JYFL-ACCLAB, in-flight separators MARA and RITU, status and prospects

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Tasca 2021,
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21. – 23.6.2021

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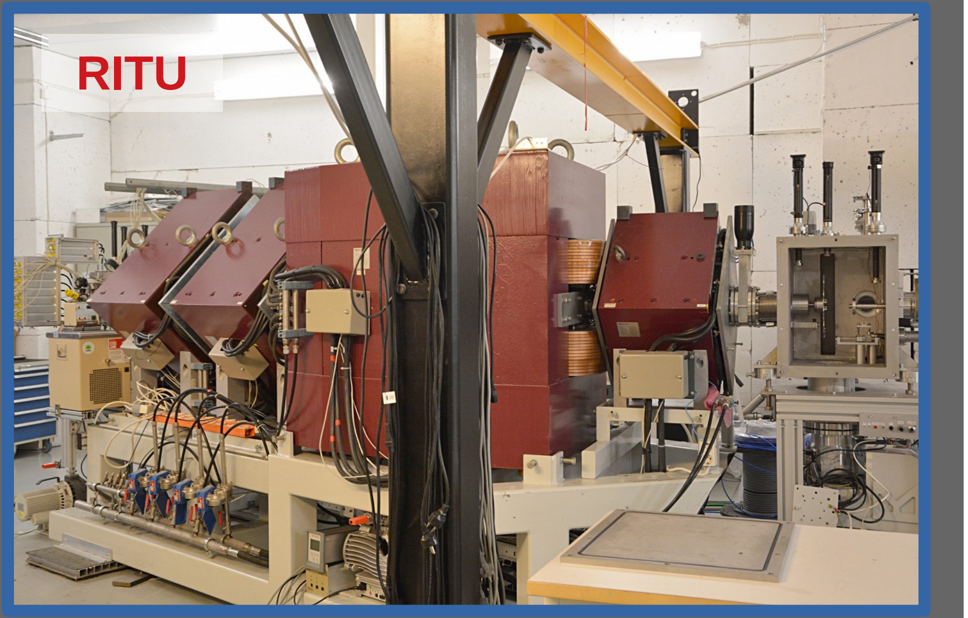
UNIVERSITY OF JYVÄSKYLÄ

In-flight recoil separators at JYFL

In-flight recoil separators at JYFL

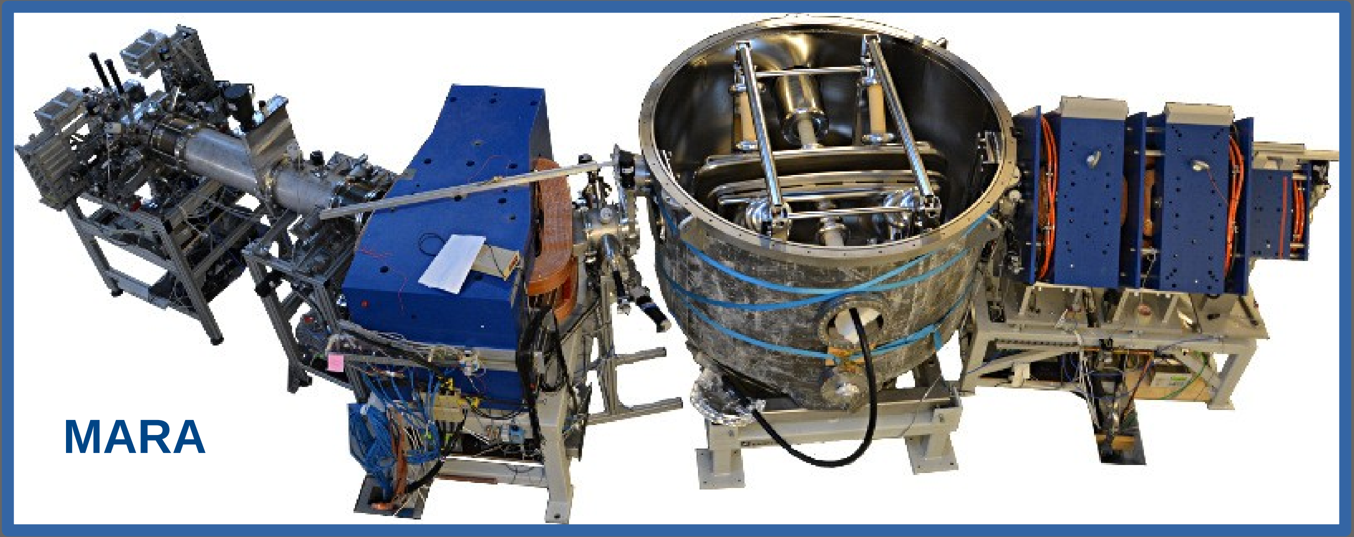


RITU gas-filled separator:

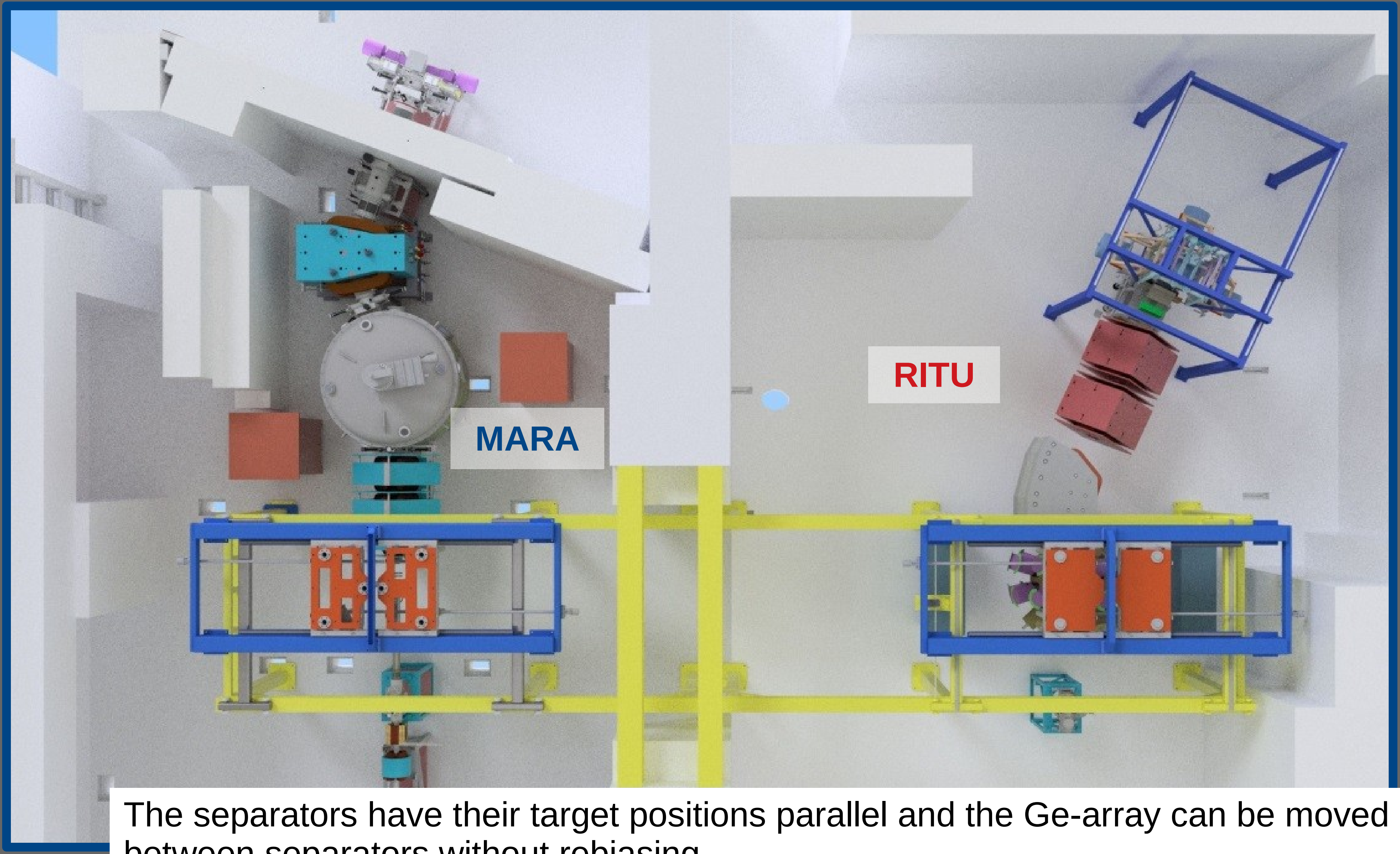
- Filled with helium (typically 0.5 – 1.5 mbar)
- Transmission independent of original charge state and kinetic energy
- Asymmetric angular acceptance (±25)x(±85) mrad^2
- Good for asymmetric fusion reactions (a beam lighter than a target)
- Ideal for transactinides

MARA vacuum mode separator:

- Symmetric angular acceptance (±50)x(±50) mrad^2
- Products are physically separated along their m/q values (typical mass resolving power: 150–200)
- Highly abundant neighboring masses can be cut down with mass slits.
- Good also for symmetric reaction and inverse kinematics



In-flight recoil separators at JYFL



The separators have their target positions parallel and the Ge-array can be moved between separators without rebiasing.

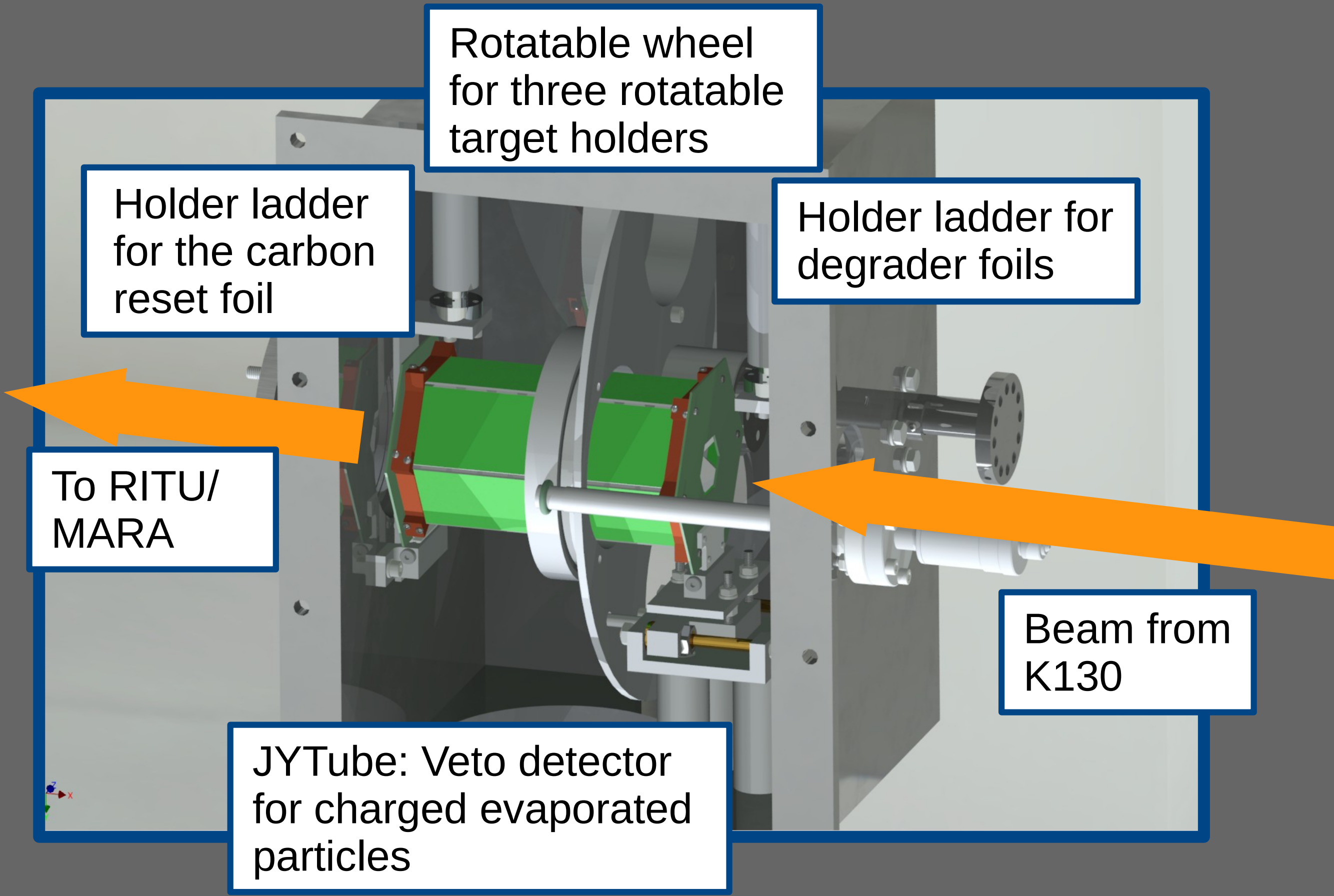
In-flight recoil separators at JYFL: **RITU**

RITU has not been used for a while. Restart of RITU experiments will take place on early 2022.

Control of valvels and magnets are moved to main control system (as in MARA).

New target chamber for decay experiments is under a construction. Copy of one at MARA. JYTube is optional.

New focal plane, very similar to MARA has been constructed.



