



Spontaneous fission in neutron-deficient Md isotopes

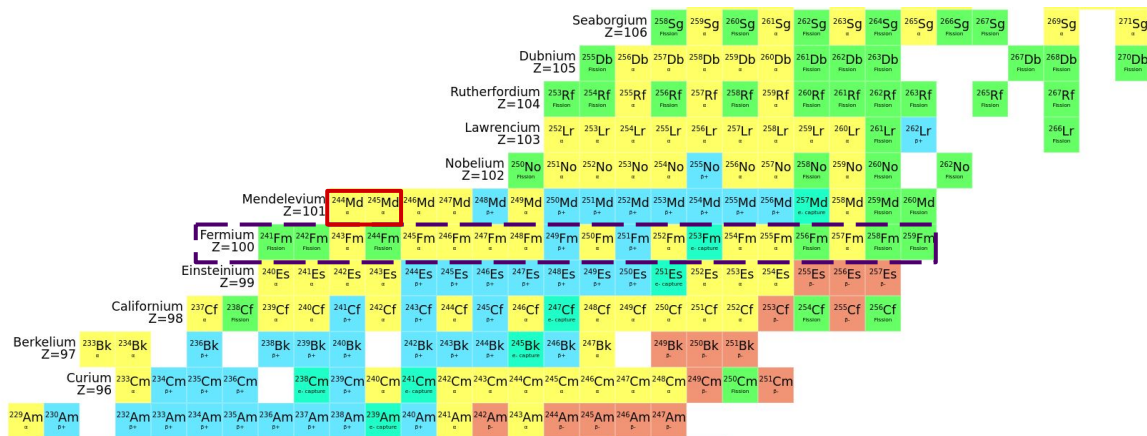
Margarida Paulino

Grand Accélérateur National d'Ions Lourds

Université de Caen Normandie

Motivation

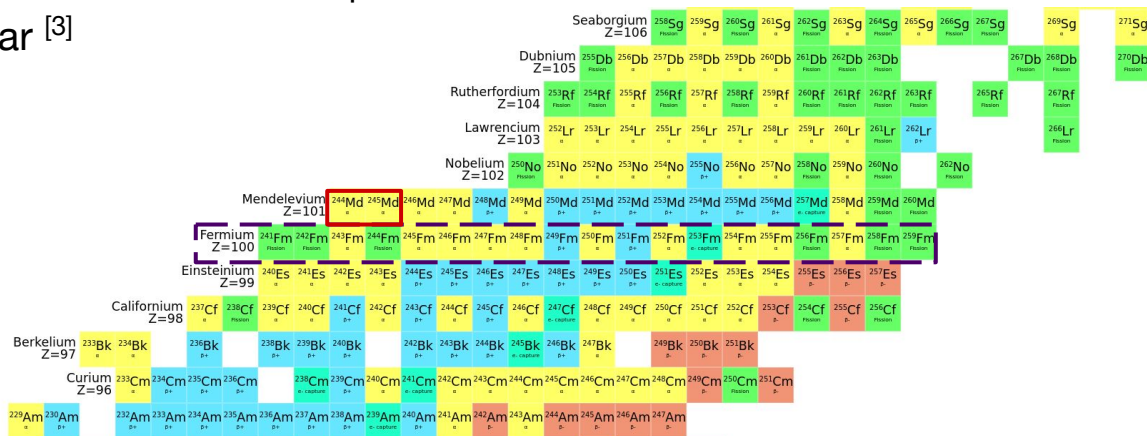
- Measure decay properties of the lightest known Md isotopes: $^{244,245}\text{Md}$
- Stability against SF is influenced by shell effects ^[1,2,3]
- Md is one proton above the **Z=100** shell gap



- [1] F. P. Heßberger, arXiv:2510.05953 [nucl-th] (2025)
[2] D. Ackermann, APP B Proc. Supp. 19, 1-A23 (2026)
[3] J. Khuyagbaatar, Eur. Phys. J. A 55, 134 (2019)

Motivation

- Measure decay properties of the lightest known Md isotopes: $^{244,245}\text{Md}$
- Investigate **mass assignment discrepancies** between two previous experiments
 - $^{40}\text{Ar} + ^{209}\text{Bi}$ @ 220 MeV, Berkeley Gas-Filled Separator (BGS) of LBNL [1]
 - $^{50}\text{Ti} + ^{197}\text{Au}$ @ 231.5, 239.8 MeV, Gas-Filled TASCA separator of GSI [2]
- Part of the PhD thesis of S. Kumar [3]



[1] J. L. Pore et al., Phys. Rev. Let. 124, 252502 (2020)

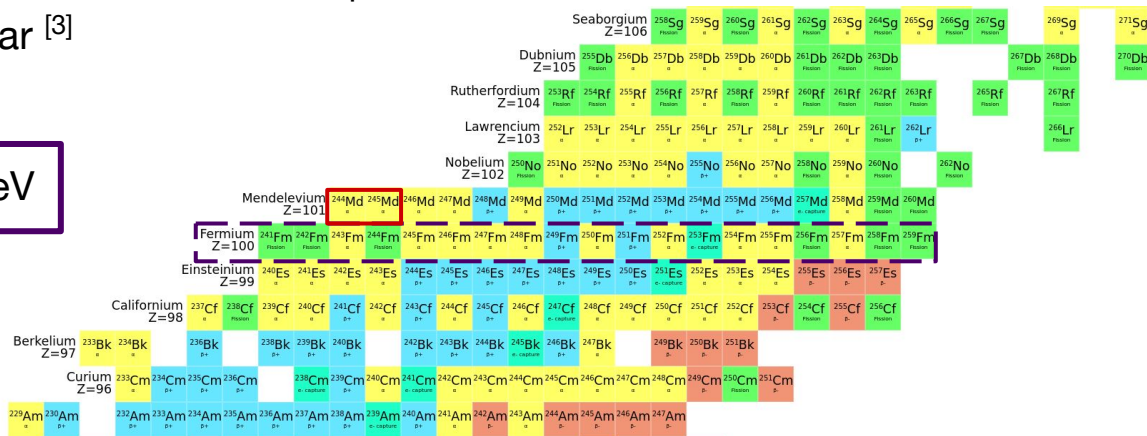
[2] J. Khuyagbaatar et al., Phys. Rev. Let. 125, 142504 (2020)

