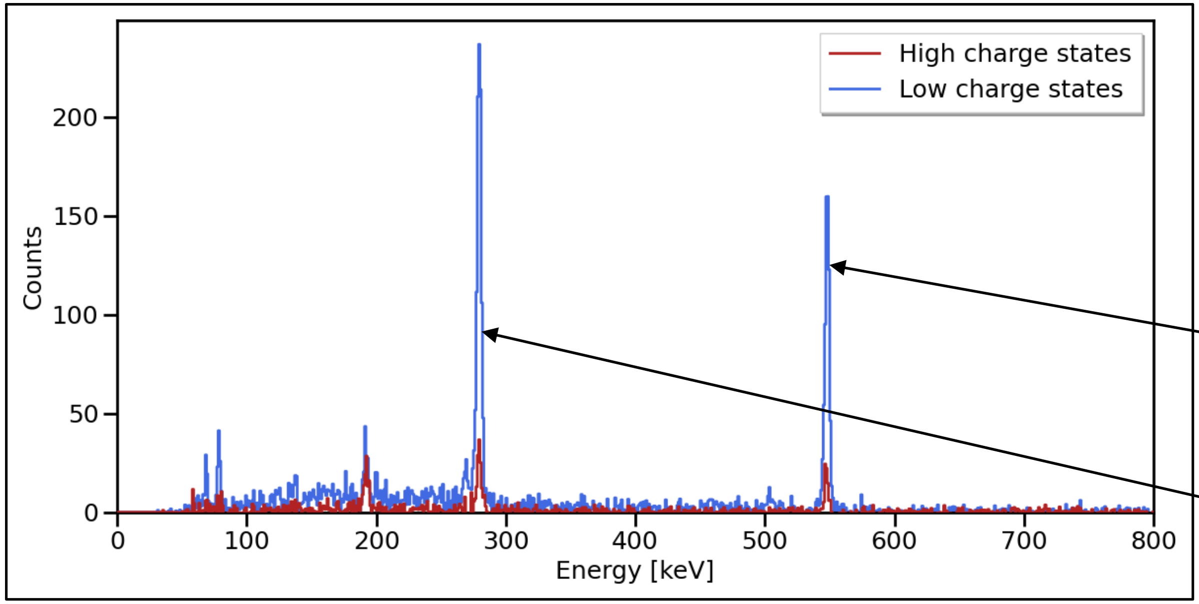
^{40}Ar on ^{197}Au at 150MeV

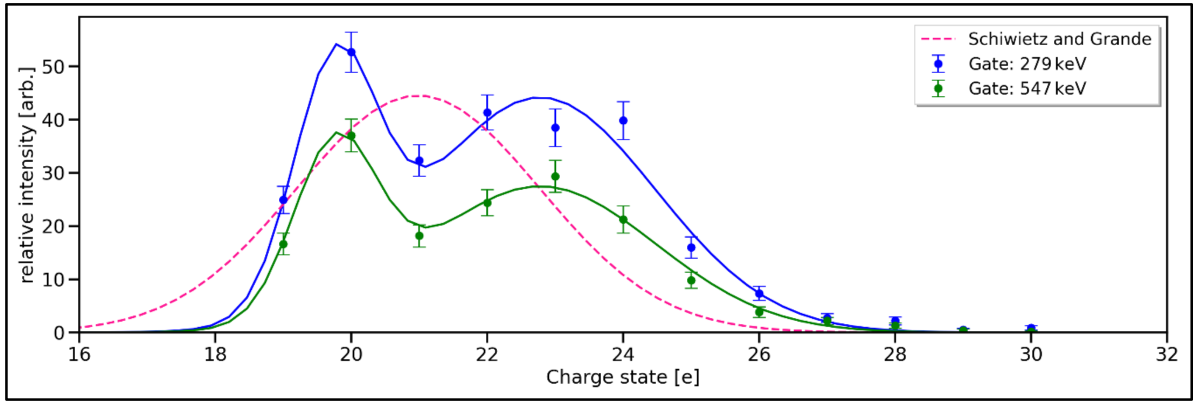


