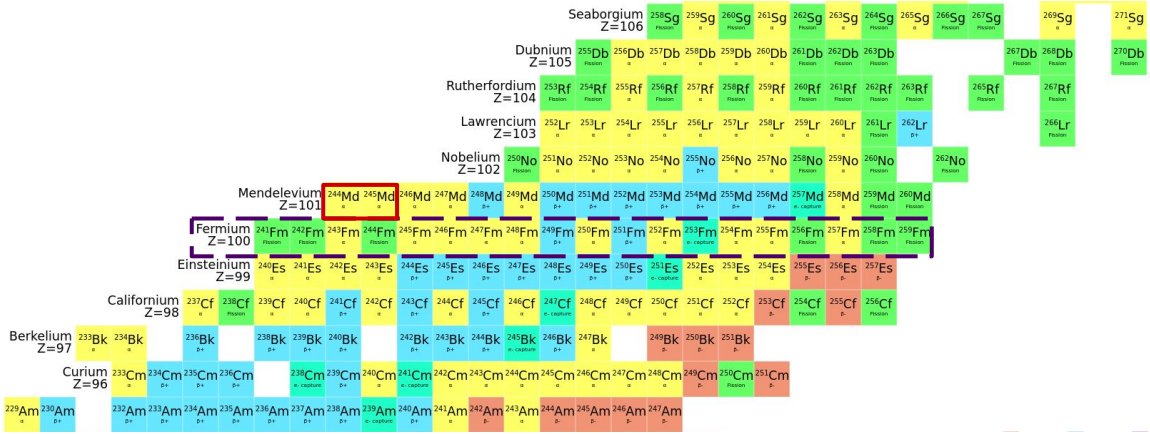
Spontaneous fission in neutron-deficient Md isotopes

Margarida Paulino

Colloque GANIL 2026

Motivation

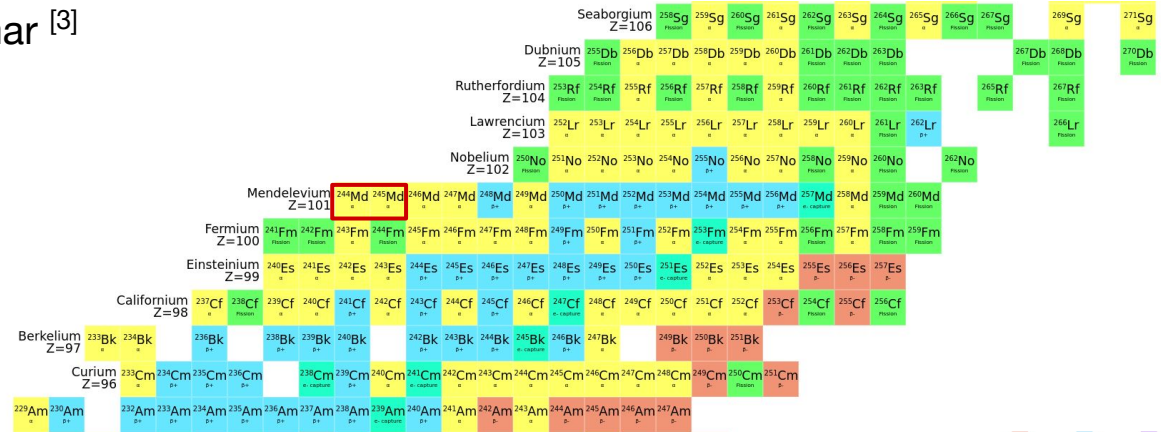
- Measure decay properties of the lightest known Md isotopes: ^{244,245}Md
- Stability against SF is influenced by shell effects [1,2,3]
- Md is one proton above the **Z=100** shell gap



[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}Md
- Investigate **mass assignment discrepancies** between two previous experiments
  - ^{40}Ar + ^{209}Bi @ 220 MeV, Berkeley Gas-Filled Separator (BGS) of LBNL [1]
  - ^{50}Ti + ^{197}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)