Rotatable wheel for three rotatable target holders

Holder ladder for the carbon reset foil

Holder ladder for degrader foils

To RITU/ MARA

Beam from K130

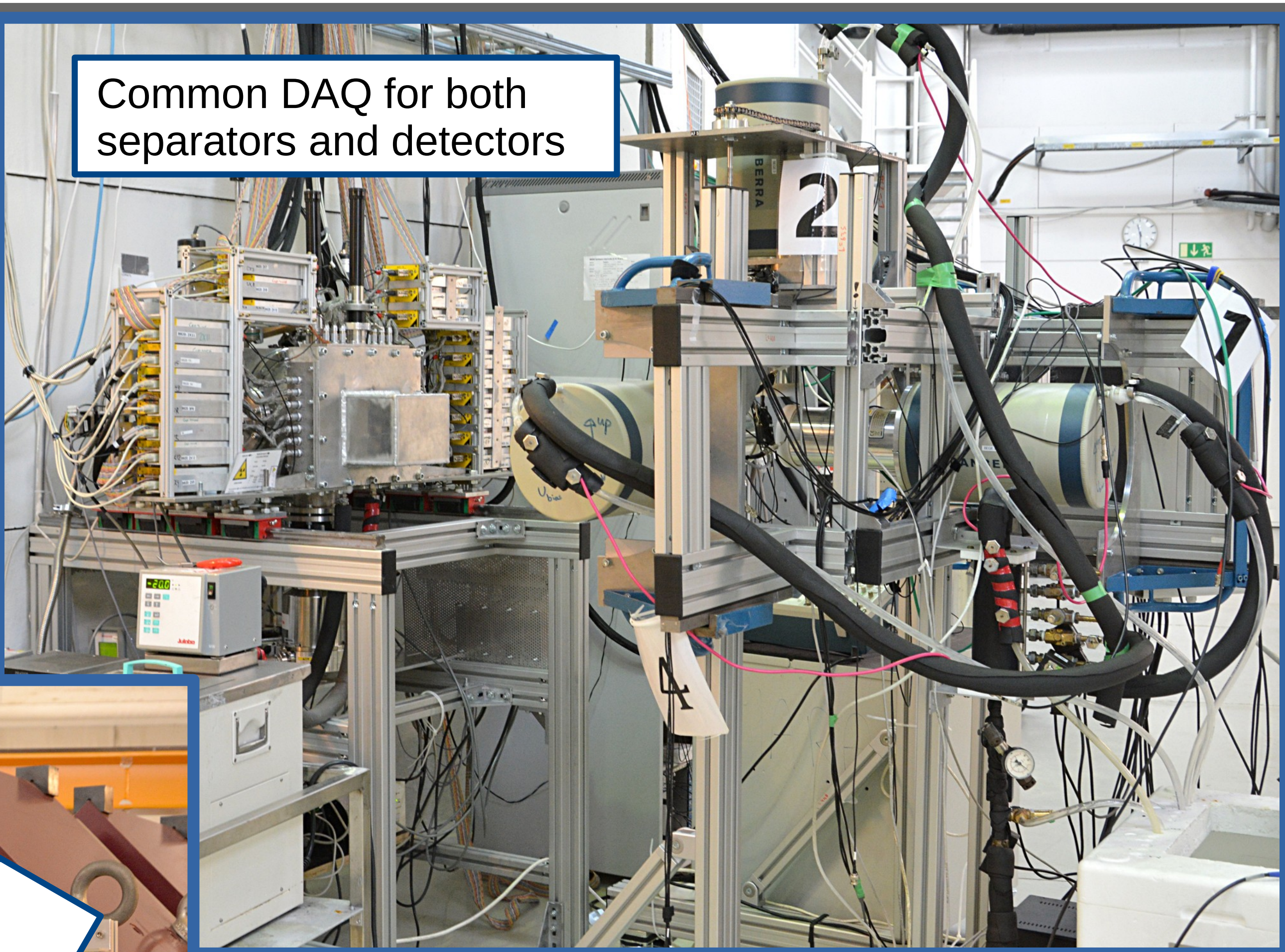
JYTube: Veto detector for charged evaporated particles

In-flight recoil separators at JYFL: **Focal planes**

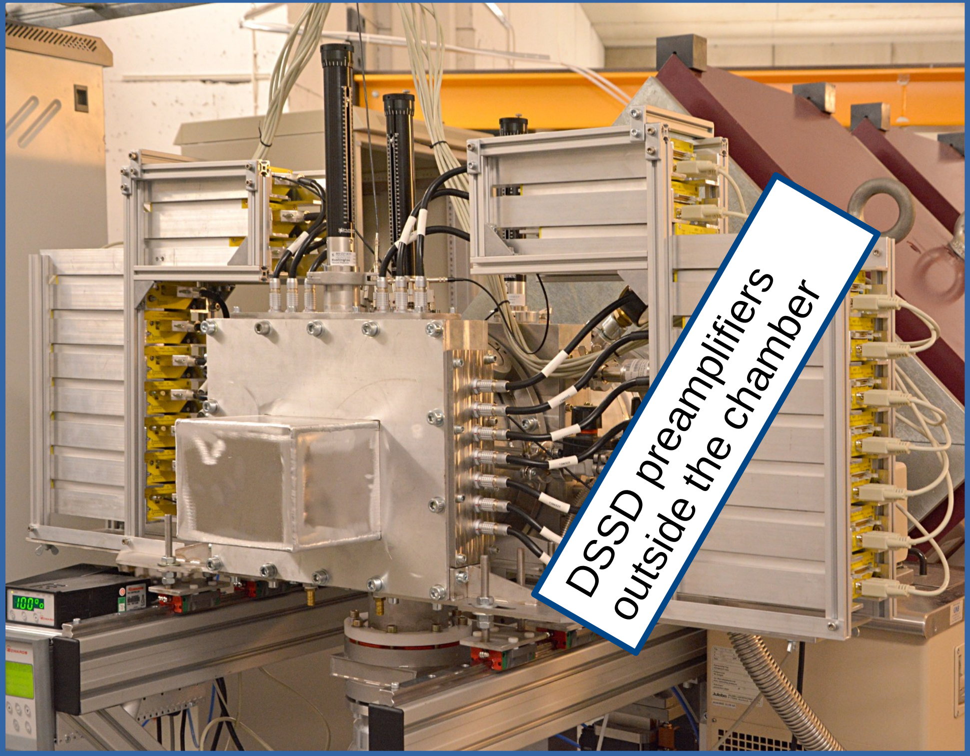
New focal plane at RITU. Same design as MARA focal plane has.

Using Micron BB20 DSSDs (128x48 mm^2, 0.67 mm strip pitch).

Recoil detection with MWPC and DSSD (E-ToF).



Common DAQ for both separators and detectors



DSSD preamplifiers outside the chamber

Punch through detectors behind the DSSD for light particle veto.

Position sensitive beta detector, Tuike, for beta decay tagging experiments.

Efficient Ge setup with three large BEGe detectors and one clover.

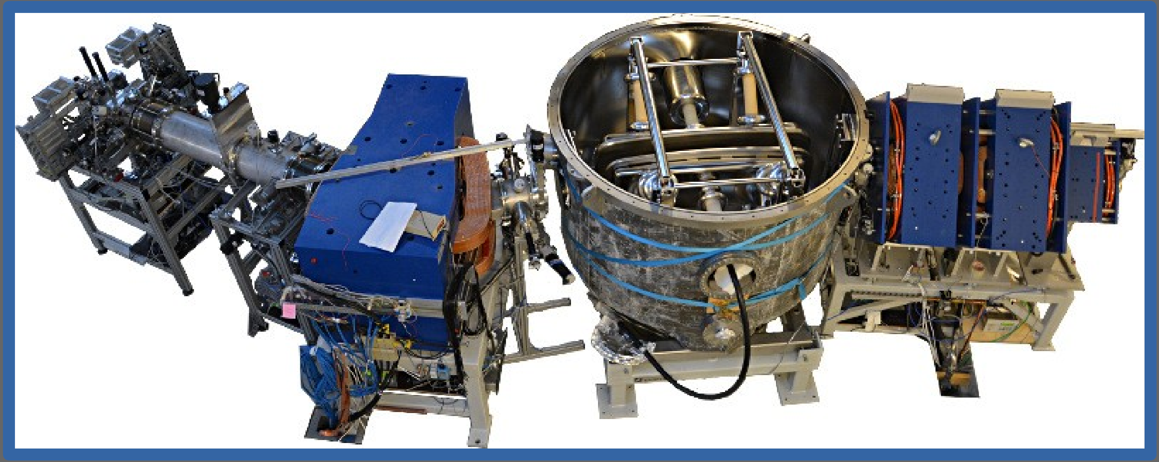
In-flight recoil separators at JYFL: MARA

MARA has been used in tens of experiments in recent years.

Most of the experiments has been in-beam experiments.

Several new isotopes identified at the proton drip line around A~170 and A~140 in decay experiments.

Many successfull experiments around N~Z line using new plastic scintillator Tuike at the focal plane and JYTube at the target in addition to normal Jurogam+MARA+FP setup.



MARA has been also used to separate heavier fusion products, heaviest being $^{211/213}$Ac [more by K. Auranen later today].

In most of the cases RITU is more suitable for nuclear structure studies of (trans)actinides. However,

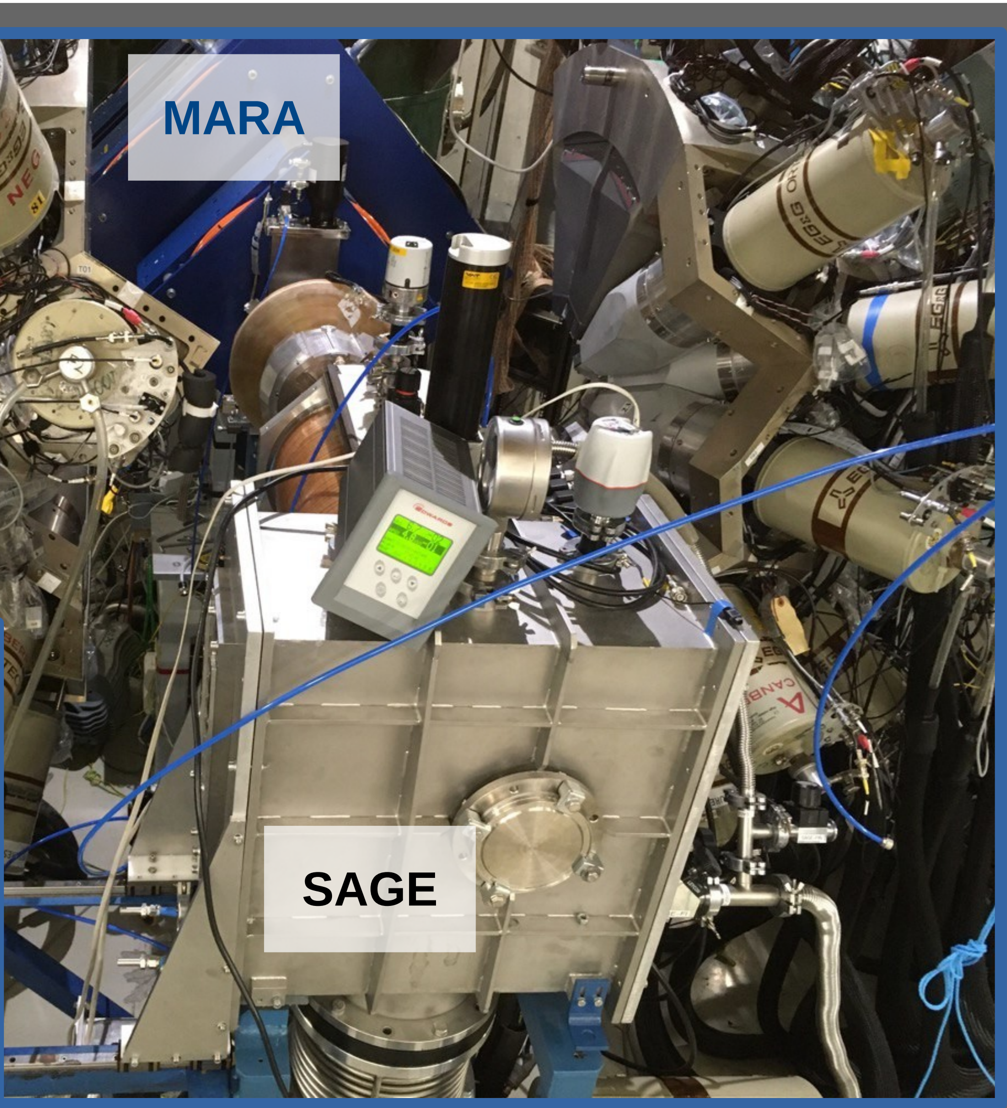
- SAGE experiments seeking for prompt conversion electrons benefit of MARA [later this talk] and
- charge plunger experiments requires a vacuum mode separator for q-state identification [later this talk].

