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

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NUSTAR Annual Meeting 2017

2.3.2017

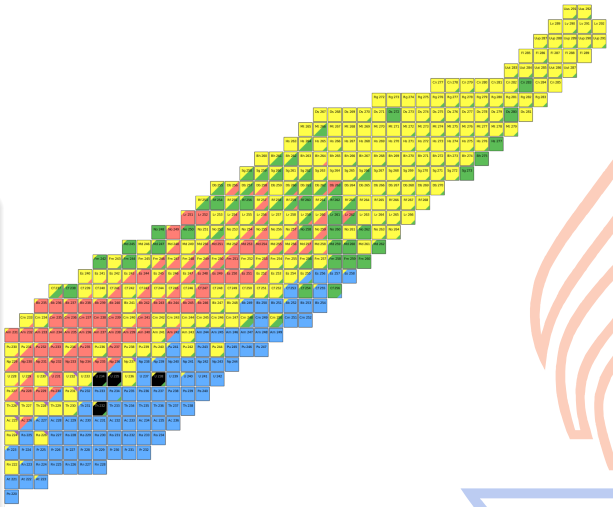
GSI, Darmstadt, Germany

Outline

Motivation

Why study neutron-deficient heavy nuclei?

- Ideal cases to study the competition of the attractive nuclear and the repulsive Coulomb forces that determine the stability of nuclei
- Provide information on the nuclear mass surface close to the proton dripline
- Help understand the processes and stability of superheavy elements (SHE)
- Study low-energy fission properties of excited nuclei via ECDF



Electron-capture delayed fission (ECDF)

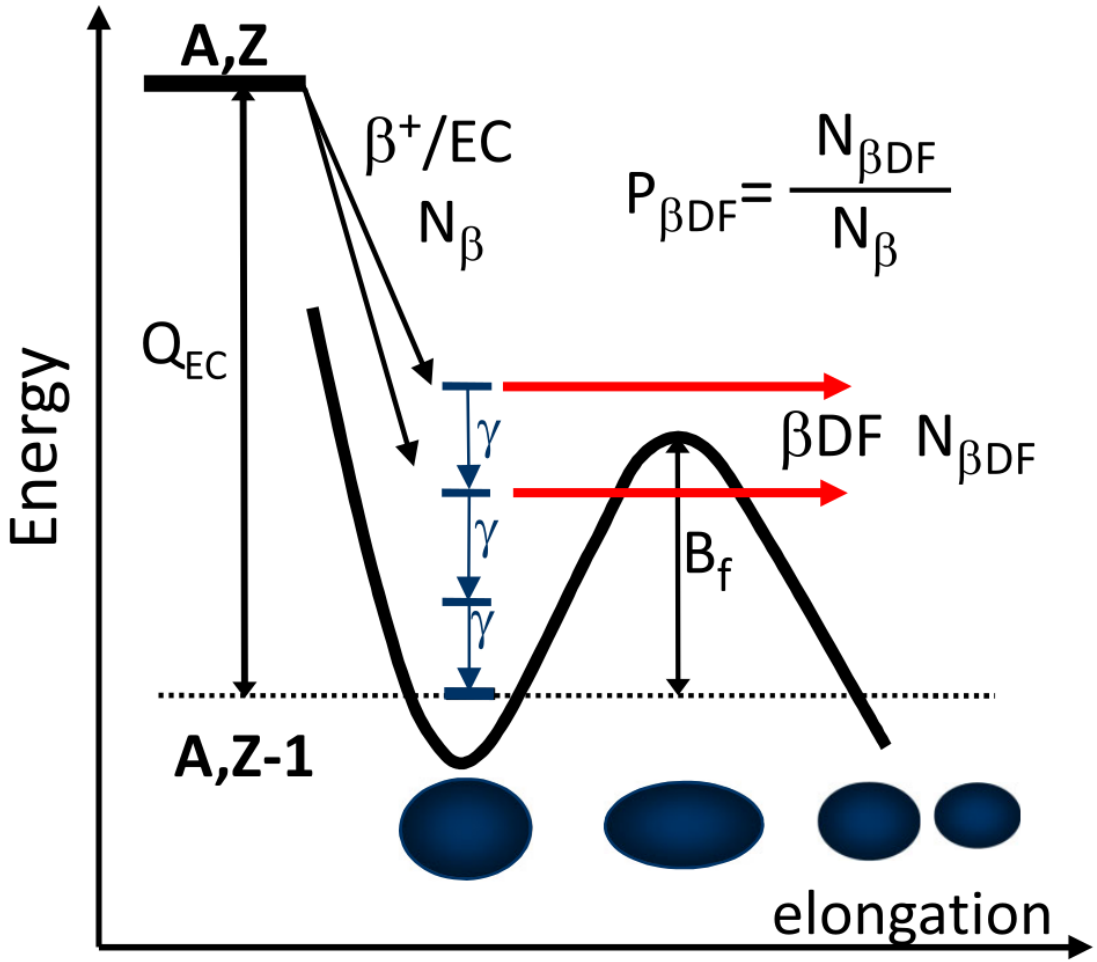


Fig. from A. Andreyev et al. Rev. Mod. Phys. 85 (2013)

- Mother nucleus EC/β^+ decays
- An excited state in the daughter nucleus is populated
- If $Q_{EC} \sim B_f$ or greater, then fission may compete with other decay modes of the excited states

R48 experiment @ JYFL (December 2014)

Experiment details:

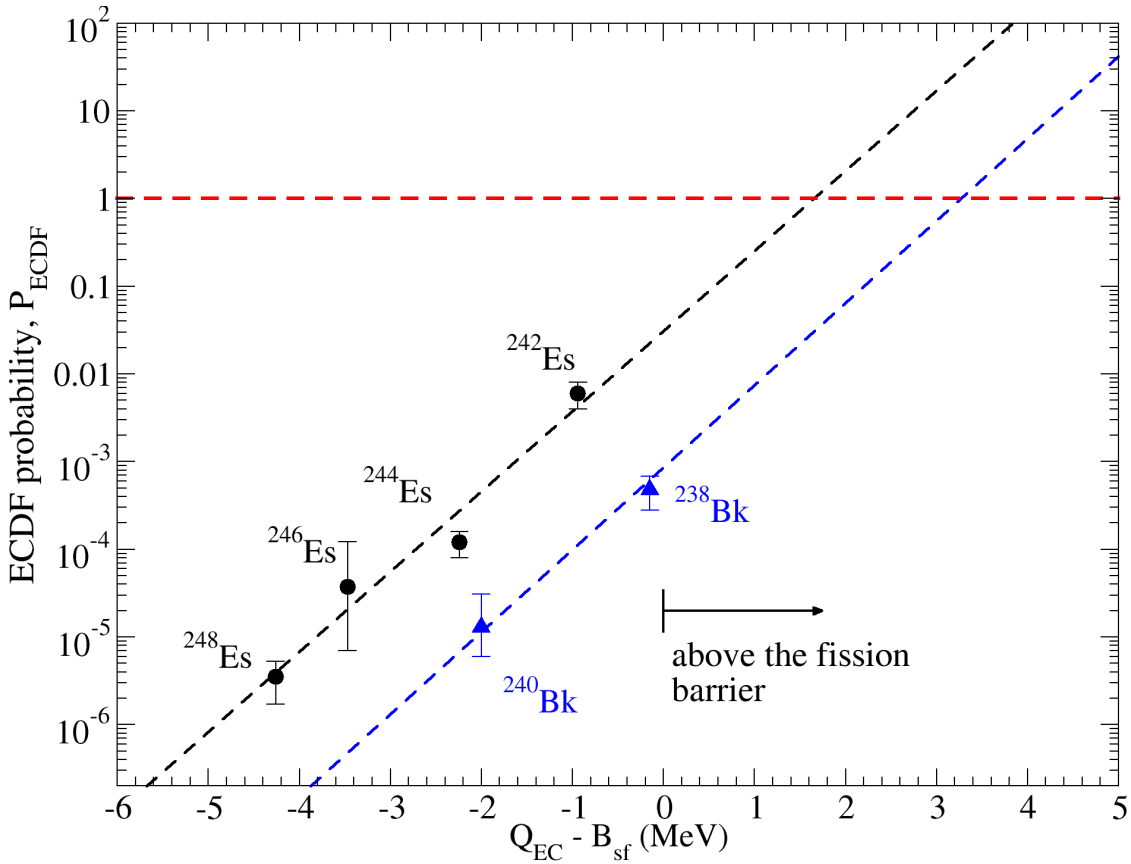
Spokespersons:
J. Khuyagbaatar (GSI),
J. Uusitalo (JYFL)

Reaction:
$^{34}S + ^{209}Bi \rightarrow ^{243}Es^*$

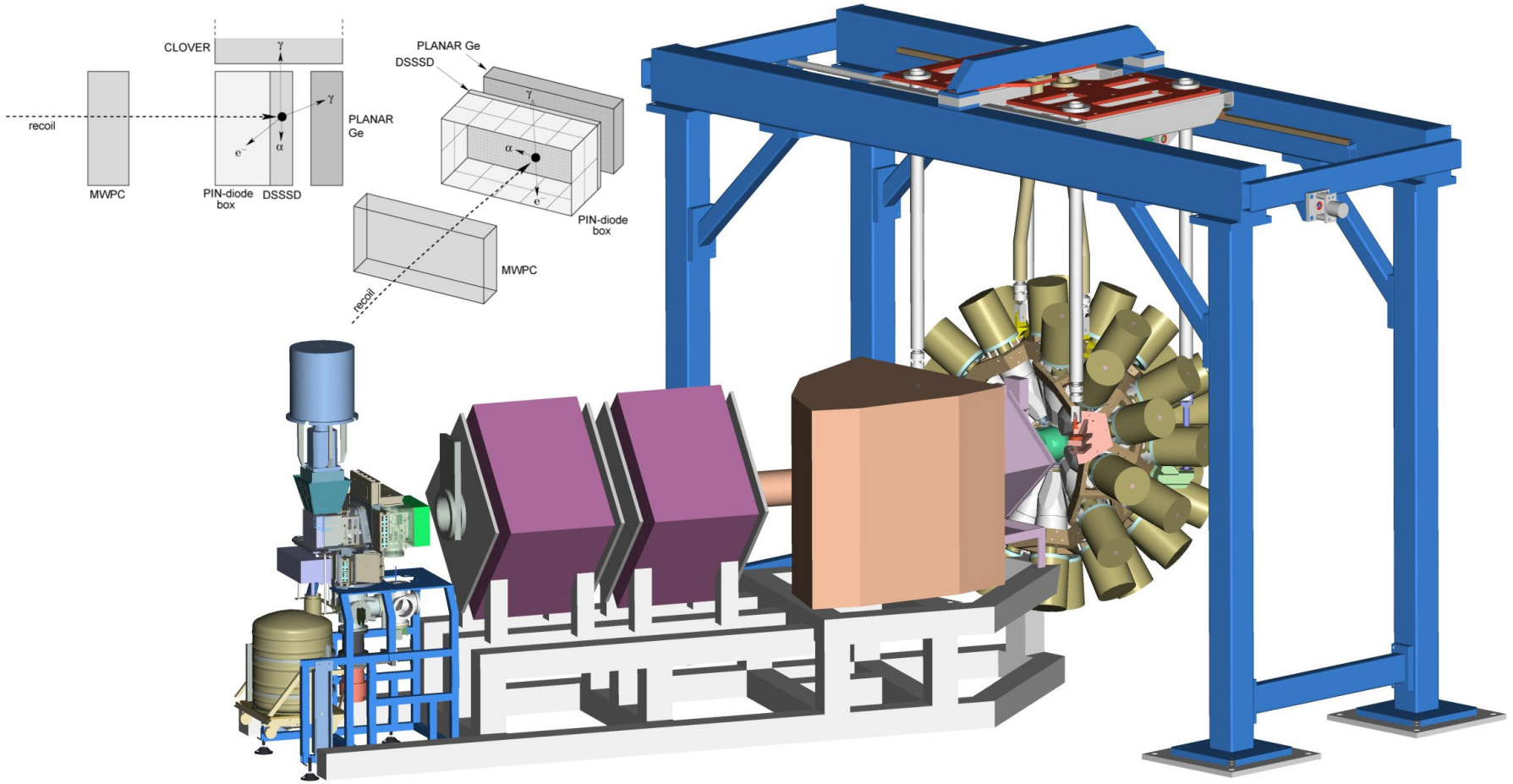
$^{209}BiO_2$ target 500 µg/cm^2
6 days of beam on target
E_{beam}=178, 174 MeV
C degrader foils: 200, 400 µg/cm2
$\rightarrow E^*$=39, 36, 35, 34 MeV
Typical I_{beam} ≃100-200 pnA
Total beam dose ≈ $3.7 \cdot 10^{17}$