[3] S. Kumar et al., Acta Phys. Pol. B Proc. Suppl. 19, 1-A24 (2026)

Motivation

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$^{209}\text{Bi}(^{40}\text{Ar}, \text{xn}) ^{249-x}\text{Md}$ @ 210, 212 MeV



[1] J. L. Pore et al., Phys. Rev. Let. 124, 252502 (2020)

[2] J. Khuyagbaatar et al., Phys. Rev. Let. 125, 142504 (2020)

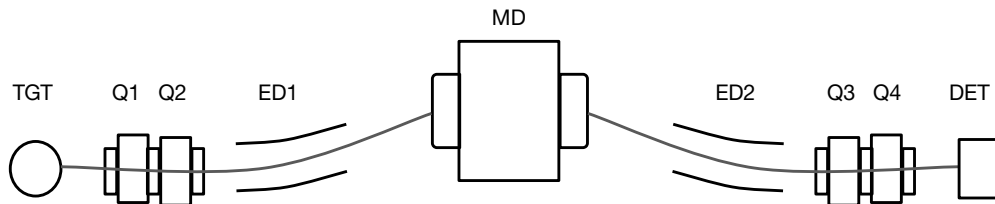
[3] S. Kumar et al., Acta Phys. Pol. B Proc. Suppl. 19, 1-A24 (2026)

Experimental setup

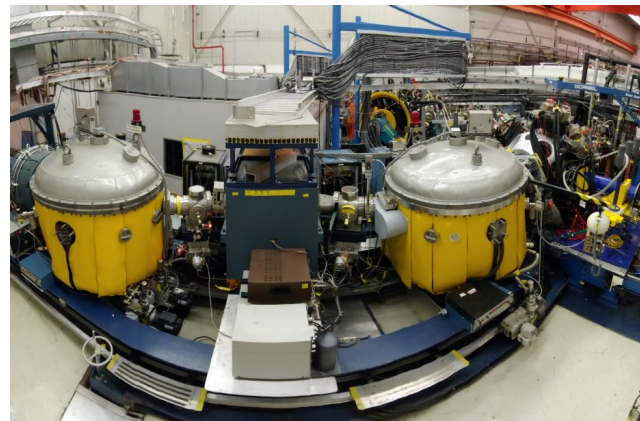
- ATLAS facility of Argonne National Laboratory
- Fragment Mass Analyzer used for A/Q identification of reaction products
- Calibration reaction: $^{174}\text{Yb}(^{40}\text{Ar}, xn)^{214-x}\text{Ra}$ @ 185 MeV

Experimental setup

- ATLAS facility of Argonne National Laboratory
- Fragment Mass Analyzer used for A/Q identification of reaction products
- Calibration reaction: $^{174}\text{Yb}(^{40}\text{Ar}, xn)^{214-x}\text{Ra}$ @ 185 MeV
- Two electric dipoles (ED1-2) + one magnetic dipole (MD)
 - Separation of reaction products and beam
 - **Dispersion of reaction products** based on A/Q