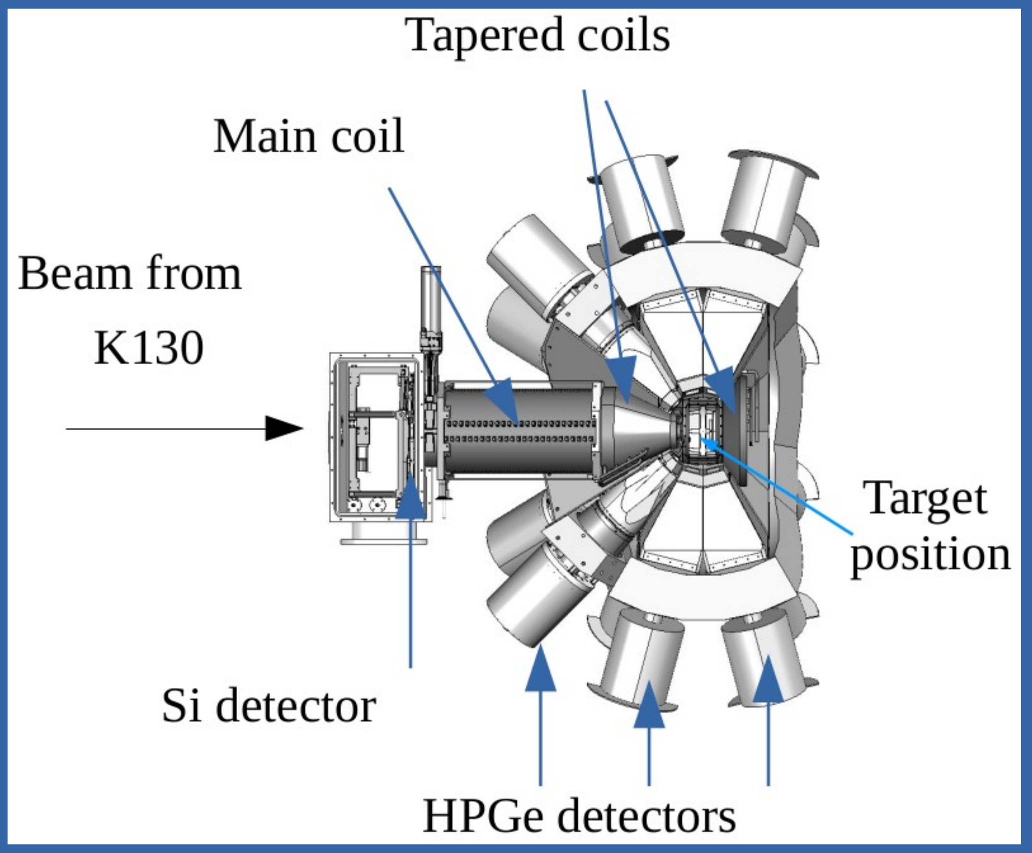
SAGE – electron spectrometer at the target area

SAGE Spectrometer for prompt conversion electrons

Solenoidal B-field transports conversion electrons from the target to the cooled Si-detector.

HV-barrier shields for delta electrons.





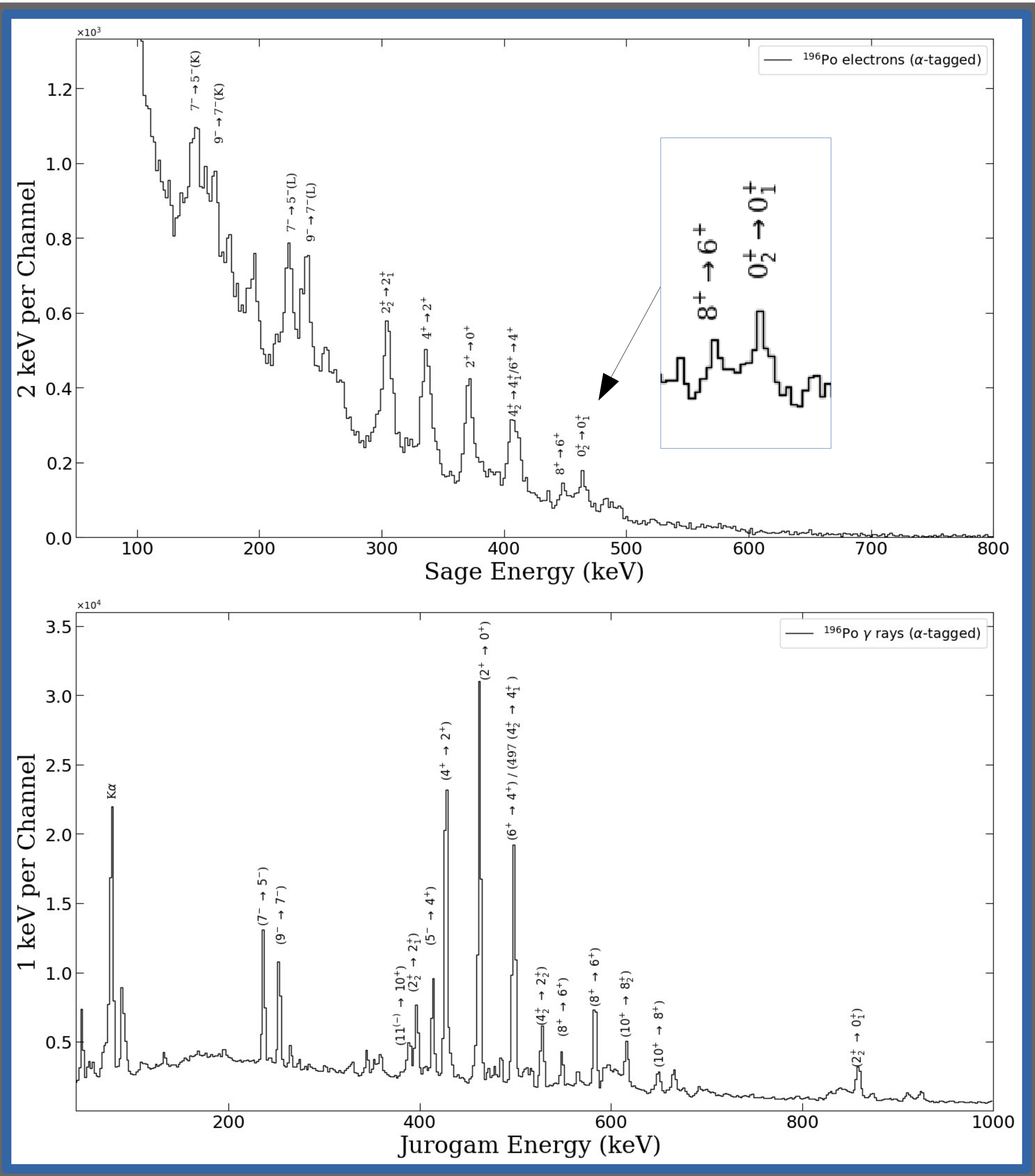
Jurogam and SAGE can be used simultaneously!
→ Electron – gamma – coincidences!

SAGE Spectrometer for prompt conversion electrons: ^{196}Po

Figure: Prompt electrons and gammas followed by ^{196}Po alpha decay at the MARA focal plane few weeks ago.

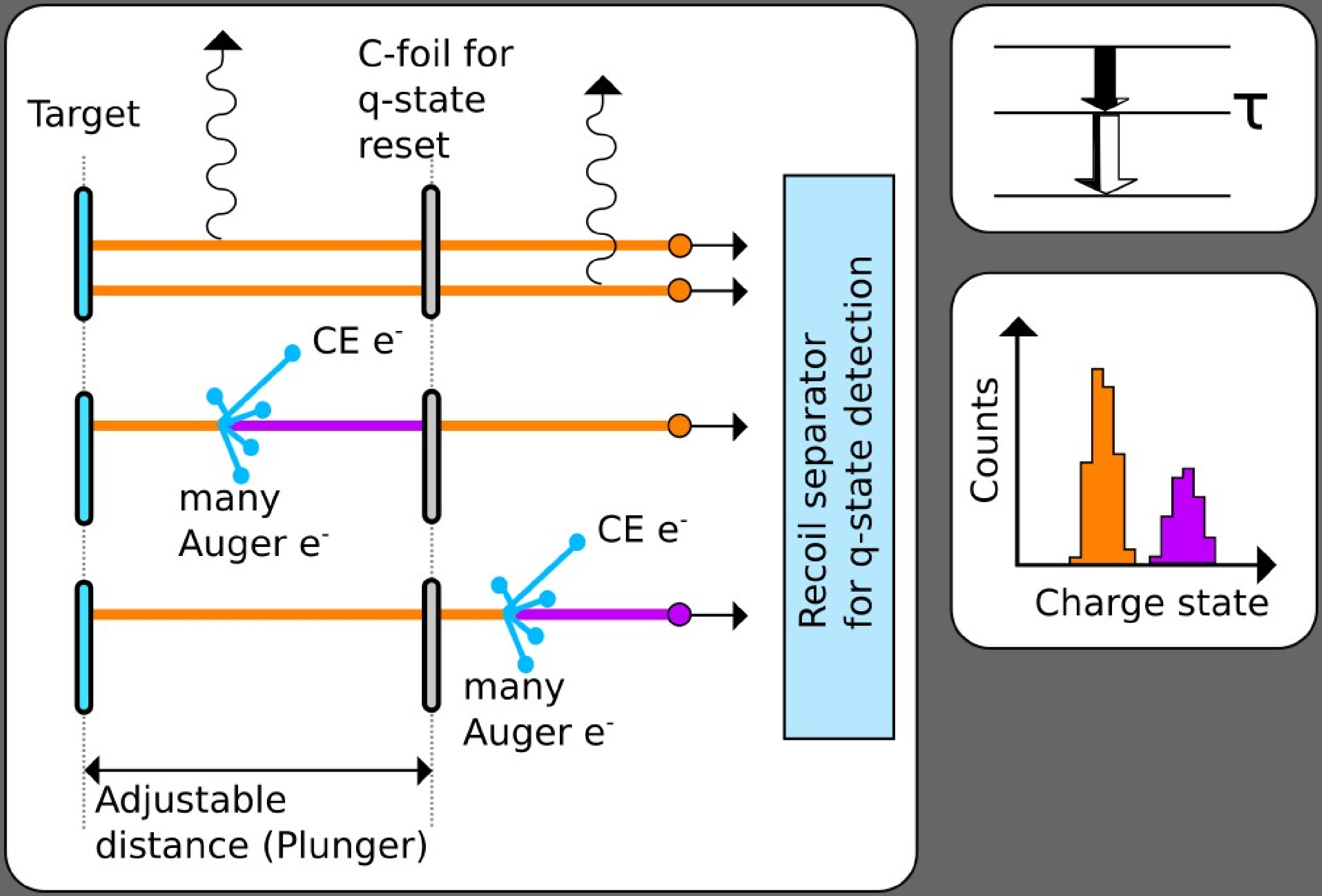
There is a 0+ → 0+ candidate.

Reaction: ^{165}Ho(^{35}Cl,4n)^{196}Po



Charge Plunger for lifetime measurements

Charge Plunger for lifetime measurements: principle



Emission of a conversion electron causes a prompt Auger cascade and the atom ends up to a high charge state. This anomalous charge state can be reset with a C-foil. The intensity ratio of normal and high charge states depends on the lifetime and the adjustable distance between the target and the reset foil. The lifetime of a converted decay can be calculated from the distance and the ratio.

Charge Plunger for lifetime measurements: ^{178}Pt

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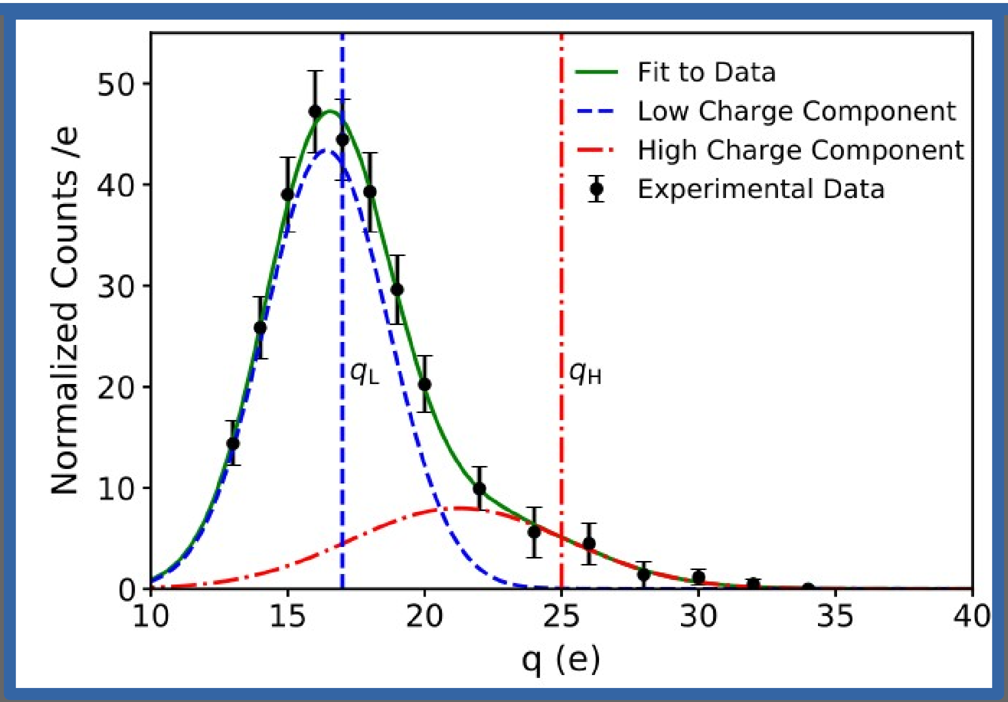
https://doi.org/10.1140/epja/s10050-021-00425-8