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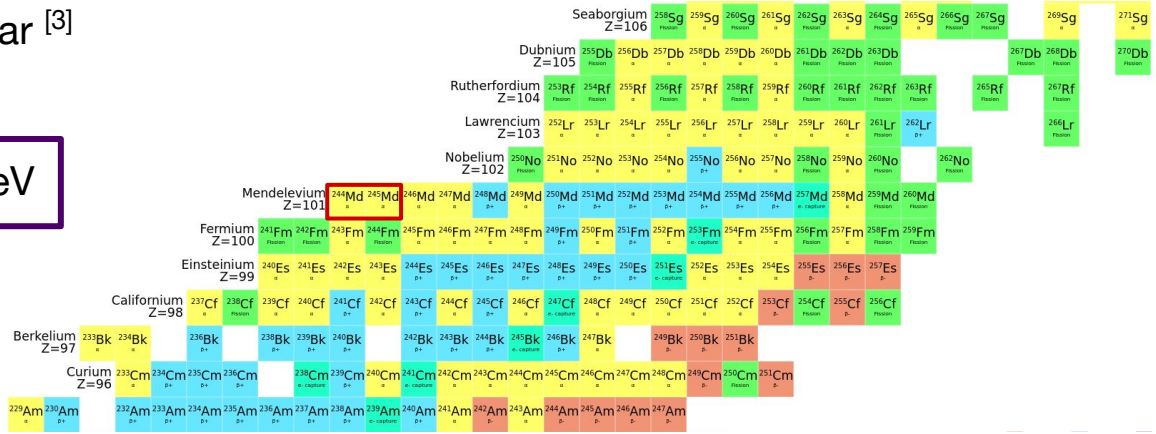
^{209}Bi(^{40}Ar, xn) $^{249-x}$Md @ 210,212 MeV



[1] J. L. Pore et al., Phys. Rev. Let. 124, 252502 (2020)
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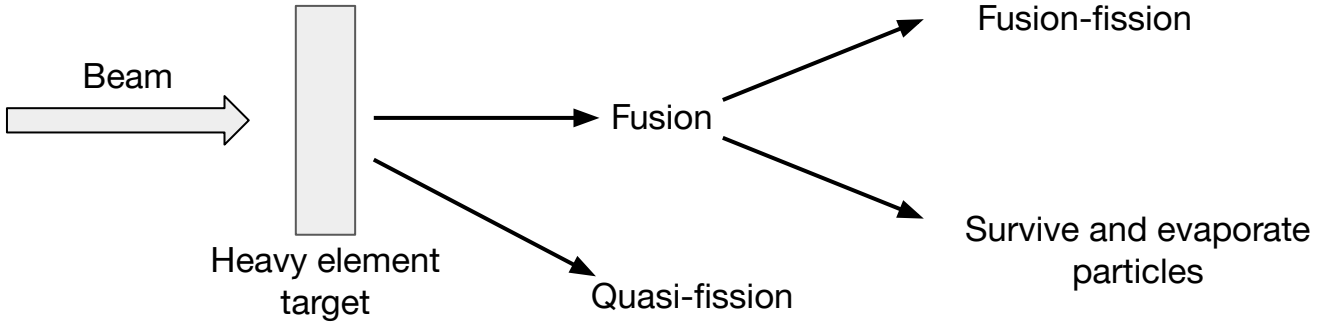
Fusion-evaporation reactions for SHN

- Medium-mass projectiles impinge on heavy targets and create excited compound states



$$\sigma = \underbrace{\frac{\pi\hbar^2}{2\mu \mathrm{E}_{\mathrm{CM}}} \sum_l (2l+1)T(l)}_{\text{Capture}} \cdot \underbrace{P_{\mathrm{form}}(l)}_{\substack{\text{Compound} \\ \text{nucleus formation}}} \cdot \underbrace{P^{\mathrm{xn}}_{\mathrm{survival}}(l)}_{\text{Survival}}$$