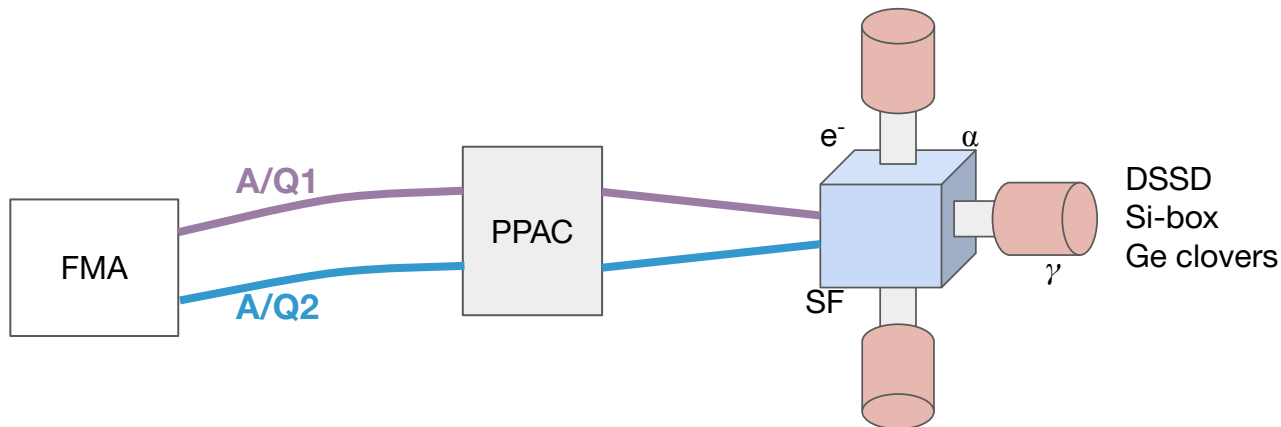
Mass assignment + Decay spectroscopy



Fragment Mass Analyzer,
www.anl.gov/phy/fragment-mass-analyzer

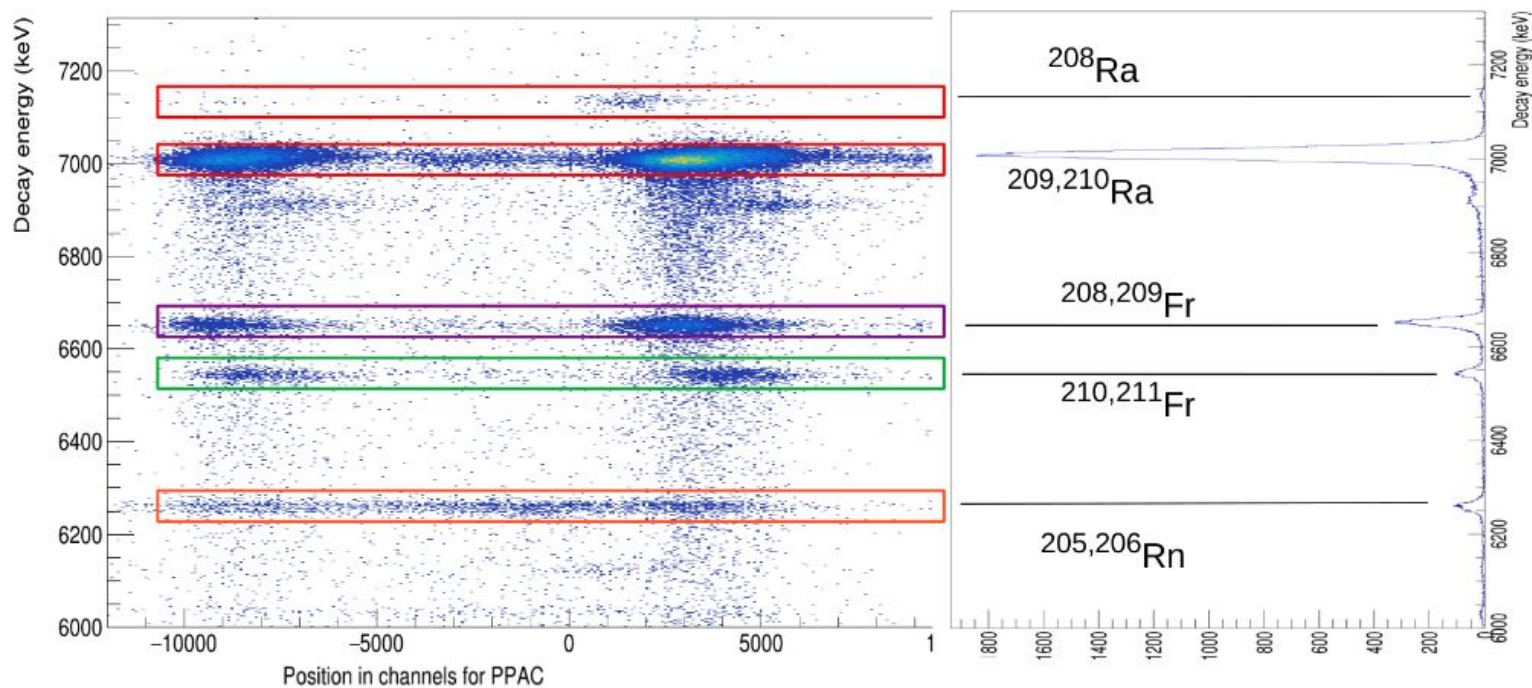
Focal plane detection

- PPAC - Recoil selection and A/Q identification
- DSSD - Recoil implantation and detection of decay products
 - Allows time and position correlation for recoils and decays - 160 front x 160 back strips
- Si-box - Four Si detectors for escaping decay products
- Ge clovers - Detection of x-rays and gamma rays



PPAC A/Q calibration

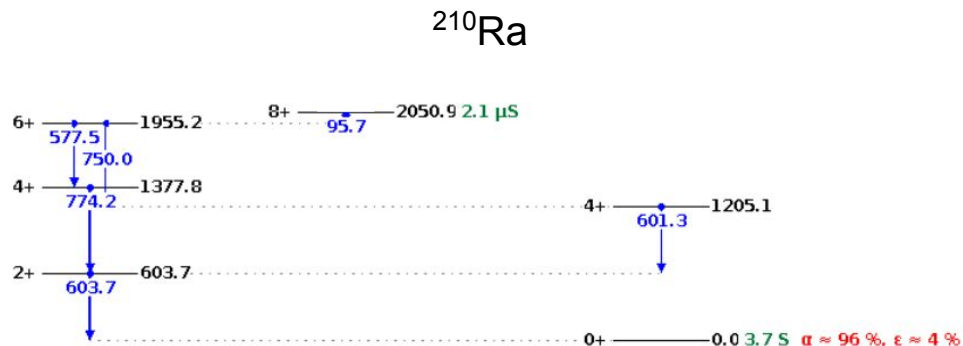
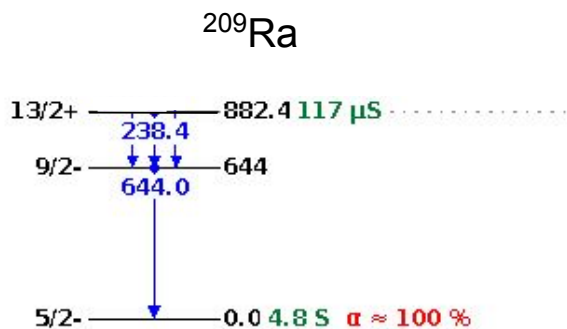
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S. Kumar, PhD Thesis