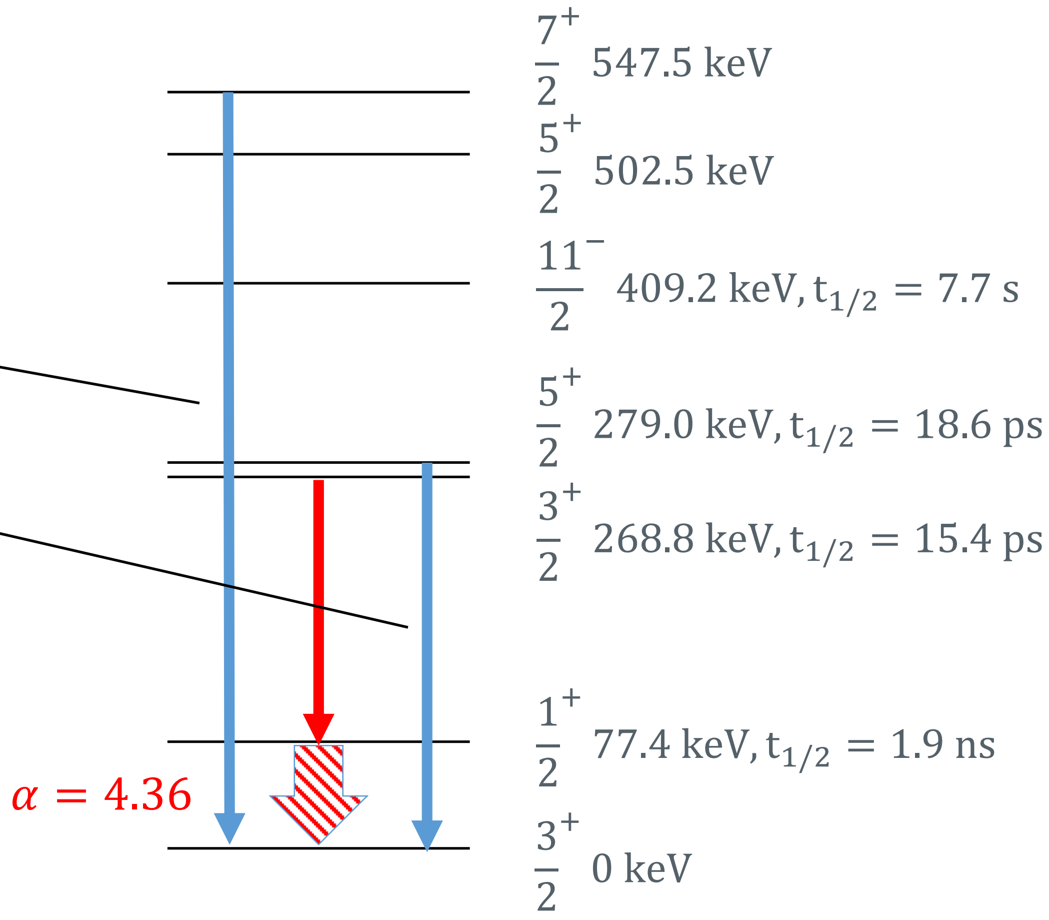


Possible scattered beam effect…

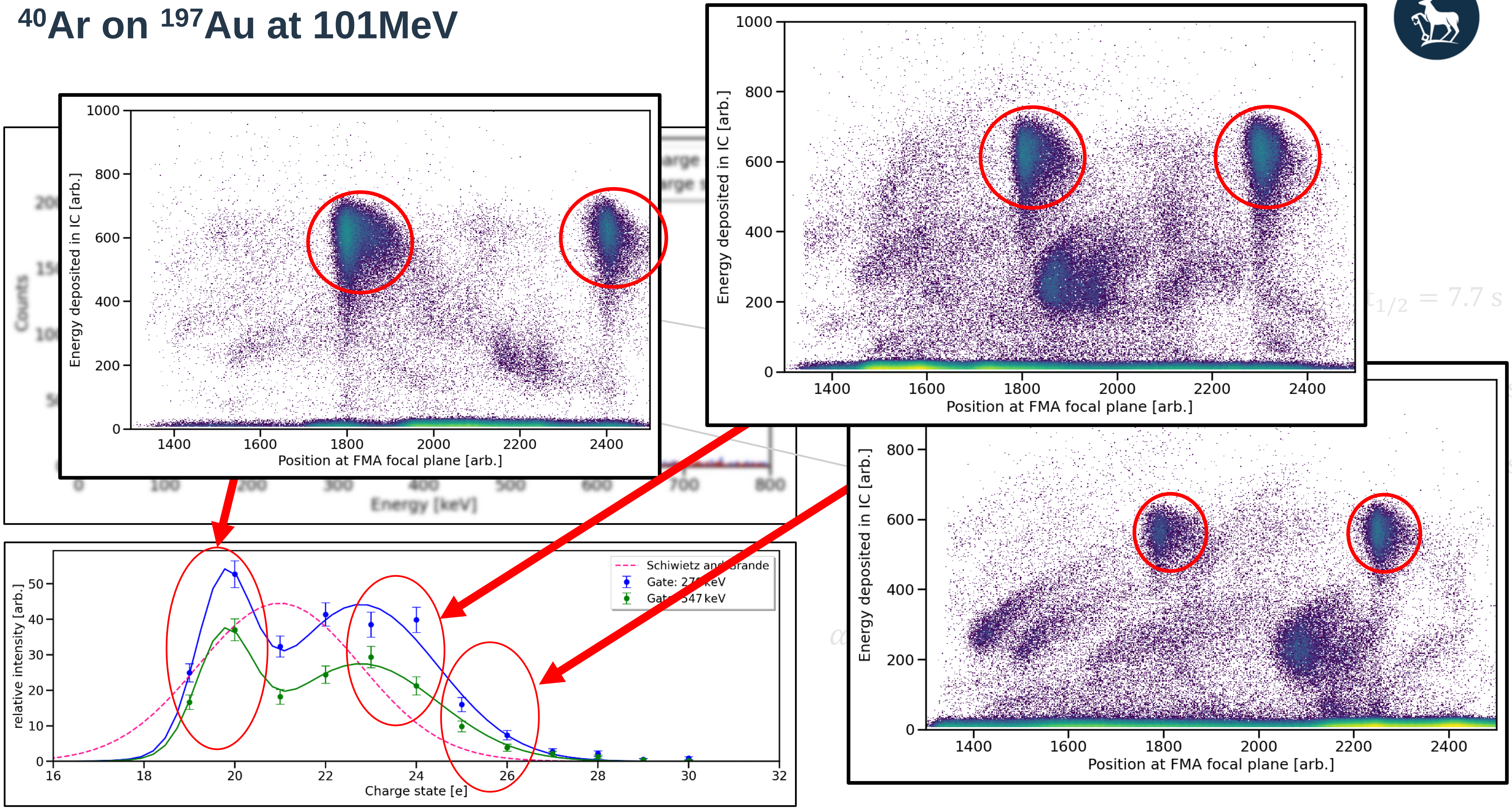
^{40}Ar on ^{197}Au at 101MeV