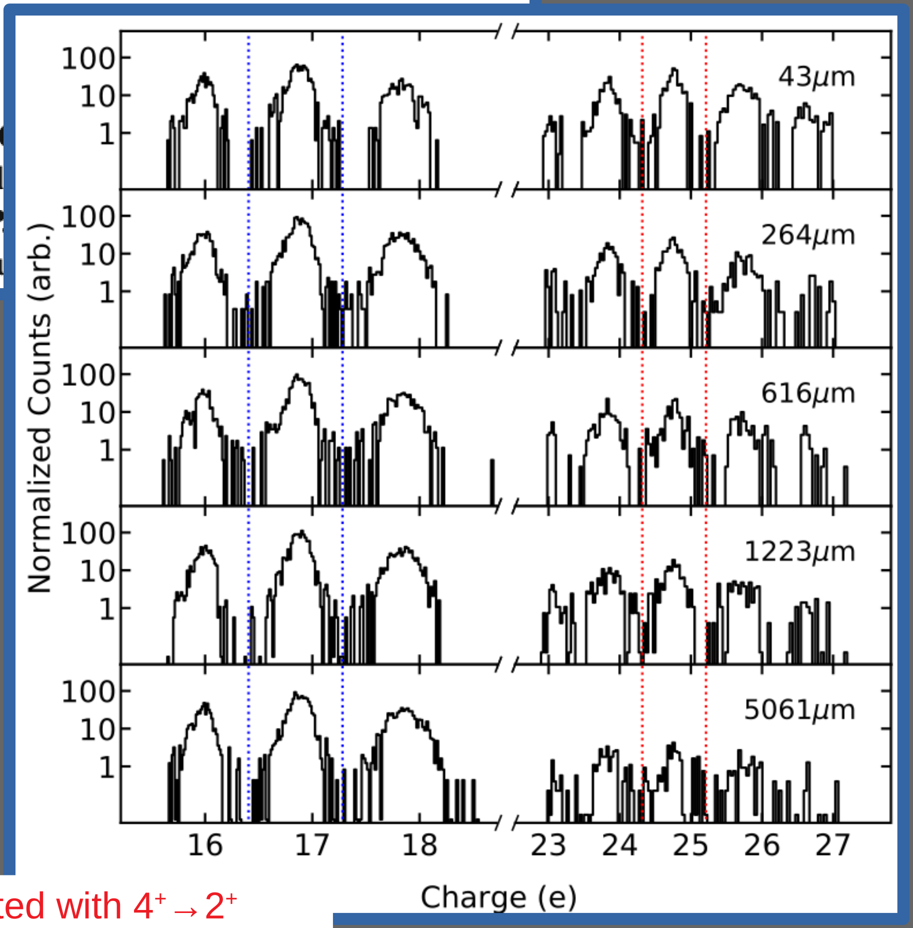
THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Experimental Physics

Lifetime measurements of yrast states in ^{178}Pt using the charge plunger method with a recoil separator

J. Heery[1,a], L. Barber[2], J. Vilhena[3], B. S. Nara Singh[3], R.-D. Herzberg[1], D. M.
G. Beeton[3], M. Bowry[3], A. Dewald[4], T. Grahn[5], P.T. Greenlees[5], A. Illana[5], R. Jul
M. Leino[5], M. Luoma[5], D. O'Donnell[3], J. Ojala[5], J. Pakarinen[5], P. Rahkila[5], P.
J. Sarén[5], J. Sinclair[3], J. F. Smith[3], J. Sorri[6,8], P. Spagnoletti[3,9], H. Tann[1,5], J. U





Gated with $4^+ \rightarrow 2^+$

Charge distribution was scanned and charge states selected to represent LOW (17) and HIGH (25) charge states.

Charge Plunger for lifetime measurements: ^{178}Pt

2+ lifetime of 430 ps was obtained with Differential Decay Curve Method (DDCM) and Two-state Bateman equation.

Result agrees well with the earlier litterature values.

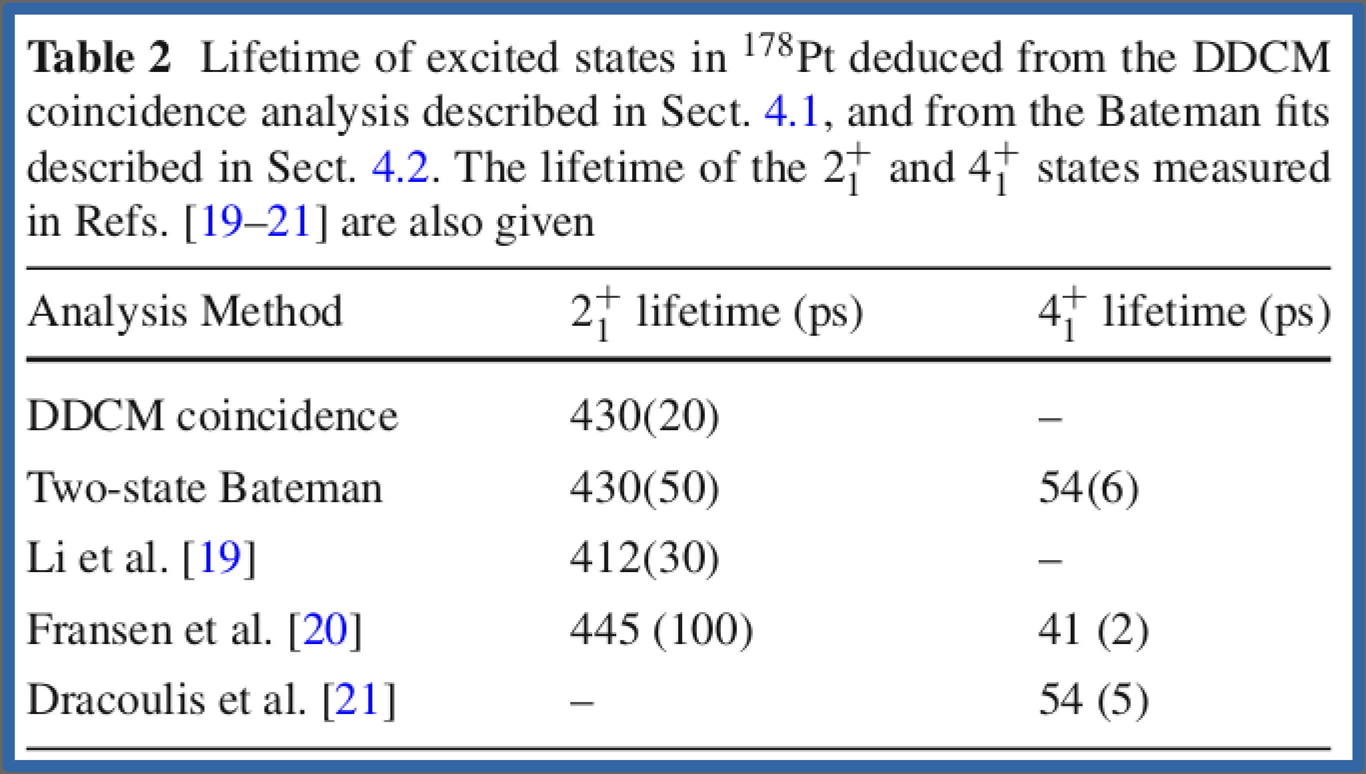


Table 2 Lifetime of excited states in ^{178}Pt deduced from the DDCM coincidence analysis described in Sect. 4.1, and from the Bateman fits described in Sect. 4.2. The lifetime of the 2_1^+ and 4_1^+ states measured in Refs. [19–21] are also given

Analysis Method	2_1^+ lifetime (ps)	4_1^+ lifetime (ps)
DDCM coincidence	430(20)	–
Two-state Bateman	430(50)	54(6)
Li et al. [19]	412(30)	–
Fransen et al. [20]	445 (100)	41 (2)
Dracoulis et al. [21]	–	54 (5)

Charge Plunger for lifetime measurements: Conclusions

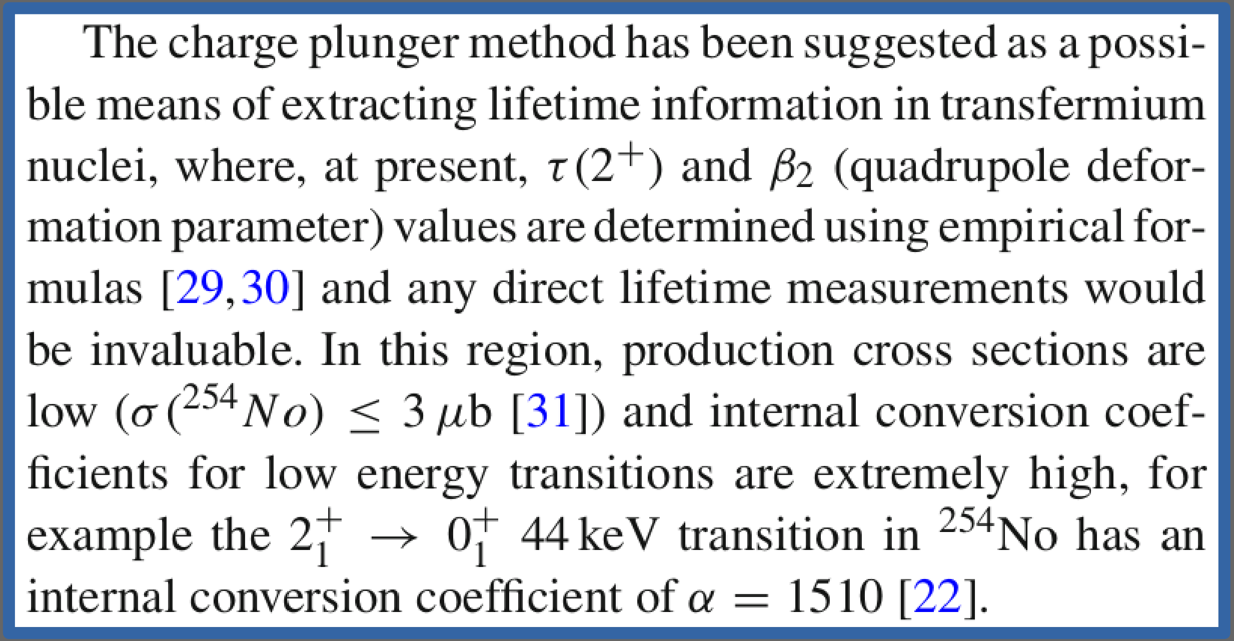
Advantages:

- Lifetime measurements of states with a converted de-excitation

Challenges:

- Multiple conversions after the recoil has come out from a target → Charge state distribution consists of more than two components
- Feeding gammas might be important to see → smaller statistics
- Fragmentation of recoils to two or more charge state components → less statistics

J.Heery at al.:



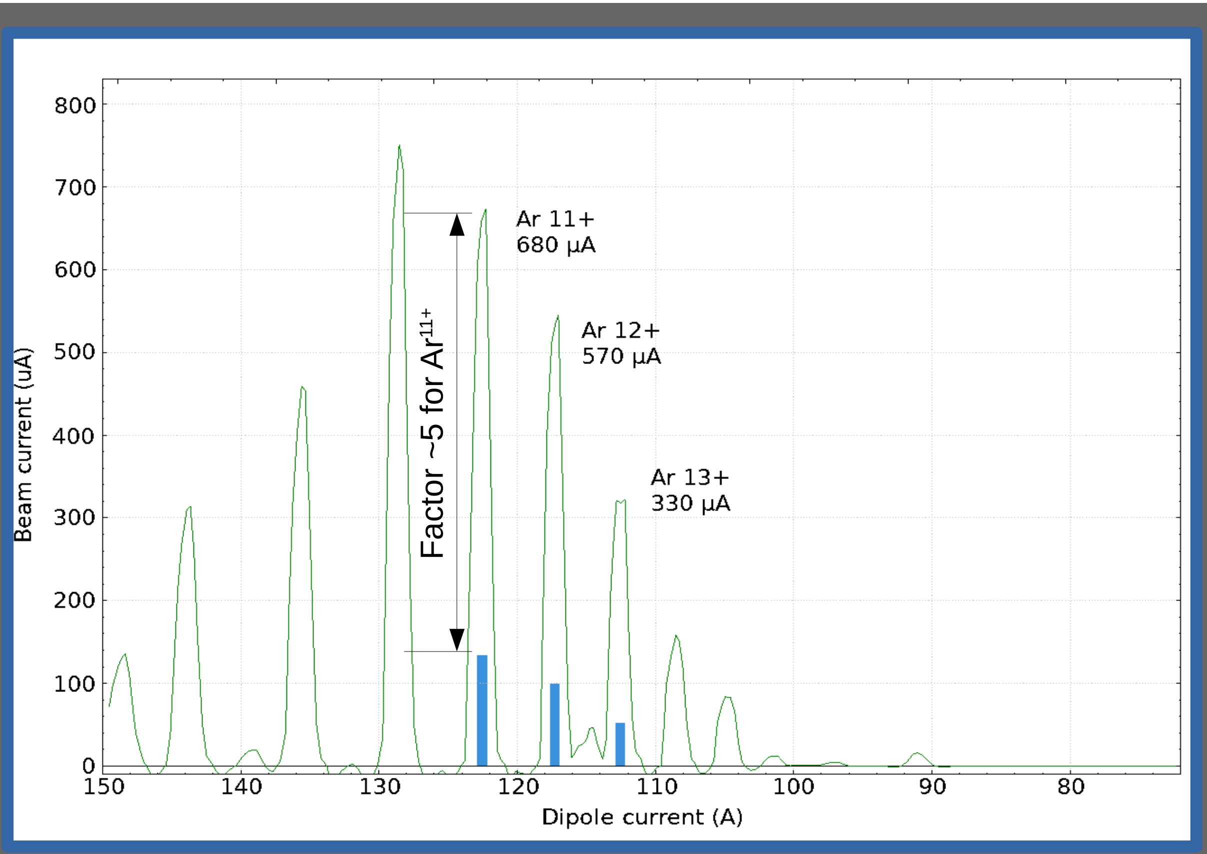
The charge plunger method has been suggested as a possible means of extracting lifetime information in transfermium nuclei, where, at present, $\tau(2^+)$ and β_2 (quadrupole deformation parameter) values are determined using empirical formulas [29,30] and any direct lifetime measurements would be invaluable. In this region, production cross sections are low ($\sigma(^{254}No) \leq 3\,\mu$b [31]) and internal conversion coefficients for low energy transitions are extremely high, for example the $2_1^+ \rightarrow 0_1^+$ 44 keV transition in ^{254}No has an internal conversion coefficient of $\alpha = 1510$ [22].