PPAC A/Q calibration

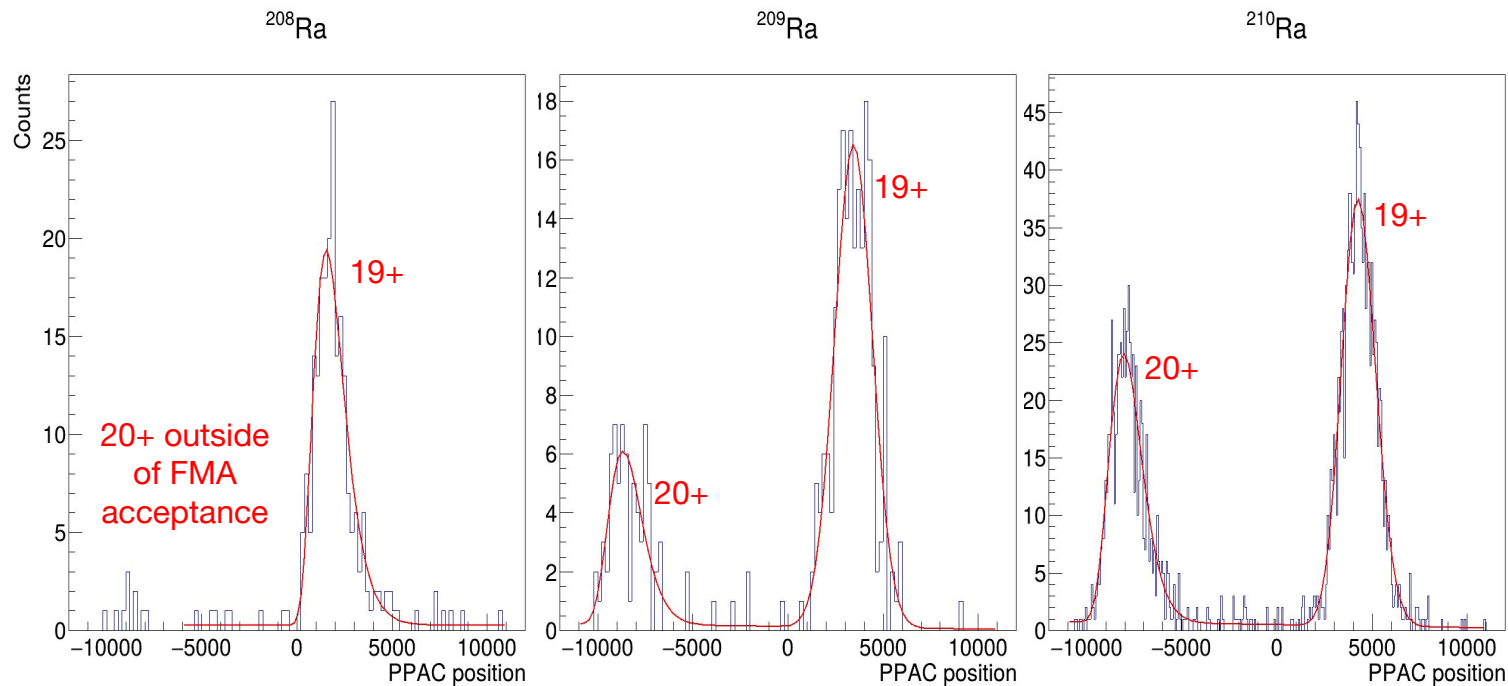
- Calibration reaction: $^{174}\text{Yb}(^{40}\text{Ar}, xn)^{214-x}\text{Ra}$
- ^{208}Ra : Tagged on the α decay
- ^{209}Ra and ^{210}Ra : Tagged on the most intense α line and γ transitions coming from each isomeric state



National Nuclear Data Center, <https://www.nndc.bnl.gov/nudat3>

PPAC A/Q calibration

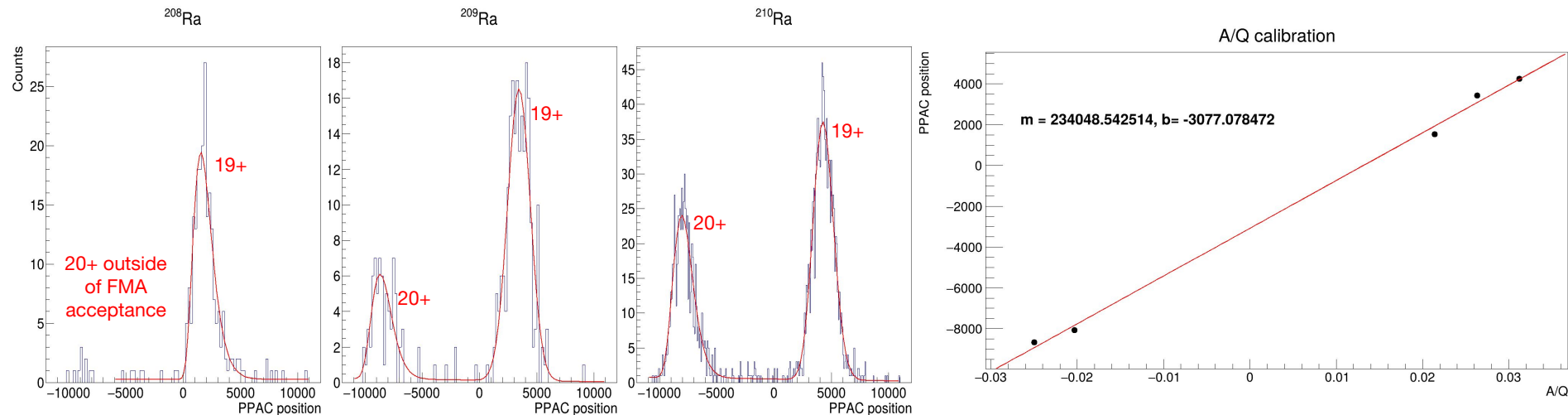
- Peaks fitted using a Gaussian with an exponential tail + a polynomial for background