RITU
DSSD-Y (80 strips)
DSSD-X (120 strips)
3 Clovers + Planar Ge + Pins at FP
2 BGO PMTs at target position

- $^{209}Bi(^{34}S,3n)^{240}Es$ reaction to study the decay properties of the new isotopes ^{240}Es and its α-decay daughter ^{236}Bk
- A relatively high ECDF probability (P_{ECDF}) expected for ^{240}Es from systematics

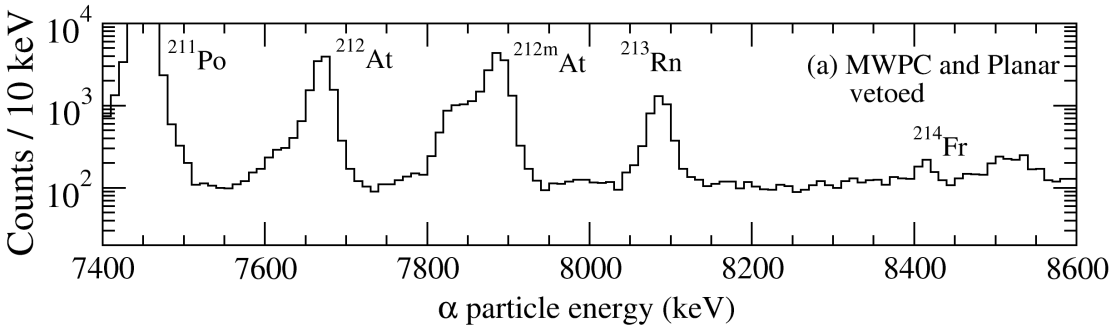


RITU and GREAT



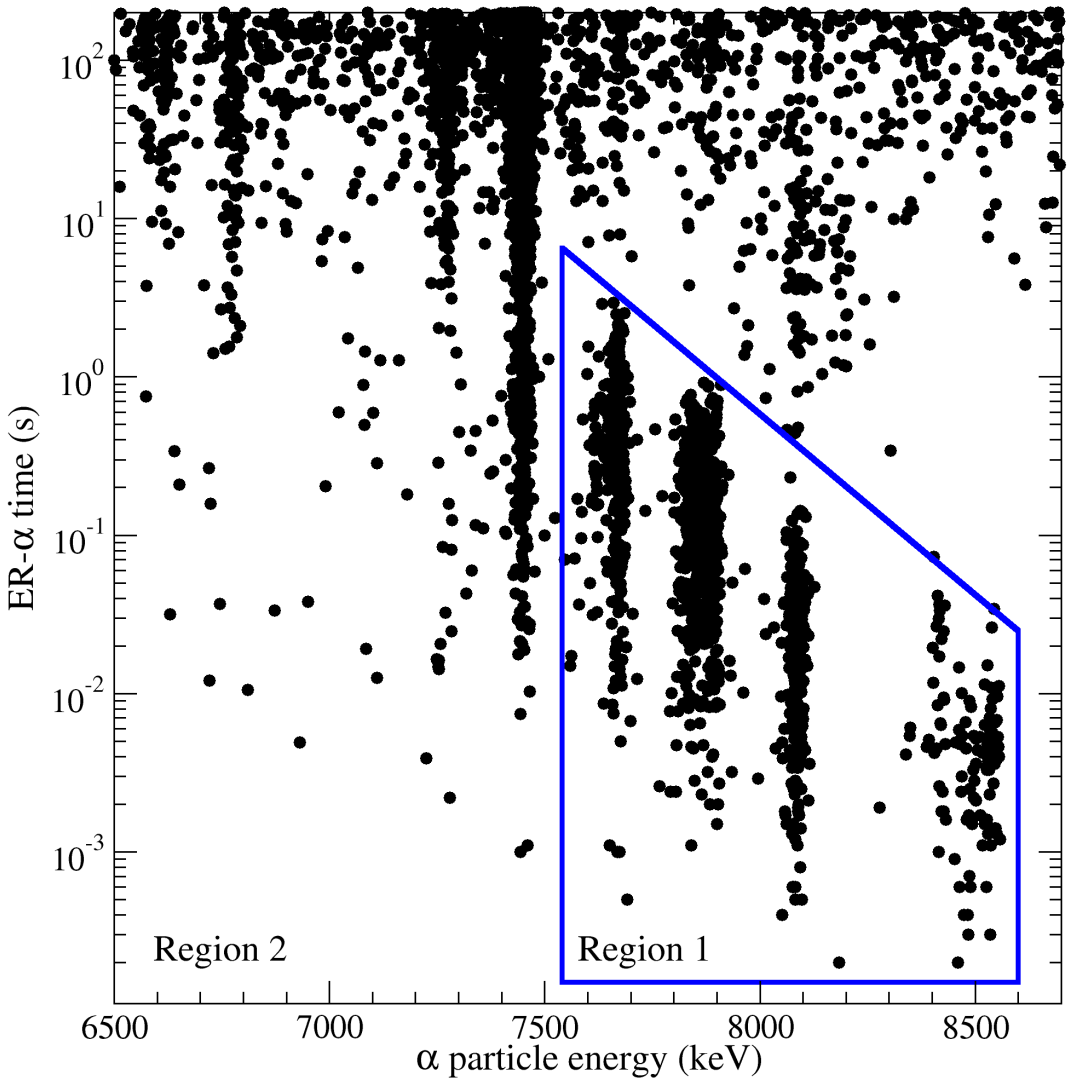
RITU gas-filled recoil separator
GREAT focal plane spectrometer