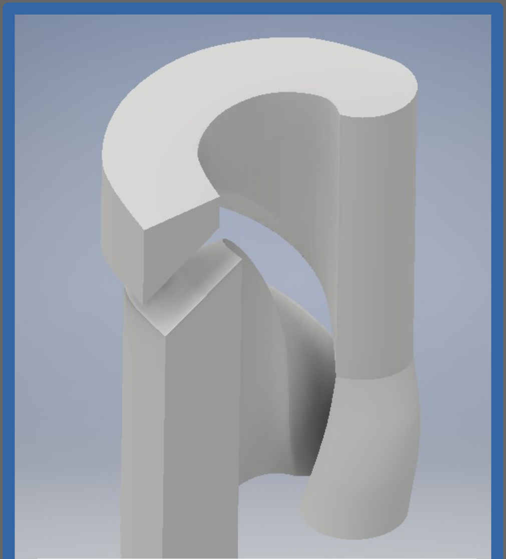
Towards higher intensities from K130

Towards higher intensities from K130 – central region update

The new ECR ion source HIISI can give 5 – 10 times more beam. However, the emittance of the heavy ion beams before the K130 is increases due to the space charge and higher B-field of HIISI. → No gain from HIISI.

These problems can be avoided by increasing the acceleration voltage before K130. A new central region part for K130, allowing the increase of the voltage, has been constructed but not tested yet.





New central region part

The transmission of the K130 is up to few percents or less. Beam line transmission is about 50 %. A conservative total transmission to a target is ~ 1%.

After careful tuning it should be possible to get close to 1 particle uA beam of Ar to the target.

Real problem: the commercial activity cannot use this new central region → laborous change of central region needed often.

JYFL-ACCLAB, in-flight separators MARA and RITU, status and prospects

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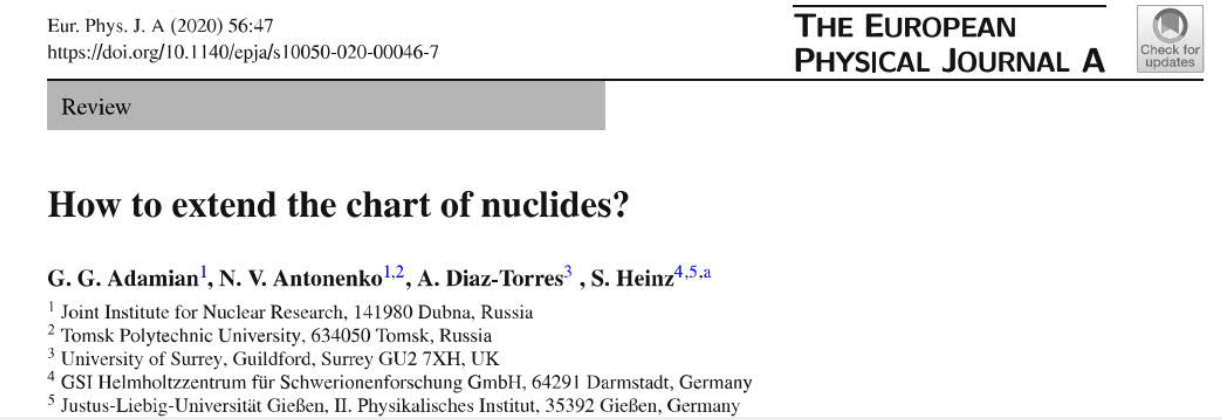
Part II

- Non-fusion studies
- Alpha-particle (proton) decay studies, sub-uranium region
  - At and beyond the proton-drip line
- Decay studies, transuranium region
- Outlook

REC SEP @ SHE CHEM TASCA 21
June 21 - 23, 2021
18th Workshop on
Recoil Separator for Superheavy Element Chemistry



Eur. Phys. J. A (2020) 56:47
https://doi.org/10.1140/epja/s10050-020-00046-7

THE EUROPEAN PHYSICAL JOURNAL A

Check for updates

Review

How to extend the chart of nuclides?

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[4] GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany
[5] Justus-Liebig-Universität Gießen, II. Physikalisches Institut, 35392 Gießen, Germany

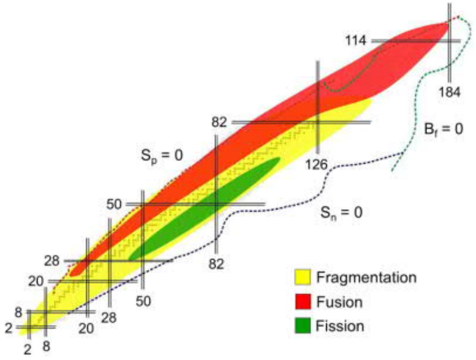


Fig. 2 Fragmentation, fusion and fission are presently the most effective reactions to produce (new) isotopes in the lab. In fragmentation reactions, neutron-rich as well as neutron-deficient nuclei up to uranium can be produced (yellow area). Fission leads to relatively neutron-rich intermediate heavy nuclei (green area). Fusion is presently the only method to synthesize transuranium and superheavy nuclei, but results in rather neutron-deficient reaction products due to the bending of the stability line (red area)

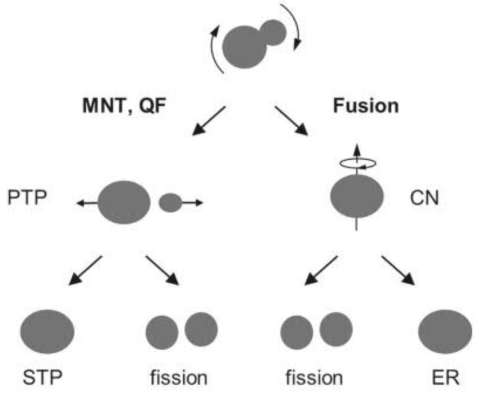


Fig. 4 The two possible evolution paths of nuclear molecules: once the molecule-like DNS is formed, it can undergo complete fusion, resulting in a CN. The de-excitation of the CN proceeds either by evaporating nucleons and γ rays, leaving an evaporation residue (ER) or by fission. Alternatively, the DNS can scission before reaching the CN state. Before scission, large amounts of nucleons can be exchanged between the reaction partners (multinucleon transfer MNT/quasi-fisson, QF). When the system breaks up, the still excited projectile-like and target-like primary transfer products (PTP) are emitted. Their de-excitation takes place via evaporation of nucleons and γ rays leading to the secondary transfer products (STP) or, particularly in the case of heavy nuclei, by fission

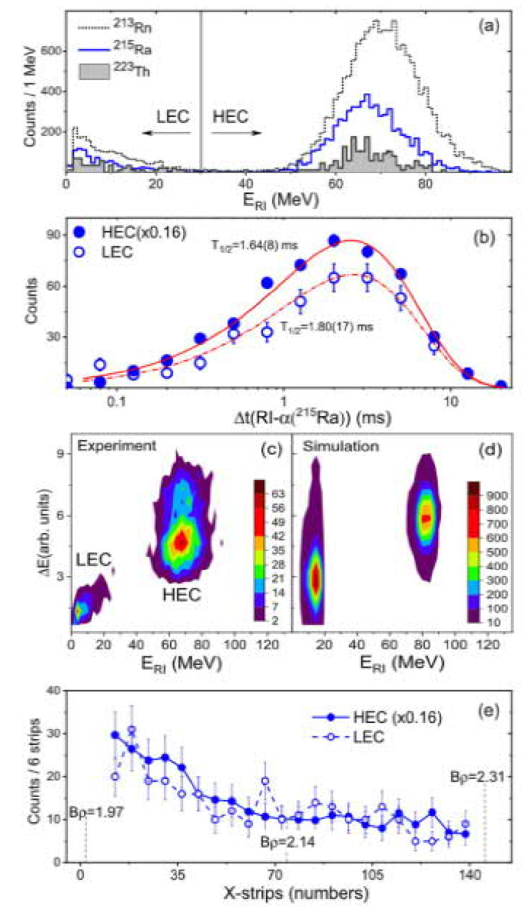
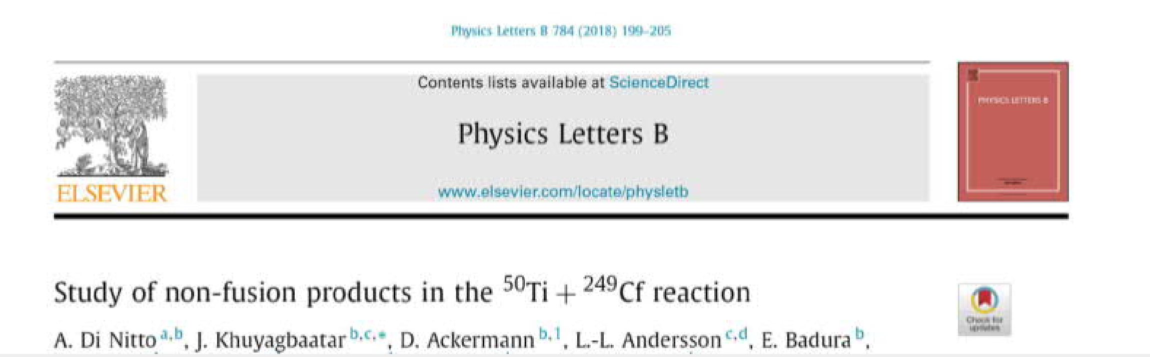


Fig. 2. (Color online.) (a) Implantation-energy distributions of ^{215}Ra, ^{213}Rn, and ^{223}Th isotopes. (b) Time distributions of α(^{215}Ra) events in beam-off periods correlated with HEC (multiplied by a factor 0.16) and LEC recoils. The half-lives obtained by fitting experimental data (circles) with universal radioactive decay functions (lines) are consistent with the literature value ($T_{1/2}$=1.67(1) ms [38]). (c) Estimated experimental and (d) SRIM simulated energy losses in the MWPC (ΔE) and DSSD (E_{RI}) detectors of RI of ^{215}Ra events. (e) Relative yields of same events as function of DSSD X-strip of HEC and LEC recoils.



Physics Letters B 784 (2018) 199–205

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Study of non-fusion products in the ^{50}Ti + ^{249}Cf reaction

A. Di Nitto[a,b], J. Khuyagbaatar[b,c,*], D. Ackermann[b,1], L.-L. Andersson[c,d], E. Badura[b],

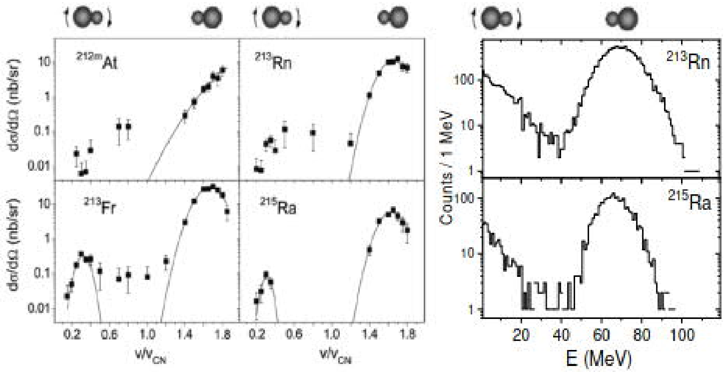
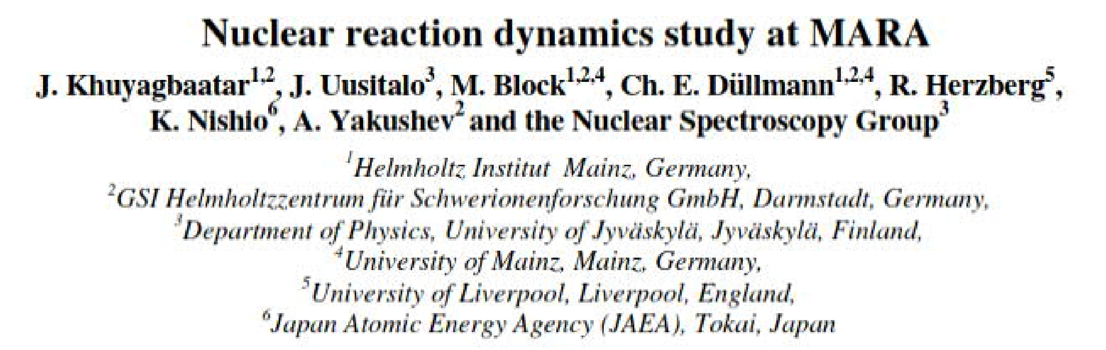


Figure 2. Left panel: The measured velocity (normalized to velocity of CN) distributions of non-fusion products in ^{64}Ni+^{207}Pb reaction at SHIP (figure is adopted from [26]). To get the cross sections at 10msr forward acceptance angle, the values given in the vertical axis has to be multiplied by a factor 100. Right panel: The measured energy distribution of non-fusion products in ^{50}Ti+^{249}Cf reactions at TASCA. Illustration of the different orientations as being the origin of the low and high velocity and energy components are given.