PPAC A/Q calibration

Center position of the PPAC:
 $A_0/Q_0 = 209/19.5$

- Peaks fitted using a Gaussian with an exponential tail + a polynomial for background



Results

- Goal: Identify SF fragments
- Searched for high energy decays in DSSD and Si-box
 - Events after a recoil in the same DSSD pixel + no PPAC signal
- One α event was seen in the first analysis at **212 MeV** and assigned to ^{245}Md

Results

No traces for the Si-box

- Found one event matching the criteria

SF

$$E_{\text{DSSD}} = 117 \text{ MeV} + E_{\text{Si-box}} = 31 \text{ MeV}$$

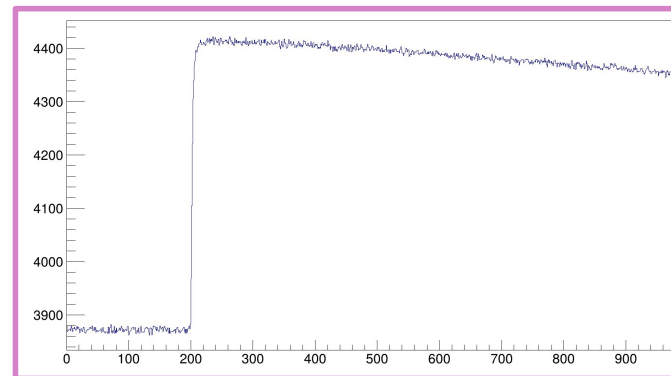
$$E_{\text{ER}} = 5.2 \text{ MeV}$$

$$\Delta t = 74 \text{ } \mu\text{s}$$

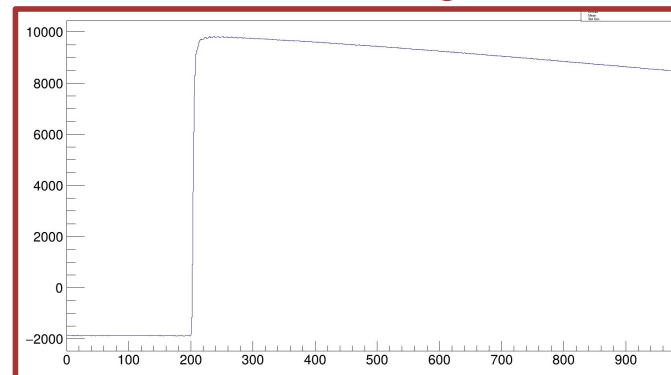