Raw α-like events



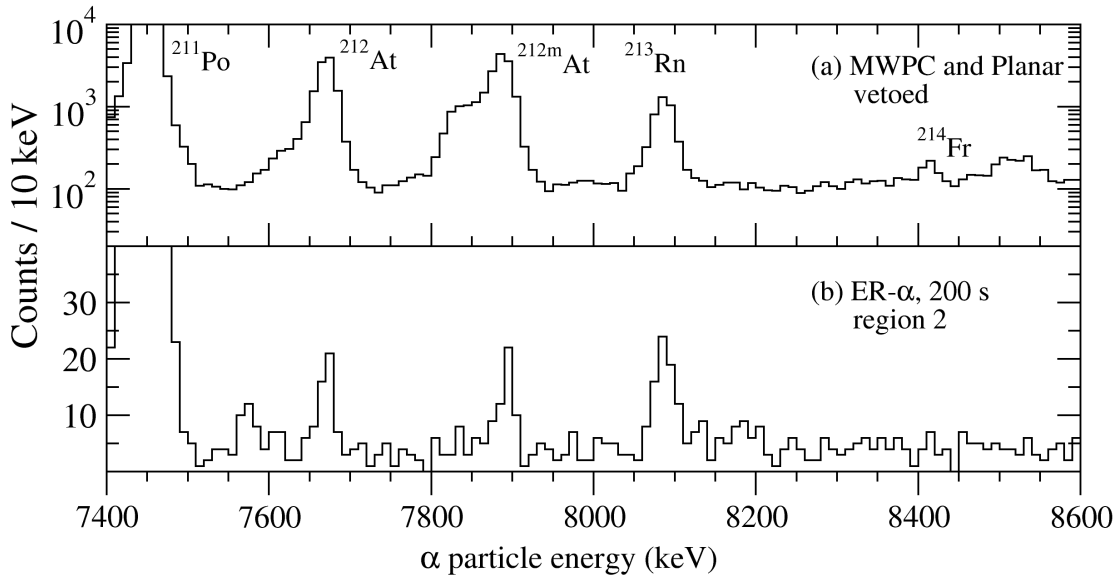
- (a) Raw α-like events, MWPC and Planar vetoed

ER-α correlations



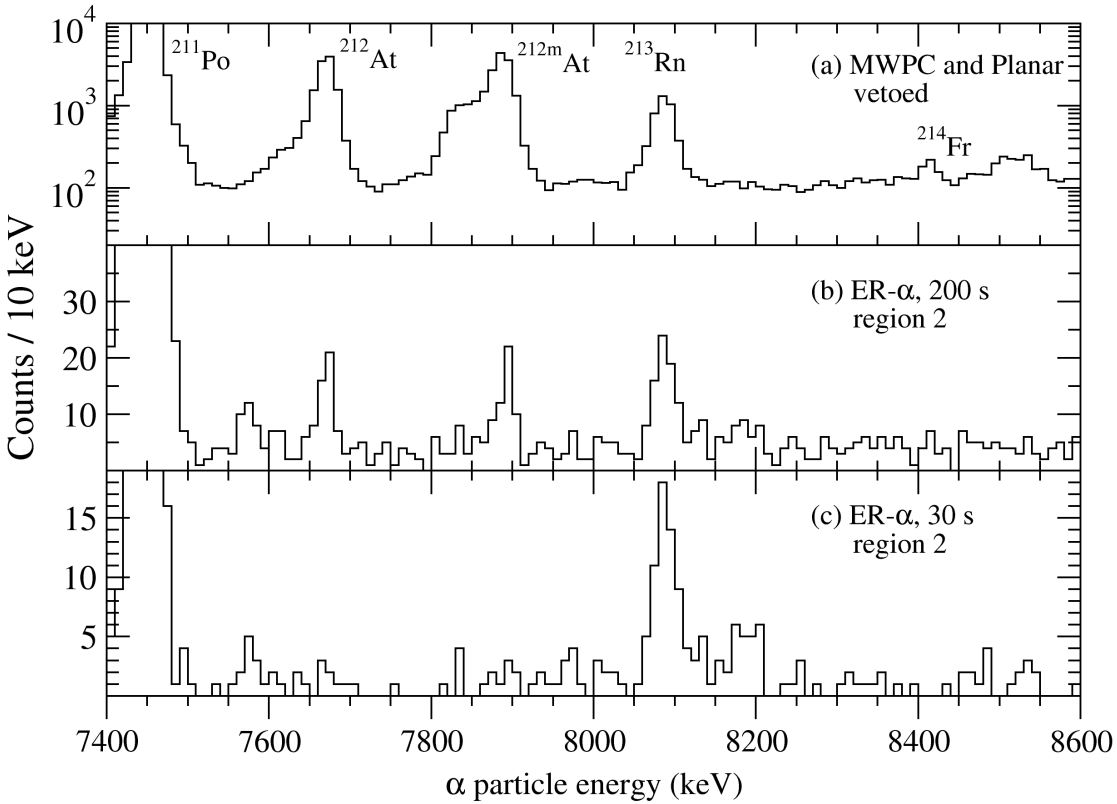
- Fusion-evaporation residue (ER) correlated α-like events, 200 s searching time
- Short-lived α-decays from slow transfer reaction products still visible (Region 1)