Nuclear reaction dynamics study at MARA

J. Khuyagbaatar[1,2], J. Uusitalo[3], M. Block[1,2,4], Ch. E. Düllmann[1,2,4], R. Herzberg[5],
K. Nishio[6], A. Yakushev[2] and the Nuclear Spectroscopy Group[3]

[1] *Helmholtz Institut Mainz, Germany,*
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[4] *University of Mainz, Mainz, Germany,*
[5] *University of Liverpool, Liverpool, England,*
[6] *Japan Atomic Energy Agency (JAEA), Tokai, Japan*

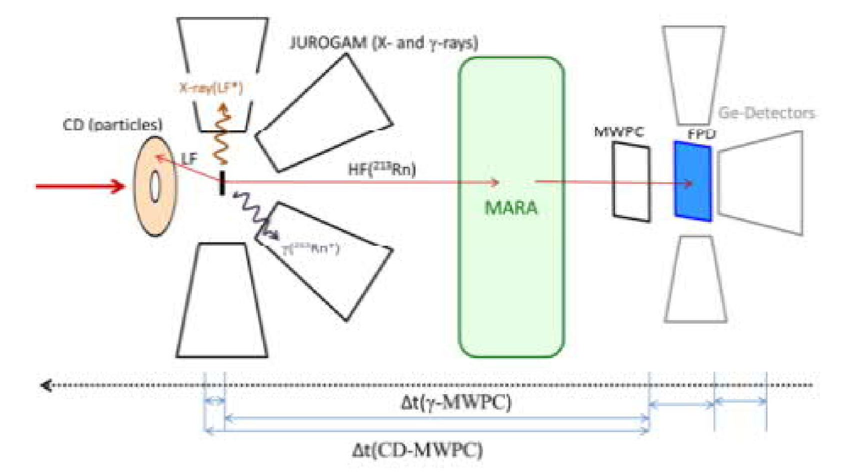


Figure 4. Schematic of the experimental setup and measurement scenario. Notations of the each instrument are given. The horizontal line marks the time scale in a backward direction showing the concept of the delayed coincident technique. See text for details.

^{65}Cu + ^{209}Bi
^{65}Cu + ^{238}U

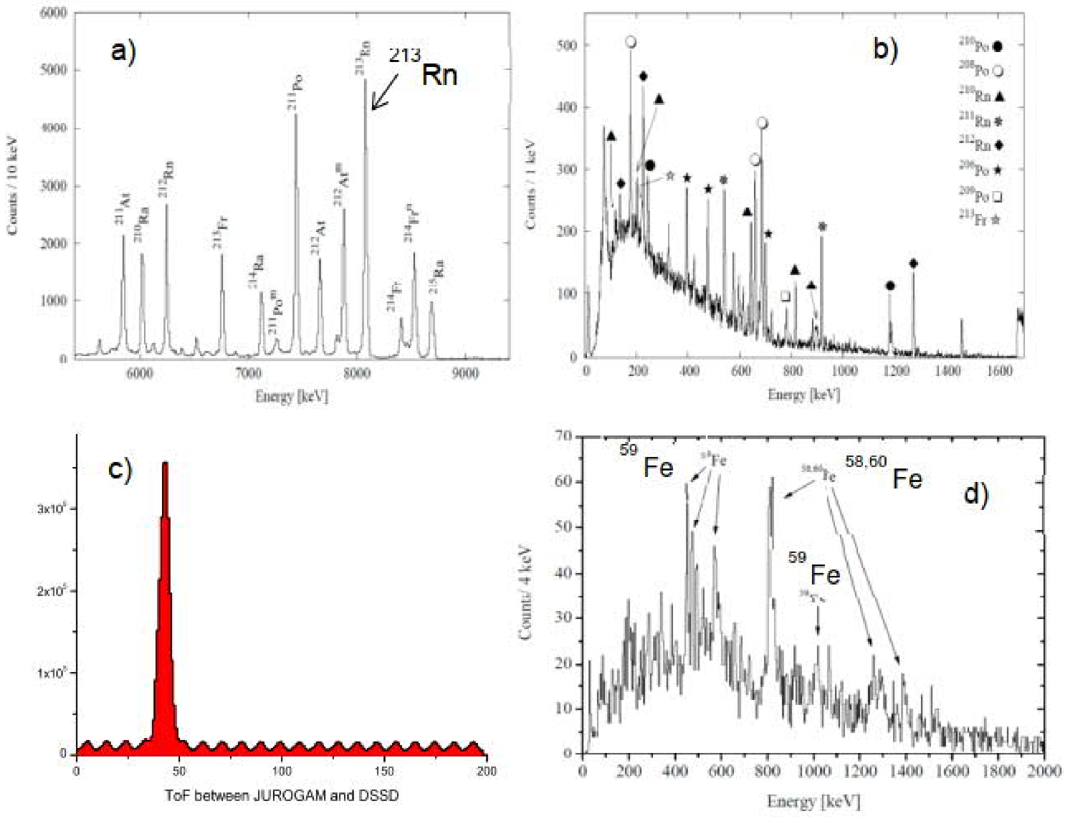
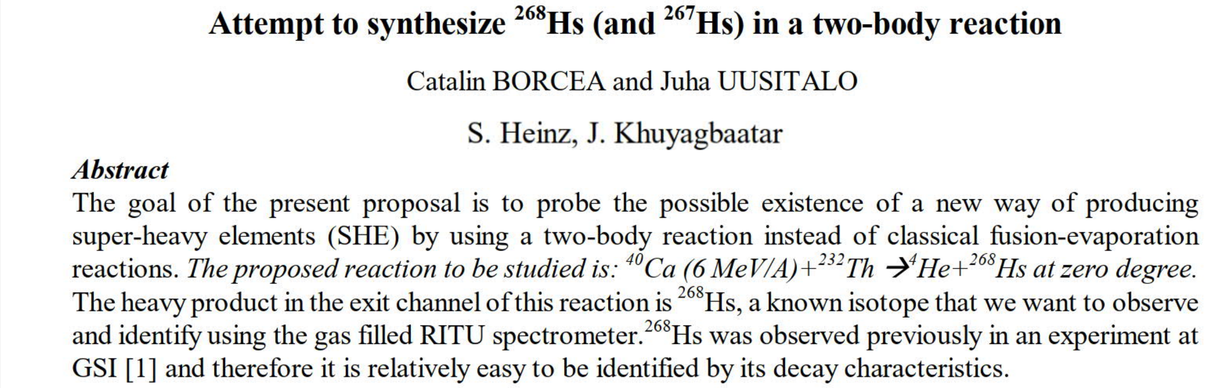


Figure 1. The experimental data obtained for the non-fusion channels of the ^{65}Cu+^{209}Bi reaction at gas-filled separator RITU [27]. Alpha a) and gamma b) spectra measured at the focal plane of the RITU. c) Time-of-flight spectrum of implanted heavy ions shown in a) in between the target and focal plane positions. d) In-beam γ-ray spectrum in delayed coincidence with the selected implantation signals associated to the decay of ^{213}Rn.



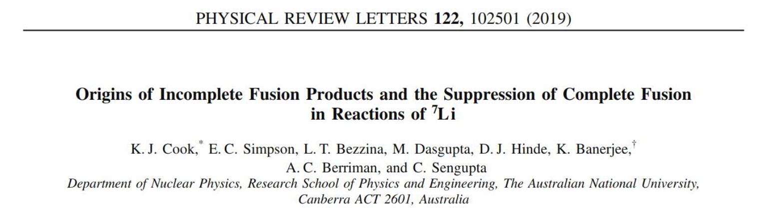
Attempt to synthesize ^{268}Hs (and ^{267}Hs) in a two-body reaction

Catalin BORCEA and Juha UUSITALO

S. Heinz, J. Khuyagbaatar

Abstract

The goal of the present proposal is to probe the possible existence of a new way of producing super-heavy elements (SHE) by using a two-body reaction instead of classical fusion-evaporation reactions. *The proposed reaction to be studied is:* $^{40}Ca\ (6\ MeV/A) + ^{232}Th \rightarrow {}^{4}He + {}^{268}Hs$ *at zero degree.* The heavy product in the exit channel of this reaction is ^{268}Hs, a known isotope that we want to observe and identify using the gas filled RITU spectrometer. ^{268}Hs was observed previously in an experiment at GSI [1] and therefore it is relatively easy to be identified by its decay characteristics.



PHYSICAL REVIEW LETTERS **122,** 102501 (2019)

Origins of Incomplete Fusion Products and the Suppression of Complete Fusion in Reactions of ^{7}Li

K. J. Cook,* E. C. Simpson, L. T. Bezzina, M. Dasgupta, D. J. Hinde, K. Banerjee,†
A. C. Berriman, and C. Sengupta
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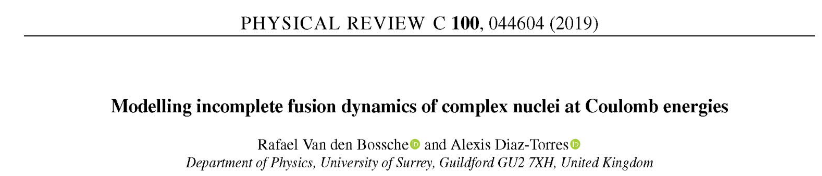

PHYSICAL REVIEW C **100**, 044604 (2019)

Modelling incomplete fusion dynamics of complex nuclei at Coulomb energies

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Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom

PHYSICAL REVIEW C **102**, 064618 (2020)

Production of transuranium isotopes in ^{20}Ne-induced incomplete fusion reactions

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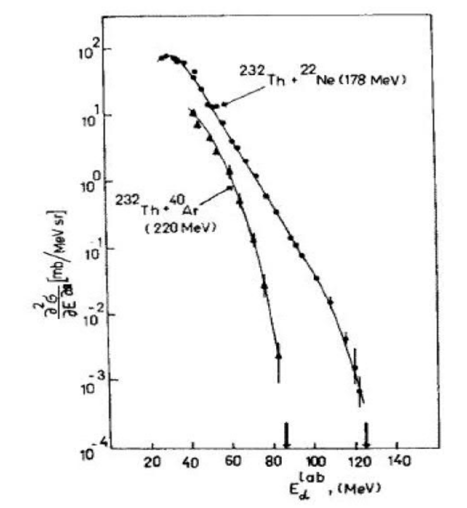


2. C. Borcea et al. Nucl. Phys. A351 (1981) 312
3. C. Borcea et al. Nucl. Phys. A391 (1982) 520
4. C. Borcea et al. Nucl. Phys. A415 (1984) 169

Alpha particle decay, proton decay?, beyond the drip line above lead

- Decay energies, half-lives, hindrance factors, spectroscopic factors
- Probing the nuclei at the limits of existence
- Link to masses
- Structure, spin and parities of decaying states,
- Deformation, prolate, oblate, spherical or octupole
- Spectroscopy with very low statistic (low cross sections)
- There where another methods are not viable any more

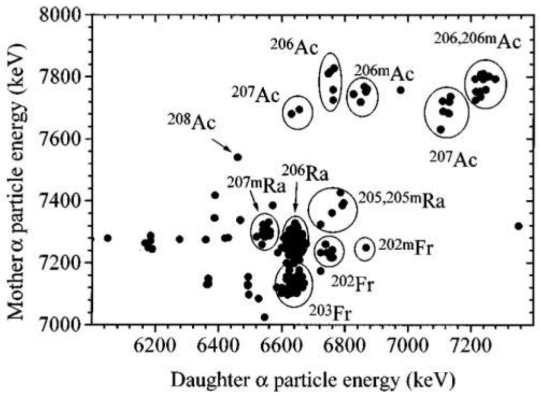
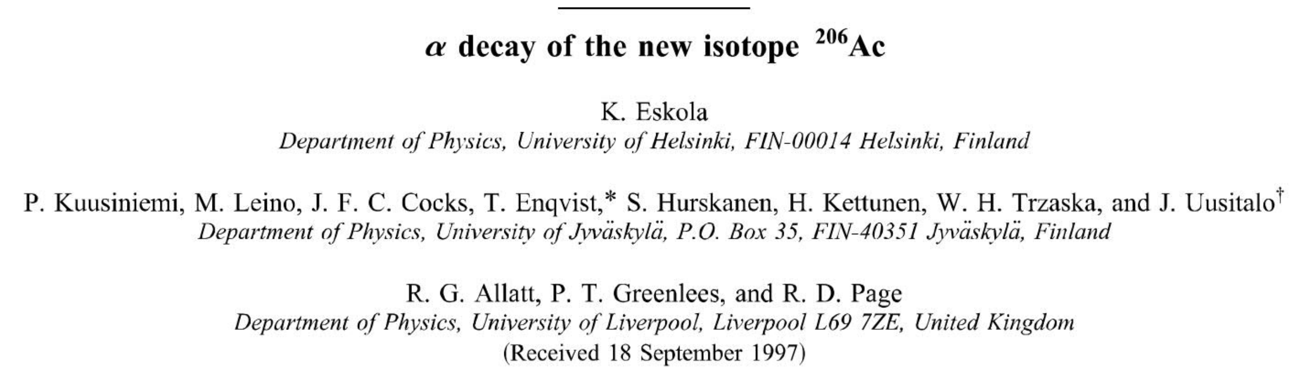


FIG. 2. Two dimensional energy distribution of all the time correlated α particle events from the bombardments of ^{175}Lu with ^{36}Ar ions. The quadruple events show up both as α_1-α_2 and α_2-α_3 events in the figure, if the energies were within the energy windows set for the first (mother) and second (daughter) α particles and the event times within the time windows set by maximum search times as given in the text.