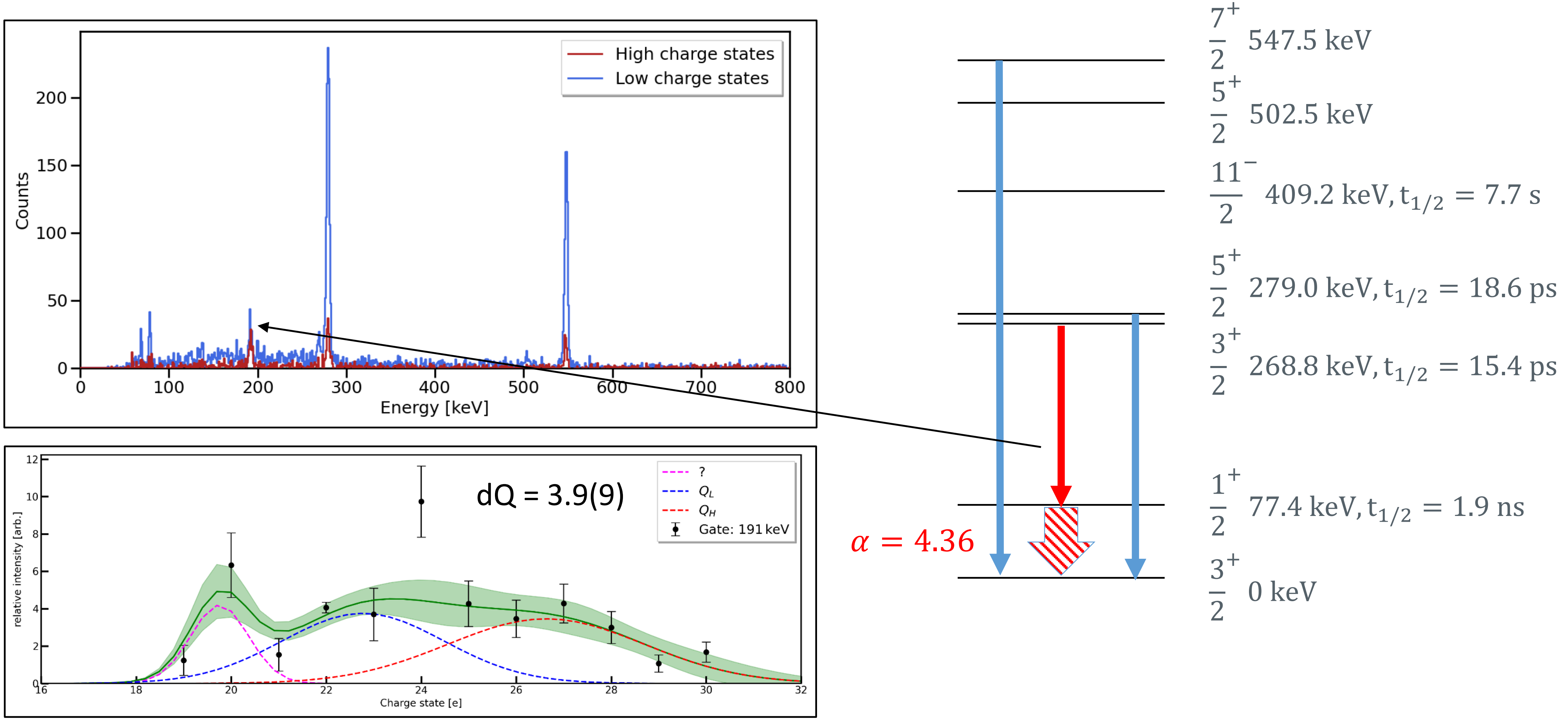




^{40}Ar on ^{197}Au at 101MeV

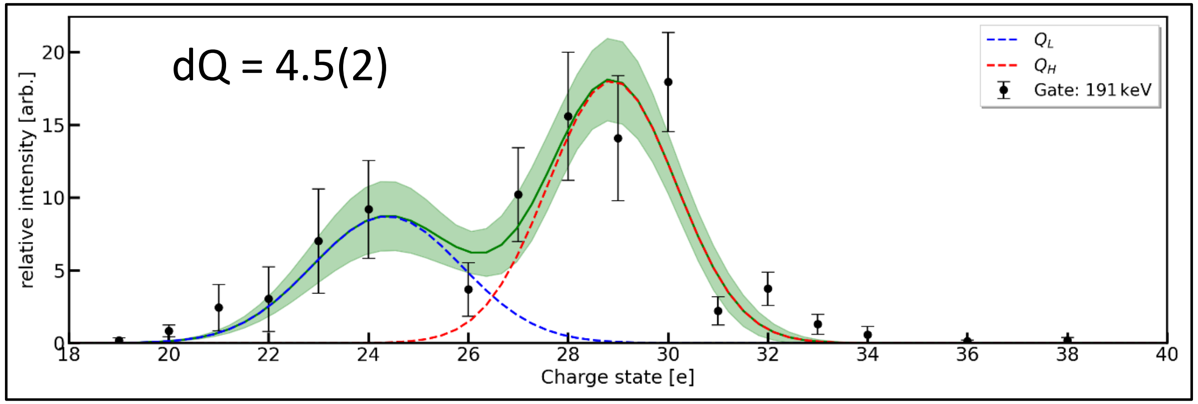