ER-α correlations



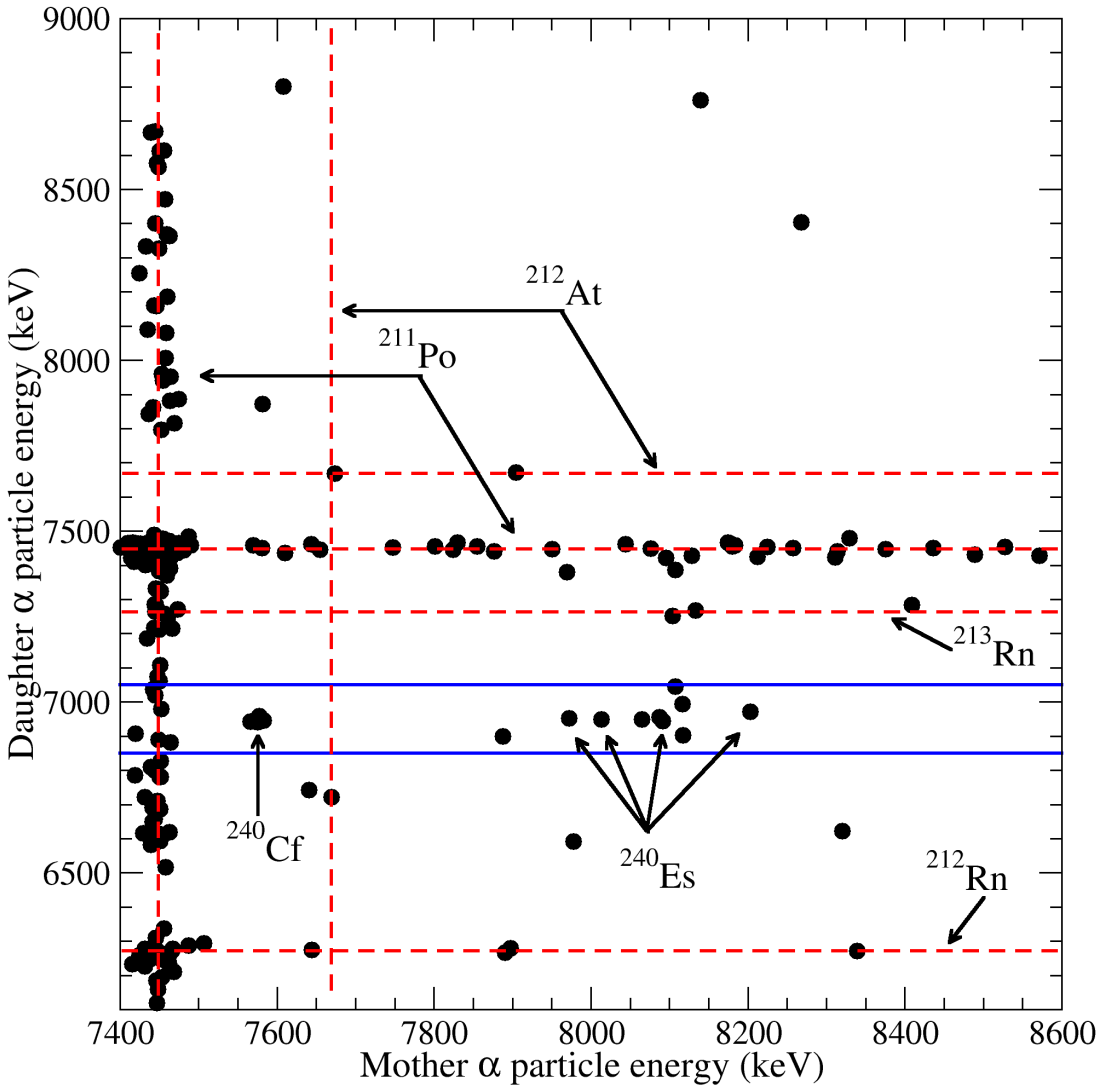
- (a) Raw α-like events, MWPC and Planar vetoed
- (b) ER-α, $\Delta t \leq 200$ s

ER-α correlations



- (a) Raw α-like events, MWPC and Planar vetoed
- (b) ER-α, $\Delta t \leq 200$ s
- (c) ER-α, $\Delta t \leq 30$ s

ER-α-α correlations



- ER-α_1-α_2,
  $\Delta t_{\mathrm{ER}-\alpha_1} \leq 200$ s,
  $\Delta t_{\alpha_1-\alpha_2} \leq 1200$ s
- Can see ER correlated α chains of interest:
  ER-α_1(7.57 MeV)-α_2(^{236}Cm)
  ER-α_1(8.19 MeV)-α_2(^{236}Cm)
  ER-α_1(8.09 MeV)-α_2(^{236}Cm)
  ER-α_1(8.02 MeV)-α_2(^{236}Cm)
  ER-α_1(7.97 MeV)-α_2(^{236}Cm)

  $\rightarrow$ attributed to ^{240}Cf and the new isotope ^{240}Es

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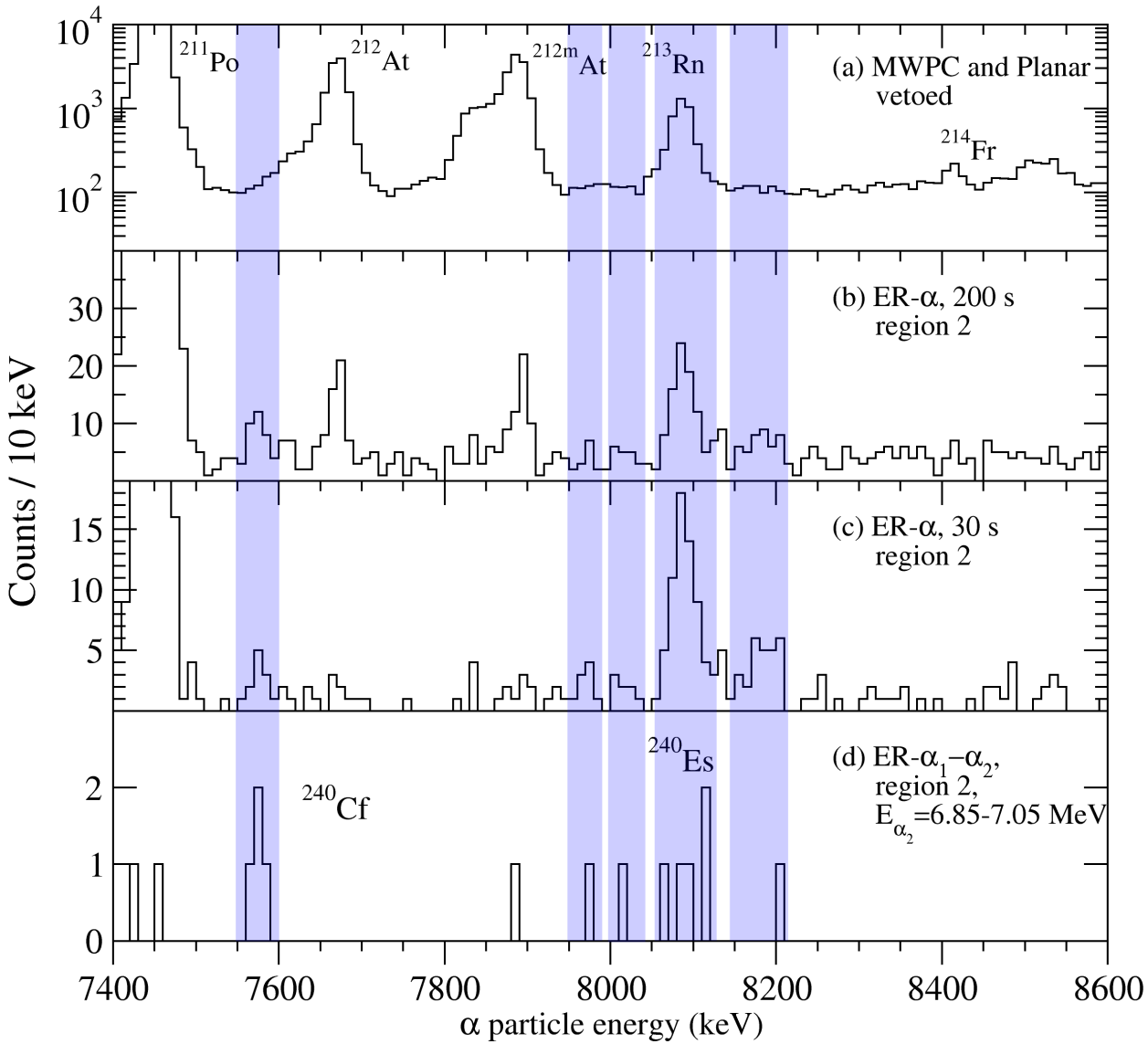
  ^{236}Cm: E_α=6.954(20) MeV,
  $T_{1/2}$=410(50) s