8 Ge events in coincidence

$$E_{\text{Beam}} = 210 \text{ MeV}$$

Trace for recoil



Trace for SF signal



Results

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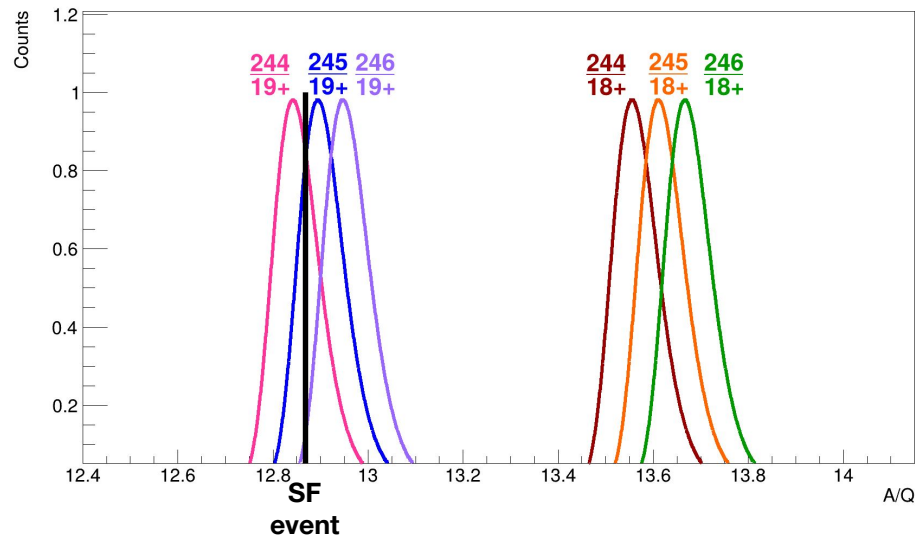
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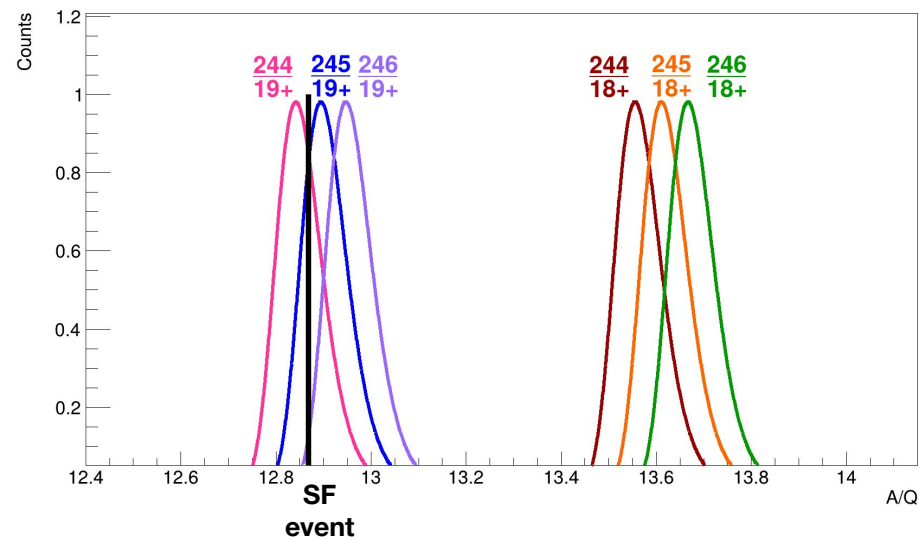
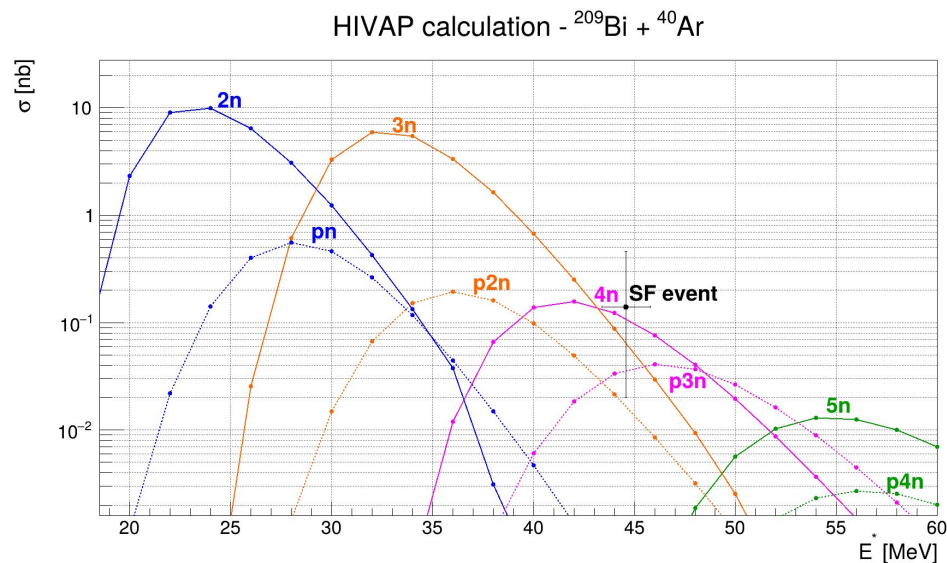
Calculated cross-section value of
 $0.14^{+0.32}_{-0.12} \text{ nb at } 210 \text{ MeV}$



Results

Calculated cross-section value of
 $0.14^{+0.32}_{-0.12}$ nb at 210 MeV

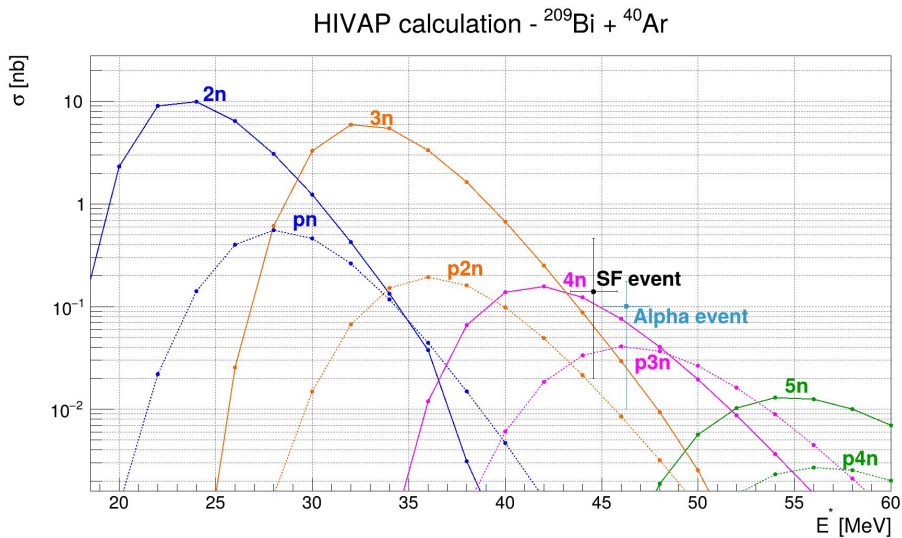
- The cross-section value is consistent with ^{245}Md



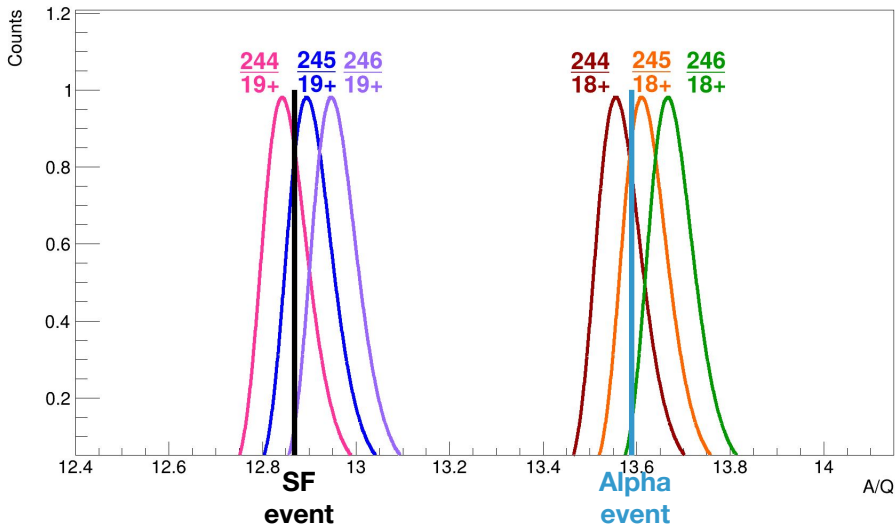
Adapted from F. P. Heßberger *et al.*, Phys. Rev. Lett. 126, 182501 (2021)