^{40}Ar on ^{197}Au at 101MeV



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

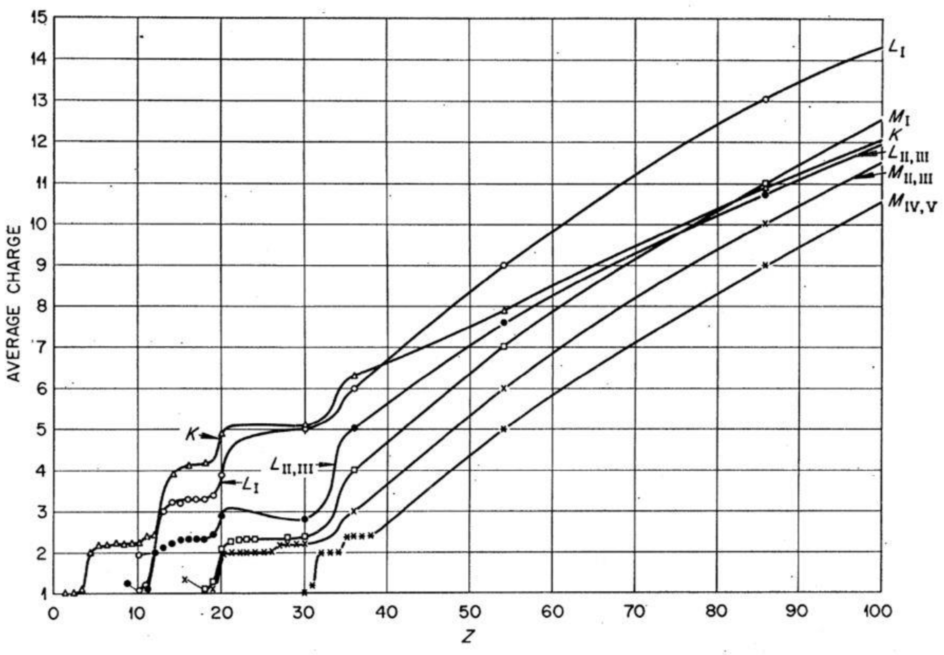