ER-α-α correlations



- (a) Raw α-like events, MWPC and Planar vetoed
- (b) ER-α, $\Delta t \leq 200$ s
- (c) ER-α, $\Delta t \leq 30$ s
- (d) ER-α_1-α_2, $\Delta t_{\mathrm{ER}-\alpha_1} \leq 200$ s, $\Delta t_{\alpha_1-\alpha_2} \leq 1200$ s and $E_{\alpha 2}$ in range 6.85-7.05 MeV

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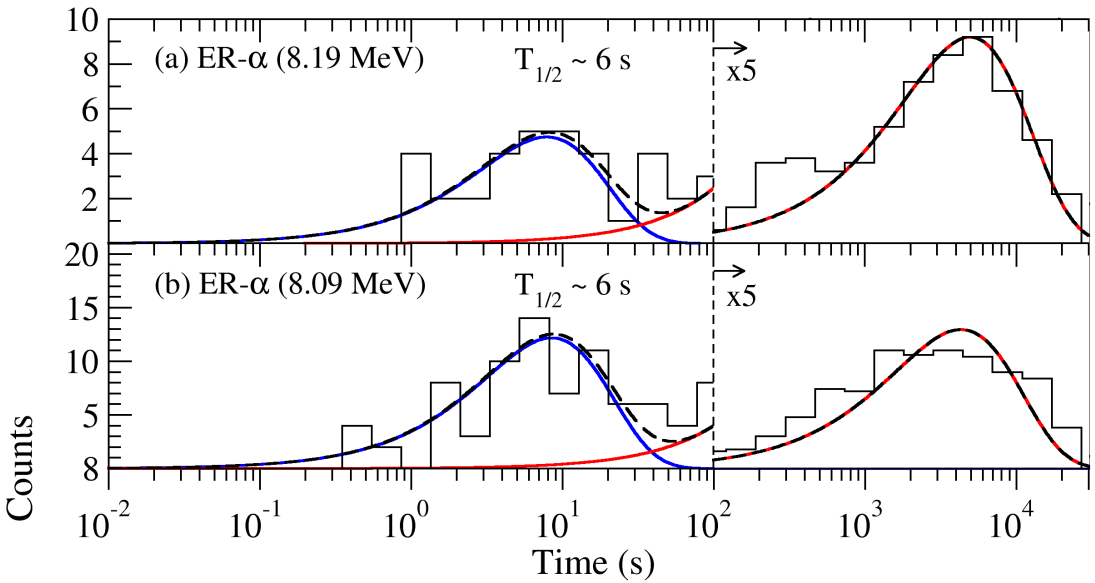
^{236}Cm: E_α=6.954(20) MeV, $T_{1/2}$=410(50) s