Results

SF and alpha events



Adapted from F. P. Heßberger *et al.*, Phys. Rev. Lett. 126, 182501 (2021)



	A = 244	A = 245	A = 246
SF event	40.37 %	42.61 %	0.73 %
Alpha event	34.53 %	52.47 %	4.32 %

Preliminary bayesian analysis by S. Kumar, PhD Thesis (2025)

Comparison with literature

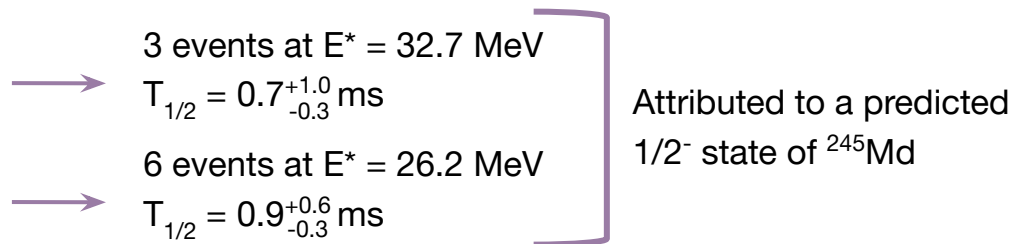
- In the **TASCA** experiment ^[1], 9 SF events were attributed to ²⁴⁵Md
- ⁵⁰Ti + ¹⁹⁷Au @ 231.5, 239.8 MeV

[1] J. Khuyagbaatar *et al.*, Phys. Rev. Let. 125, 142504 (2020)

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Comparison with literature

- In the **TASCA** experiment [1], 9 SF events were attributed to ^{245}Md
- $^{50}\text{Ti} + ^{197}\text{Au}$ @ 231.5, 239.8 MeV

→ 3 events at $E^* = 32.7$ MeV
 $T_{1/2} = 0.7^{+1.0}_{-0.3}$ ms

→ 6 events at $E^* = 26.2$ MeV
 $T_{1/2} = 0.9^{+0.6}_{-0.3}$ ms

Attributed to a predicted $1/2^-$ state of ^{245}Md

- + 2 **unassigned** SF events at 1.5 and 15.6 μs
- + 8 SF events with longer decay times

This work

$^{40}\text{Ar} + ^{209}\text{Bi}$
1 event at $E^* = 44.6$ MeV
TKE ≈ 148 MeV
Decay time = 74^{+171}_{-62} μs

[1] J. Khuyagbaatar *et al.*, Phys. Rev. Lett. 125, 142504 (2020)

Conclusions

- The neutron-deficient $^{244,245}\text{Md}$ were studied for possible SF decay
- The experiment was performed at the ATLAS facility of Argonne National Laboratory
- One SF event was observed
 - Mass between 244 and 245
 - Cross-section close to $4n$ channel
- Higher statistics could help explain the event seen in this experiment and the low decay time events in TASCA
 - Could be done in S^3 , in GANIL