UNIVERSITY OF SURREY

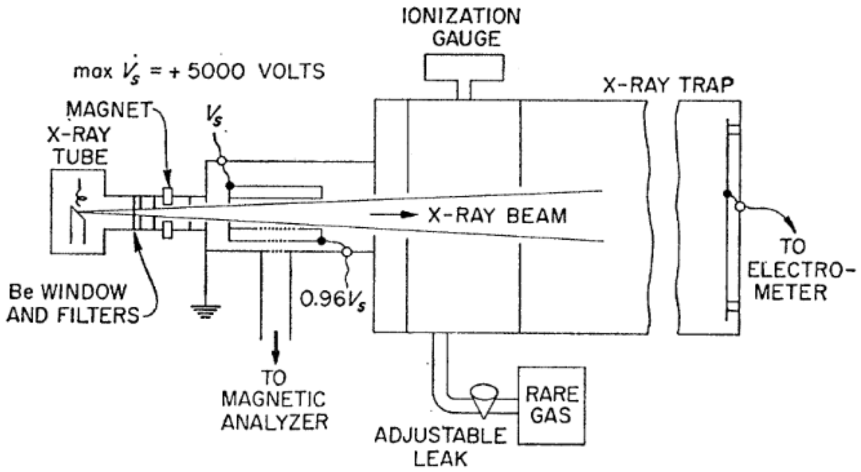
BACKUP SLIDES

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)