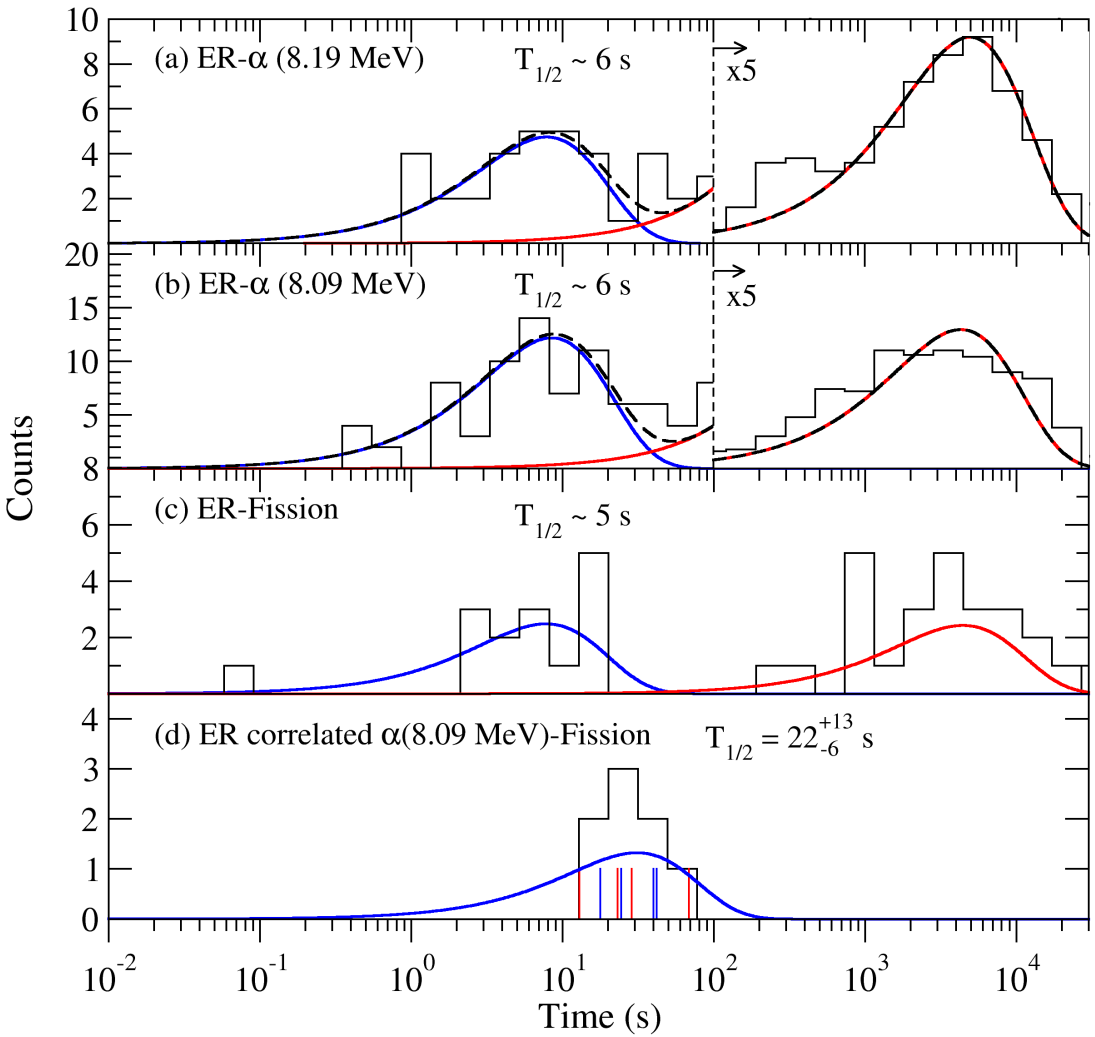
ER-α, ER-fission, ER-α-fission time distributions



- 27 ER-α(8.19 MeV) events with $T_{1/2} \sim 6$ s
- 60 ER-α(8.09 MeV) events with $T_{1/2} \sim 6$ s

  $\rightarrow$ attributed to α decay of ^{240}Es

ER-α, ER-fission, ER-α-fission time distributions



- 27 ER-α(8.19 MeV) events with $T_{1/2} \sim 6$ s
- 60 ER-α(8.09 MeV) events with $T_{1/2} \sim 6$ s

  $\rightarrow$ attributed to α decay of ^{240}Es

- 15 ER-fission events with $T_{1/2} \sim 5$ s

  $\rightarrow$ attributed to ECDF of ^{240}Es

- 8 ER-α(8.09MeV)-fission events (4 of them are escape αs) with $T_{1/2} = 22^{+13}_{-6}$ s

  $\rightarrow$ attributed to ECDF of ^{236}Bk

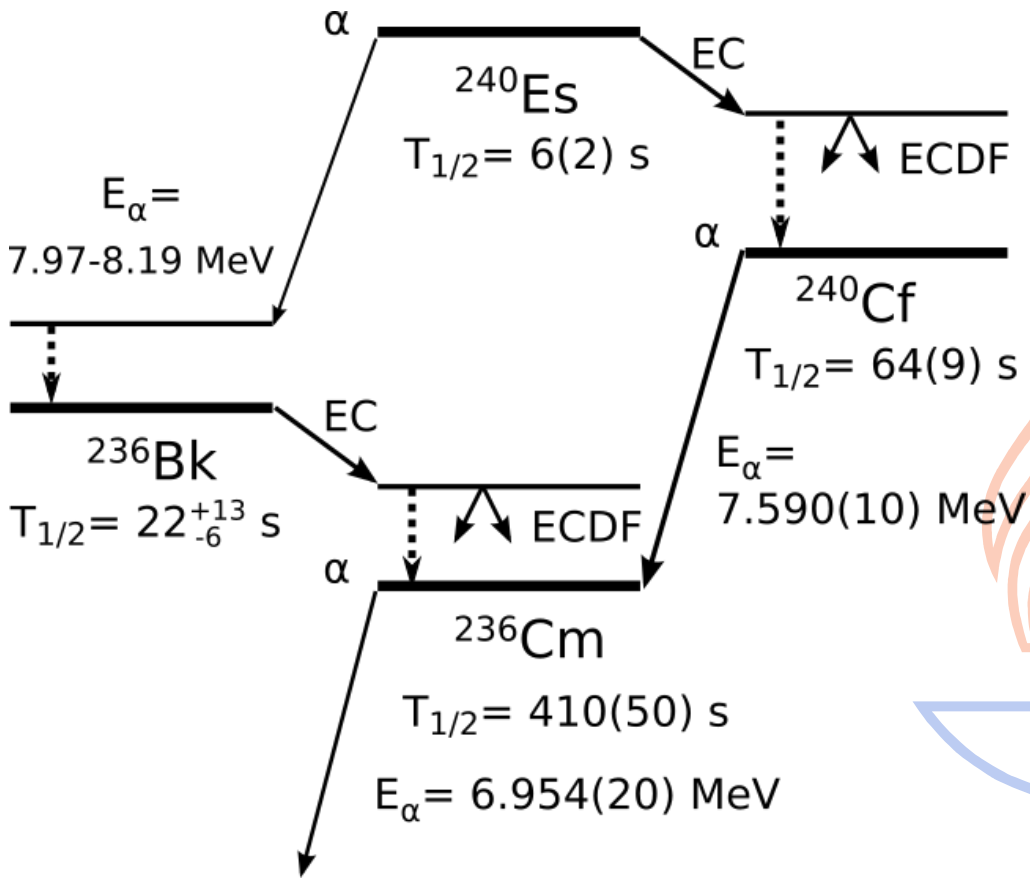
Decay properties of the new isotopes $^{240}_{99}Es_{141}$ and $^{236}_{97}Bk_{139}$