α decay of the new isotope ^{206}Ac

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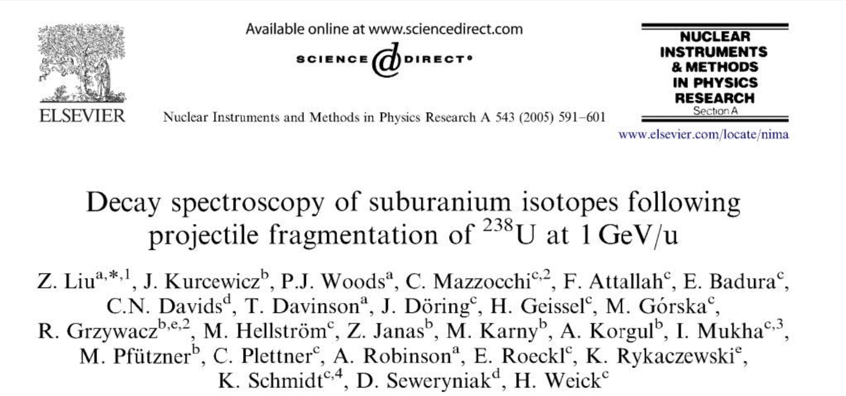
(Received 18 September 1997)

^{36}Ar + ^{175}Lu → ^{206}Ac + 5n
~ 110 h, ~35 pnA, macro-pulsed beam
^{207}Ac 20 nb
^{206}Ac 5 nb



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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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Decay spectroscopy of suburanium isotopes following projectile fragmentation of ^{238}U at 1 GeV/u

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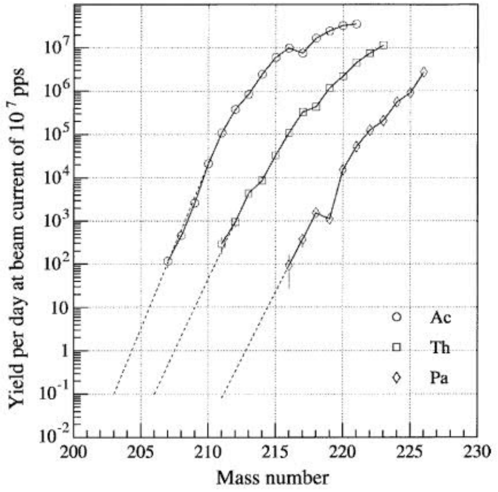
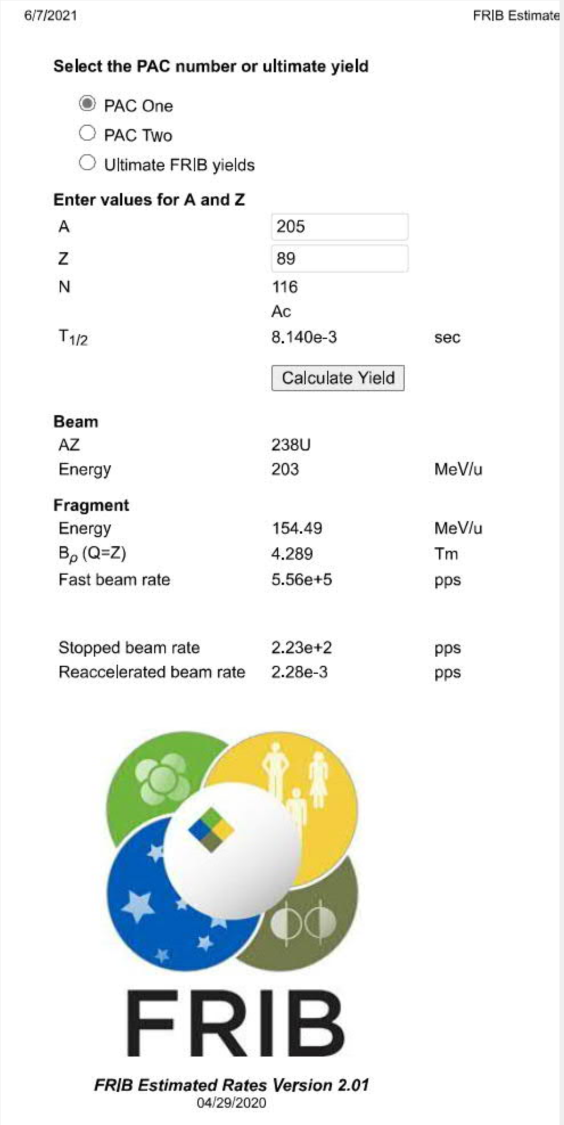


Fig. 6. Yields for fully stripped protactinium, thorium and actinium isotopes observed at the final focus (S4). The experimental values are connected by solid lines. For each element, the yields of the lightest isotopes are fitted in a straight line and extrapolated to more proton-rich ones (dashed line). The dips at ^{219}Pa($T_{1/2} = 53$ ns), ^{218}Th($T_{1/2} = 109$ ns) and ^{217}Ac($T_{1/2} = 69$ ns) [20] are due to the fact that their half-lives are shorter than their time of flight from target to S4.

^{211}Pa 20 pb	K. Auranen et al., PRC 102, 034305 (2020)
^{208}Th 22 pb	J. A. Heredia et. al., EPJ 46, 337 (2010)
^{209}Th 1 nb	H. Ikezoe et. al., PRC 54, 2043(1996)
^{210}Th 3 nb	J. Uusitalo et. al., PRC 52, 113 (1995)
^{211}Th 30 nb,	-=-
^{205}Ac 70 pb	Z. Y. Zhang et. al., PRC 89, 014308 (2014)
^{206}Ac 5nb	K. Eskola et. al., PRC 57, 417 (1998)
^{207}Ac 20 nb,	-=-

200 pnA beam (~ 10^{12} pps), 30 % transmission, 0.5 mg/cm^2 target
-> Yields

20 pb	1/day
1 nb	50/day



6/7/2021 FRIB Estimate

Select the PAC number or ultimate yield

● PAC One
○ PAC Two
○ Ultimate FRIB yields

Enter values for A and Z

A	205	
Z	89	
N	116	
	Ac	
$T_{1/2}$	8.140e-3	sec

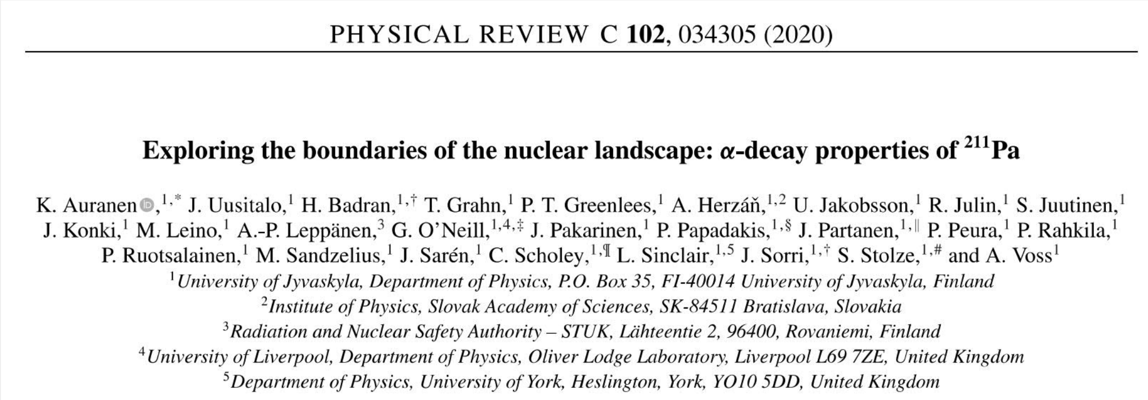
Beam

AZ	238U	
Energy	203	MeV/u

Fragment

Energy	154.49	MeV/u
B_ρ (Q=Z)	4.289	Tm
Fast beam rate	5.56e+5	pps
Stopped beam rate	2.23e+2	pps
Reaccelerated beam rate	2.28e-3	pps

FRIB Estimated Rates Version 2.01
04/29/2020



PHYSICAL REVIEW C **102**, 034305 (2020)

Exploring the boundaries of the nuclear landscape: α-decay properties of ^{211}Pa

K. Auranen,[1,*] J. Uusitalo,[1] H. Badran,[1,†] T. Grahn,[1] P. T. Greenlees,[1] A. Herzáň,[1,2] U. Jakobsson,[1] R. Julin,[1] S. Juutinen,[1] J. Konki,[1] M. Leino,[1] A.-P. Leppänen,[3] G. O'Neill,[1,4,‡] J. Pakarinen,[1] P. Papadakis,[1,§] J. Partanen,[1,∥] P. Peura,[1] P. Rahkila,[1] P. Ruotsalainen,[1] M. Sandzelius,[1] J. Sarén,[1] C. Scholey,[1,¶] L. Sinclair,[1,5] J. Sorri,[1,†] S. Stolze,[1,#] and A. Voss[1]

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[4] *University of Liverpool, Department of Physics, Oliver Lodge Laboratory, Liverpool L69 7ZE, United Kingdom*
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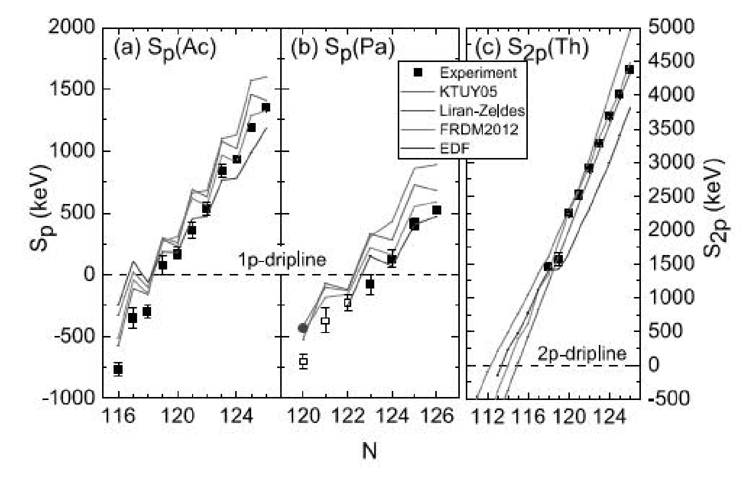
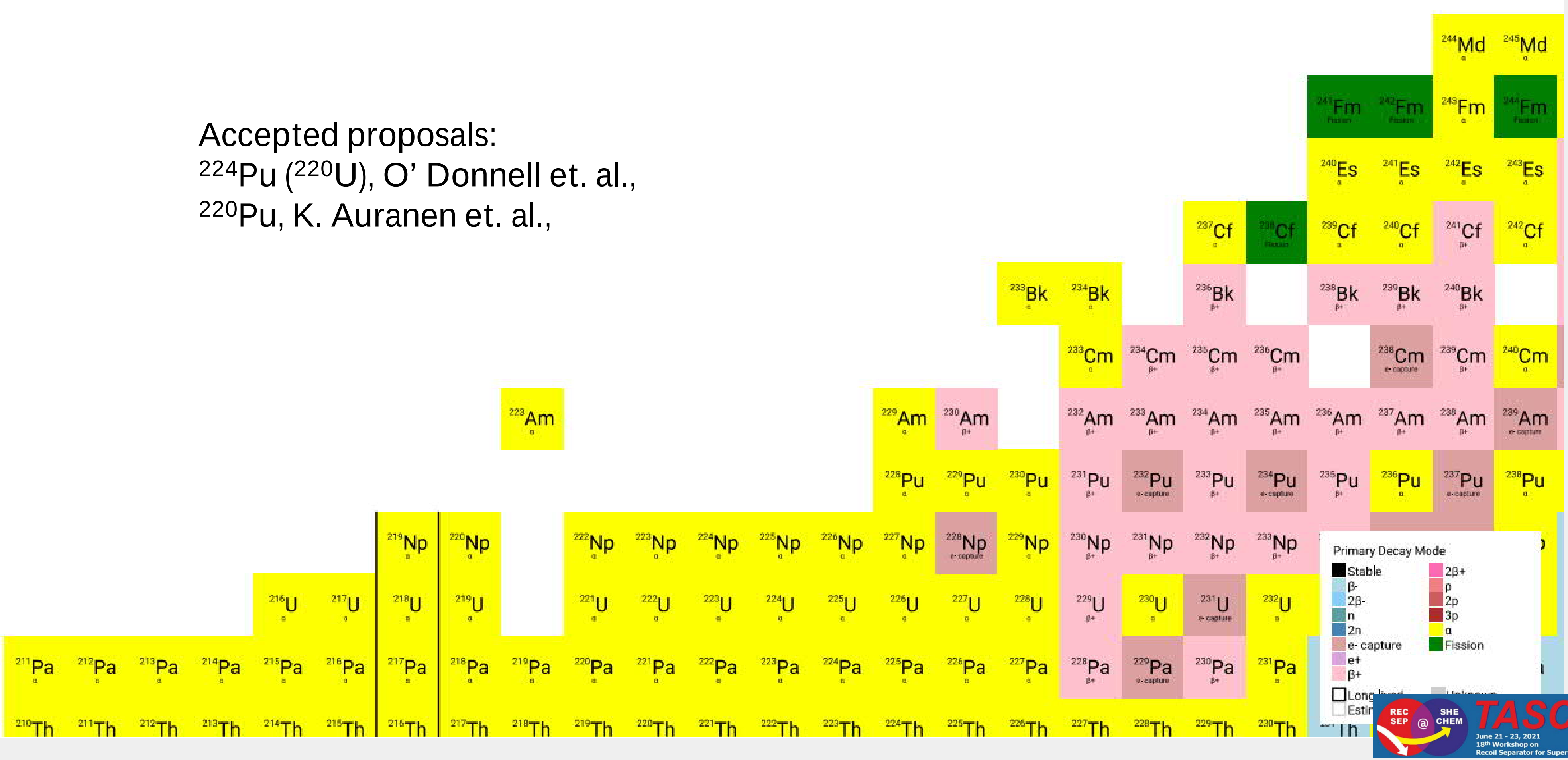


^{36}Ar + ^{181}Ta → ^{211}Pa + 6n, 20 pb

Kalle Auranen, see talk today

Actinide region (transactinides): Alpha decay, fission, EC-delayed fission, K-isomers etc..