Collaboration

GANIL

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D. Ackermann

J. Piot

S. Kumar

A. Bahini

Ch. Stodel

H. Savajols

IJCLab

A. Lopez-Martens

A. Korichi

K. Hauschild

IRFU/DPhN

B. Sulignano

Argonne National Laboratory

A. Ertoprak

C. Müller-Gattermann

D. Potterveld

D. Seweryniak

F. G. Kondev

K. Bhatt

M. Carpenter

M. Siliciano

N. Sensharma

R. Chakma

T. Lauritsen

V. Karayonchev

W. Reviol

University of York

A. McFarlane

Comenius University

B. Andel

J. Mišt

S. Antalic

University of Massachusetts Lowell

C. Burns

University of Surrey

R. S. Sidhu

GSI

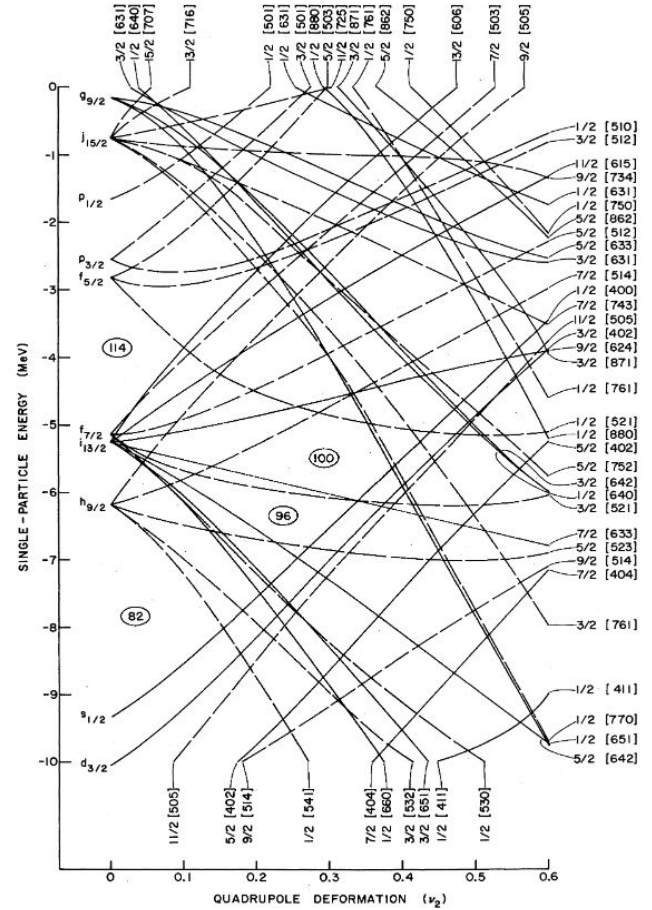
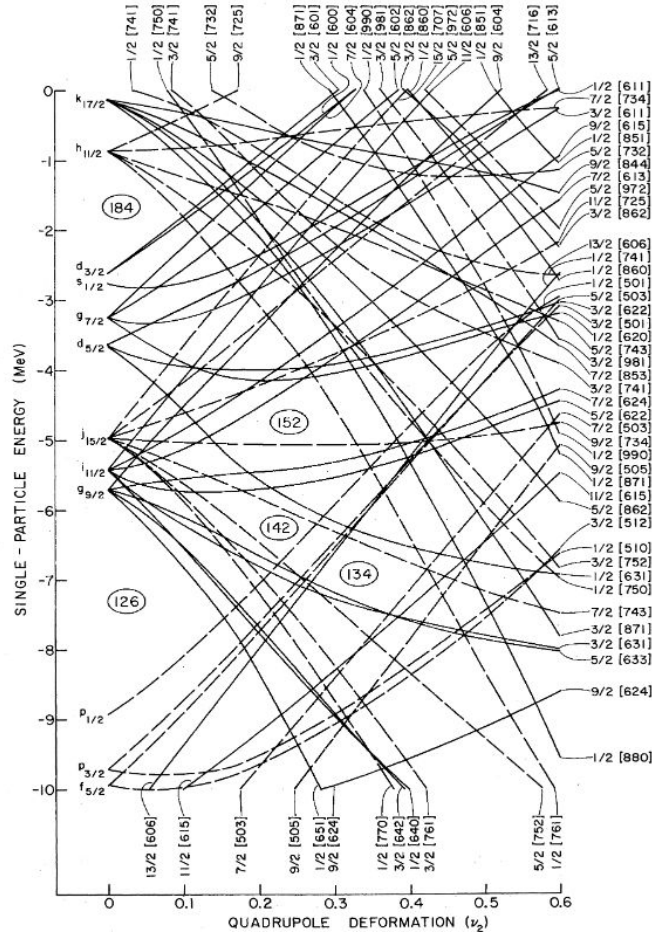
S. Raeder

Back-up

Alpha event

- $E_{\text{ER}} = 5.2 \text{ MeV}$
- 1st decay - 8686 keV in the DSSD, 250 ms after the ER
- 2nd decay - 316 keV in DSSD + 7547 keV in Si-box, 336 ms after 1st decay
- $E_{\text{Beam}} = 212 \text{ MeV}$

Taken from R. R. Chasman *et al.*,
Rev. of Modern Physics, 49 4
(1977)



[illegible]

Zakopane Conference on Nuclear Physics 2026

208,209,210Ra decay energies

Author: C.J. Chiara and F.G. Kondev Citation: Nuclear Data Sheets 111,141 (2010)

Parent Nucleus	Parent E(level)	Parent J π	Parent T _{1/2}	Decay Mode	GS-GS Q-value (keV)	Daughter Nucleus	Decay Scheme	ENSDF file
²⁰⁸ ₈₈ Ra	0.0	0+	1.3 s 2	α : 95 SY %	7273 5	²⁰⁴ ₈₆ Rn		

Alphas:

Energy (keV)	Intensity (%)	Dose (MeV/Bq-s)
7133 5	95 %	6.8

Author: F.G. Kondev Citation: Nuclear Data Sheets 166, 1 (2020)

Parent Nucleus	Parent E(level)	Parent J π	Parent T _{1/2}	Decay Mode	GS-GS Q-value (keV)	Daughter Nucleus	Decay Scheme	ENSDF file
²⁰⁹ ₈₈ Ra	0.0	5/2-	4.8 s 2	α : 100 %	7143.1 27	²⁰⁵ ₈₆ Rn		

Alphas:

Energy (keV)	Intensity (%)	Dose (MeV/Bq-s)
6376 10	0.200 %	0.0128
6625 5	0.50 %	0.033
7006 3	99 %	7.0

Author: F.G. Kondev Citation: Nuclear Data Sheets 201, 346 (2025)

Parent Nucleus	Parent E(level)	Parent J π	Parent T _{1/2}	Decay Mode	GS-GS Q-value (keV)	Daughter Nucleus	Decay Scheme	ENSDF file
²¹⁰ ₈₈ Ra	0.0	0+	3.9 s 1	α : 96 %	7151 3	²⁰⁶ ₈₆ Rn		

Alphas:

Energy (keV)	Intensity (%)	Dose (MeV/Bq-s)
6452 3	0.030 % 4	0.0019 3
7014 4	100 % 14	7.0 10

National Nuclear Data Center, <https://www.nndc.bnl.gov/nudat3>

Cross-section calculation

- Target thickness - 0.45 mg/cm^2 , ^{209}Bi
- Average current - 394 pA
- Irradiation time - 19 hours
- FMA efficiency - 6%
- Detection efficiency - 55%