Decay properties of ^{240}Es

- ER-α, ER-α-α, ER-fission correlations analysed
- E_α = 8.19(3) MeV, 8.09(3) MeV, (8.02(3) MeV, 7.97(3) MeV)
- $T_{1/2}$ = 6(2) s
- b_α = 0.7(1)
  b_{EC} = 0.3(1)
- P_{ECDF} = 0.16(6)

Decay properties of ^{236}Bk

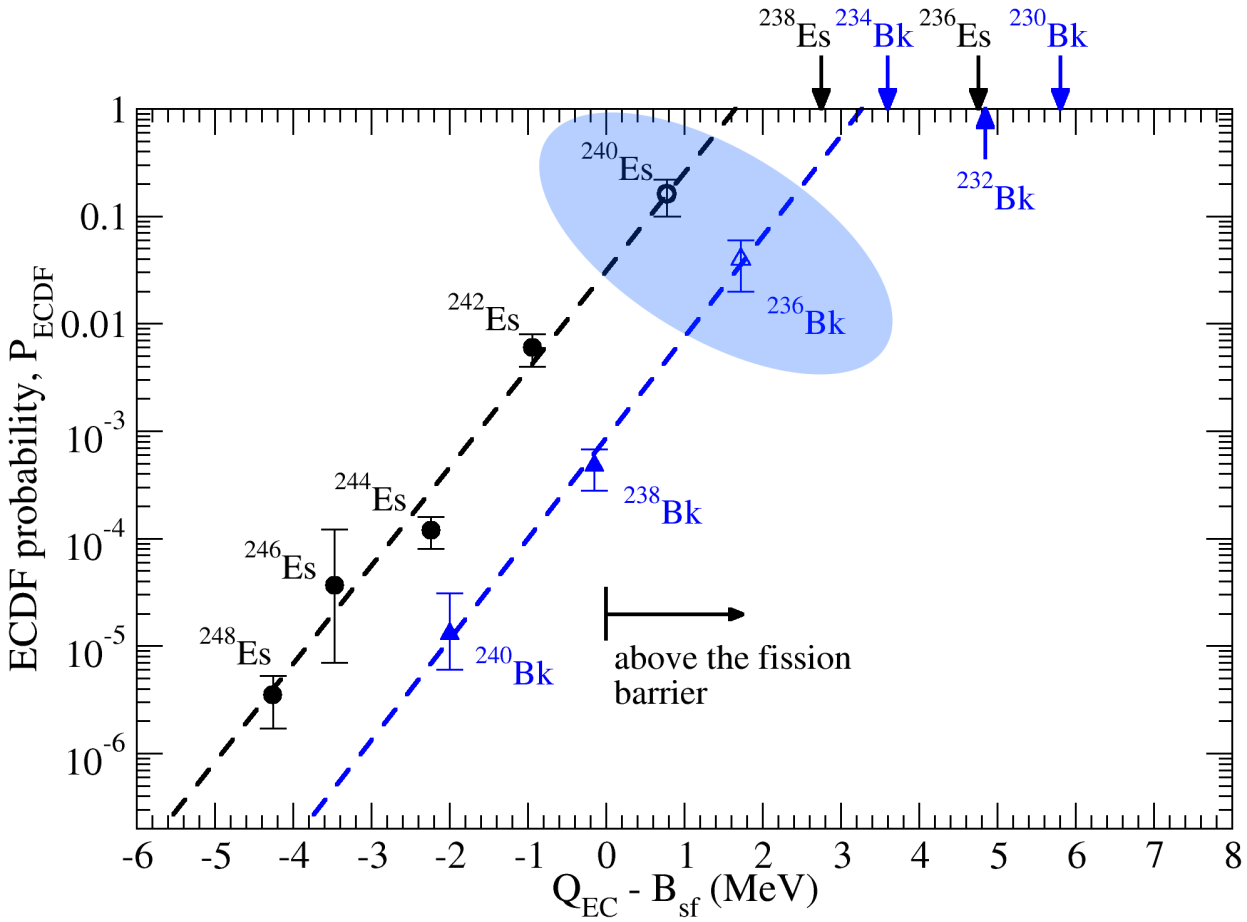
- ER-α(^{240}Es)-fission, 8 events
- $T_{1/2} = 22^{+13}_{-6}$ s
- No α-decay branch seen
- P_{ECDF} = 0.04(2)



The proposed decay scheme of ^{240}Es and ^{236}Bk

J. Konki et al. Physics Letters B 764 (2017) 265
(Data for ^{240}Cf and ^{236}Cm are from literature.)

ECDF probability systematics in Es and Bk isotopes



- Probability increases exponentially as a function of the energy difference $Q_{EC} - B_{sf}$
- Similar behaviour observed for other neutron-deficient nuclei (Am, Np, Tl)
- Probability expected to approach saturation ($P_{ECDF} \rightarrow 1$) in the next lighter odd-odd Es and Bk isotopes

Q_β and B_{sf} from P. Möller et al. 1997, 2009
Other P_{ECDF} from A. Andreyev et al. Rev. Mod. Phys. 85 (2013)

See also:
L. Ghys et al. Phys. Rev. C 91 (2015) 044314
M. Veselský et al. Phys. Rev. C 86 (2012) 024308

Thank you!

J. Khuyagbaatar, J. Uusitalo, P. T. Greenlees, K. Auranen, H. Badran, M. Block, R. Briselet, D. M. Cox, M. Dasgupta, A. Di Nitto, Ch. E. Düllmann, T. Grahn, K. Hauschild, A. Herzán, R.-D. Herzberg, F. P. Heßberger, D. J. Hinde, R. Julin, S. Juutinen, E. Jäger, B. Kindler, J. Krier, M. Leino, B. Lommel, A. Lopez-Martens, D. H. Luong, M. Mallaburn, K. Nishio, J. Pakarinen, P. Papadakis, J. Partanen, P. Peura, P. Rahkila, K. Rezynkina, P. Ruotsalainen, M. Sandzelius, J. Sarén, C. Scholey, J. Sorri, S. Stolze, B. Sulignano, Ch. Theisen, A. Ward, A. Yakushev and V. Yakusheva