Accepted proposals:

^{224}Pu (^{220}U), O’ Donnell et. al.,

^{220}Pu, K. Auranen et. al.,

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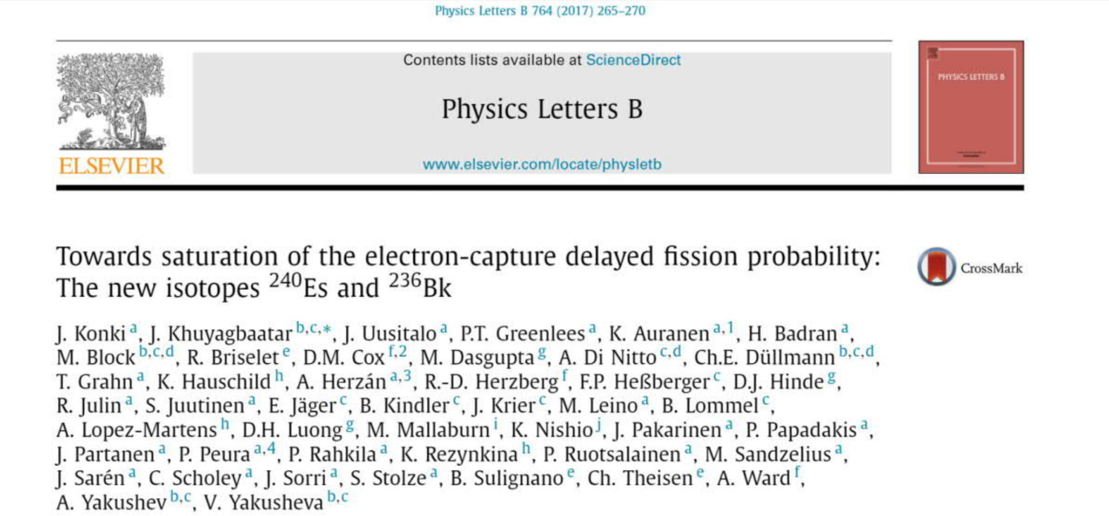
18th Workshop on

Recoil Separator for Superheavy Element Chemistry



Physics Letters B 764 (2017) 265–270

Contents lists available at ScienceDirect

Physics Letters B

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Towards saturation of the electron-capture delayed fission probability: The new isotopes ^{240}Es and ^{236}Bk

J. Konki [a], J. Khuyagbaatar [b,c,*], J. Uusitalo [a], P.T. Greenlees [a], K. Auranen [a,1], H. Badran [a],
M. Block [b,c,d], R. Briselet [e], D.M. Cox [f,2], M. Dasgupta [g], A. Di Nitto [c,d], Ch.E. Düllmann [b,c,d],
T. Grahn [a], K. Hauschild [h], A. Herzán [a,3], R.-D. Herzberg [f], F.P. Heßberger [c], D.J. Hinde [g],
R. Julin [a], S. Juutinen [a], E. Jäger [c], B. Kindler [c], J. Krier [c], M. Leino [a], B. Lommel [c],
A. Lopez-Martens [h], D.H. Luong [g], M. Mallaburn [i], K. Nishio [j], J. Pakarinen [a], P. Papadakis [a],
J. Partanen [a], P. Peura [a,4], P. Rahkila [a], K. Rezynkina [h], P. Ruotsalainen [a], M. Sandzelius [a],
J. Sarén [a], C. Scholey [a], J. Sorri [a], S. Stolze [a], B. Sulignano [e], Ch. Theisen [e], A. Ward [f],
A. Yakushev [b,c], V. Yakusheva [b,c]

^{34}S + ^{209}Bi → ^{240}Es + 3n

~ 150 pnA, ~6 nb

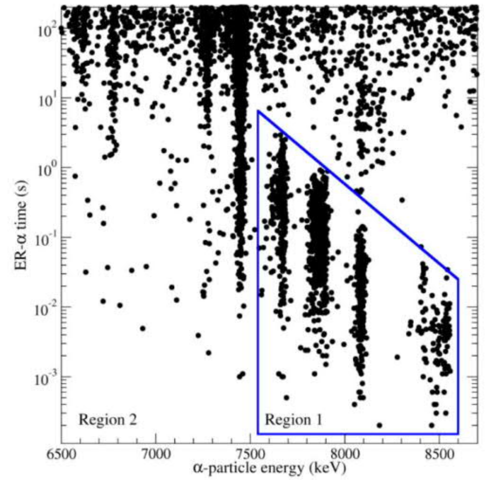


Fig. 2. A two-dimensional plot of the ER–α correlation times on a logarithmic scale as a function of the α-particle energies observed in the ^{34}S + ^{209}Bi reaction. The maximum searching time was 200 s.

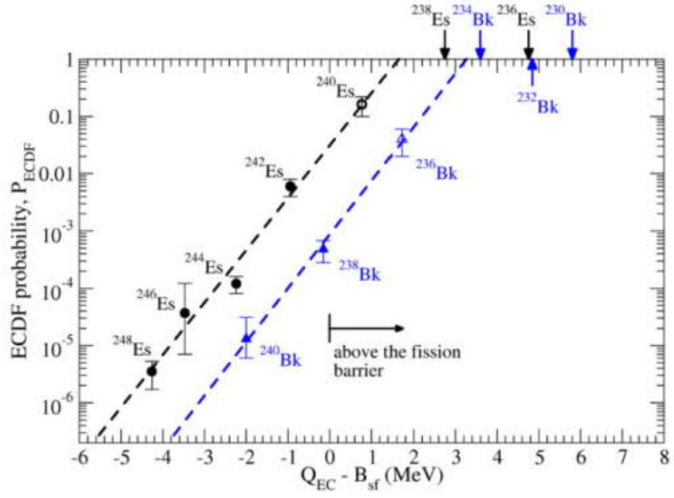
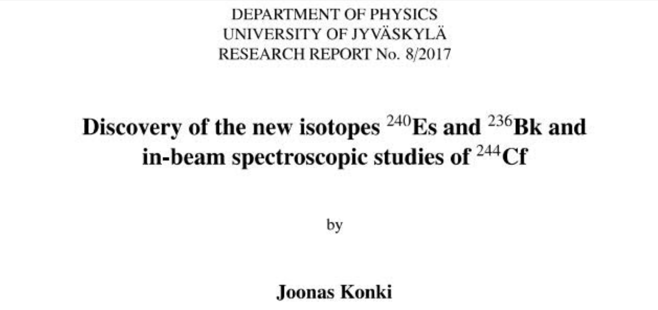


Fig. 6. Electron-capture delayed fission (ECDF) probability (P_{ECDF}) as a function of $Q_{EC} - B_{sf}$ of neutron-deficient Es and Bk isotopes. The data points for ^{240}Es and ^{236}Bk are from this work (open symbols). The other P_{ECDF} values (closed symbols) are from [4], Q_{EC} from [19] and B_{sf} from [21].



DEPARTMENT OF PHYSICS
UNIVERSITY OF JYVÄSKYLÄ
RESEARCH REPORT No. 8/2017

Discovery of the new isotopes ^{240}Es and ^{236}Bk and in-beam spectroscopic studies of ^{244}Cf

by

Joonas Konki

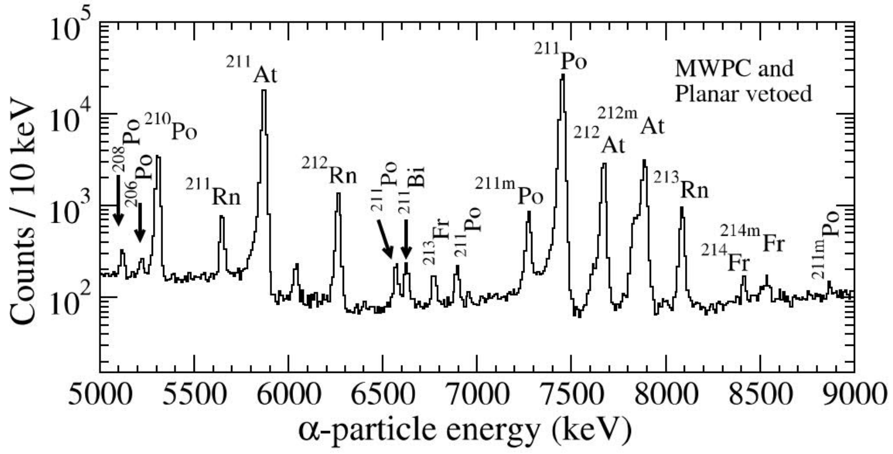


Figure 4.4. Energy spectrum of the α particles from the ^{34}S + ^{209}Bi reaction measured in the DSSDs and vetoed with the gas counter (MWPC) and the Planar detector.

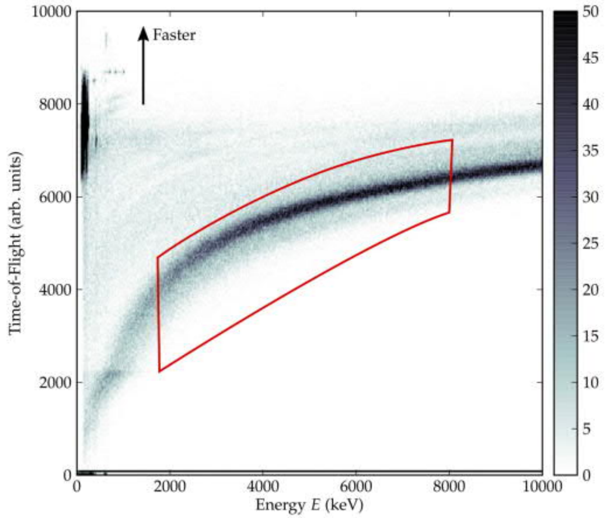


Figure 4.2. Fusion-evaporation residue (ER) identification matrix in the ^{34}S + ^{209}Bi reaction using the E-ToF method. The energy in the DSSDs is measured from the X side of the detector. The approximate gate used in the analysis is indicated by the red region. Please see the text for further details.

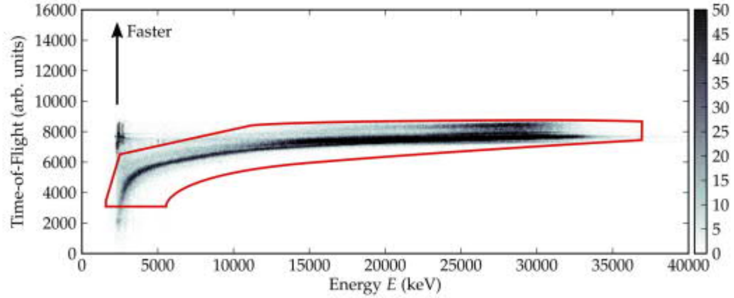


Figure 4.3. Transfer-reaction product (TR) identification matrix in the ^{34}S + ^{209}Bi reaction using the E-ToF method. The energy in the DSSDs is measured from the Y side of the detector. The approximate gate used in the analysis is indicated by the red region. Please see the text for further details.

CONCLUSIONS

- MARA has turned out to be a very versatile separator
  - Asymmetric, symmetric, inverse kinematics used
  - Mass range starting from A = 45 up to A = 213 has been covered
  - MARA-LEB (2023 →)

- At RITU an upgrade process is ongoing
  - GREAT DSSD → BB20 DSSD
    - Pixel size: 1 mm^2 → 0,45 mm^2
    - Total number of pixels: 4800 → 13824
    - Detector size: 2 x 40 mm x 60 mm → 48 mm x 128 mm
  - New MWPC, higher sensitivity
  - K-130 cyclotron central region upgrade
    - Factor of five increase in beam intensity
  - RITU focal-plane sepctroscopy campaign starting 2022

THANK YOU!