Experimental setup

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

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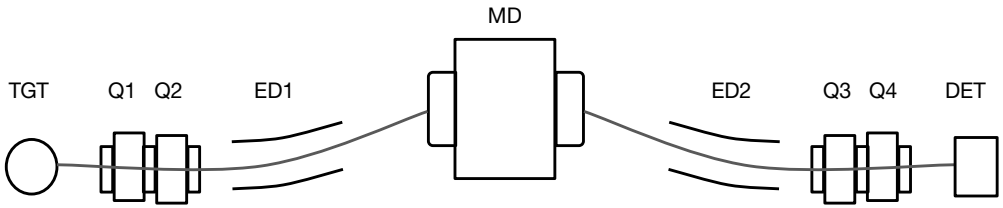
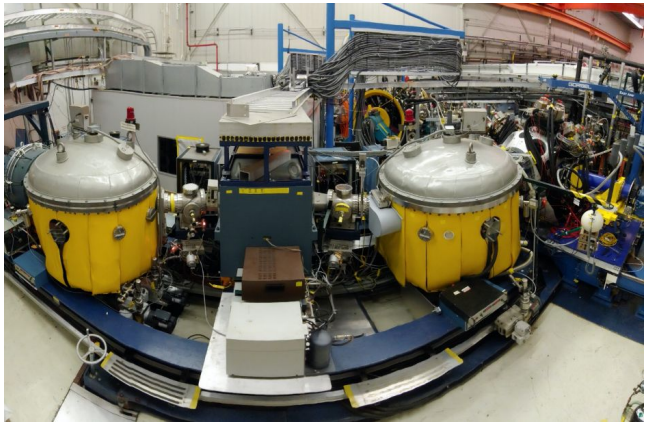
- Calibration reaction: ^{174}Yb(^{40}Ar, xn)$^{214-x}$Ra @ 185 MeV
- Two electric dipoles (ED1-2) + one magnetic dipole (MD)
  - Separation of reaction products and beam
  - **Dispersion of reaction products** based on A/Q



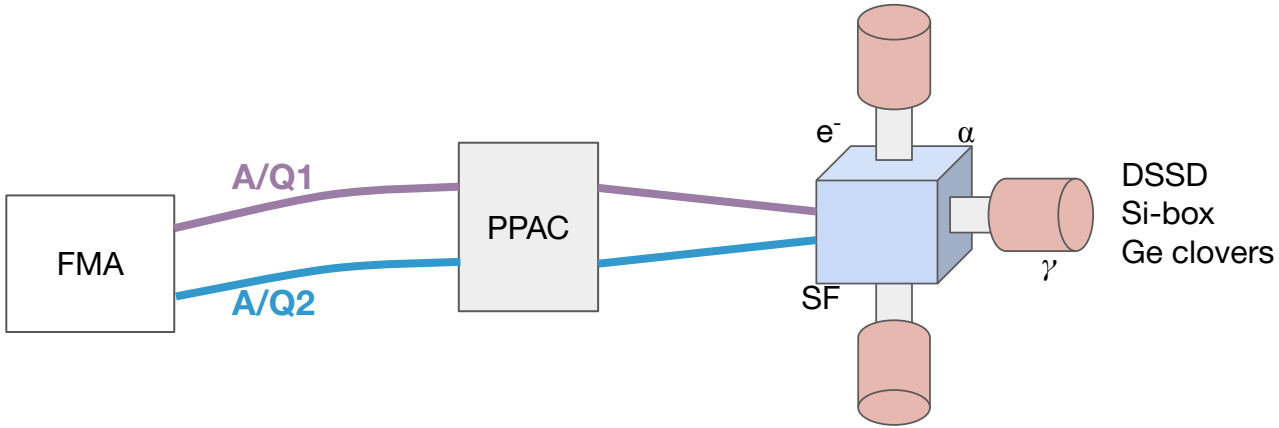
Mass assignment + Decay spectroscopy



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

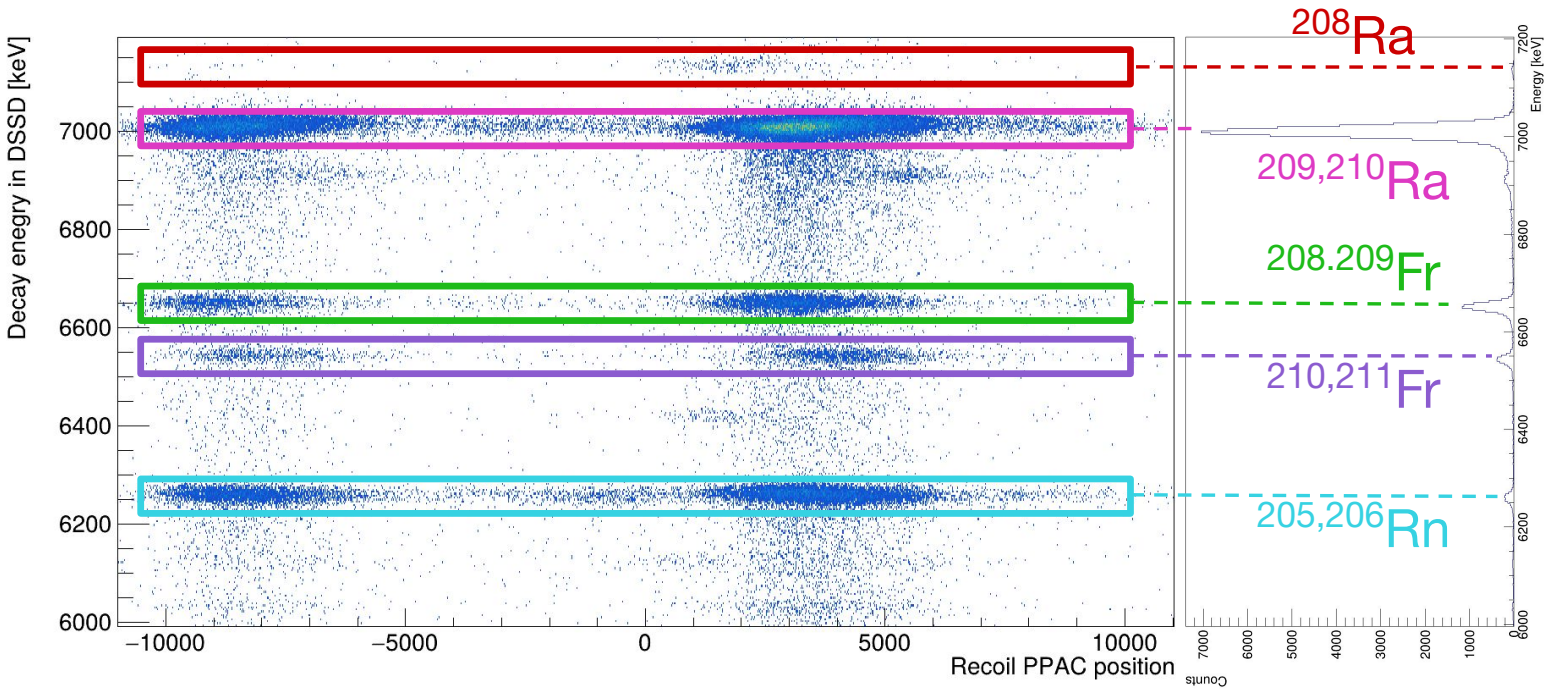
Focal plane detection

- 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

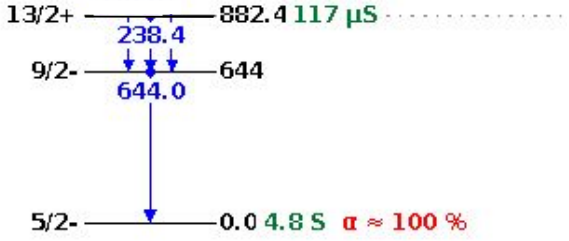
- Calibration reaction: $^{174}Yb(^{40}Ar,xn)^{214-x}Ra$



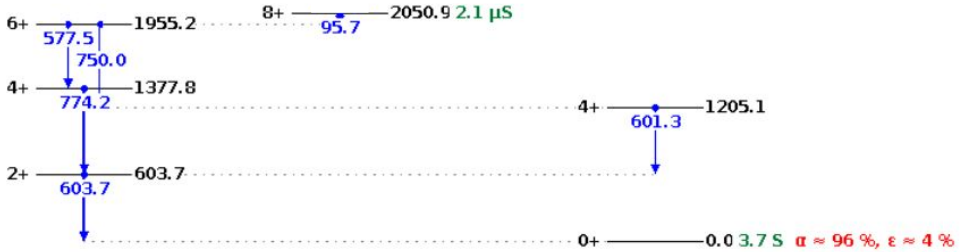
PPAC A/Q calibration

- Calibration reaction: ^{174}Yb(^{40}Ar,xn)$^{214-x}$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

^{209}Ra



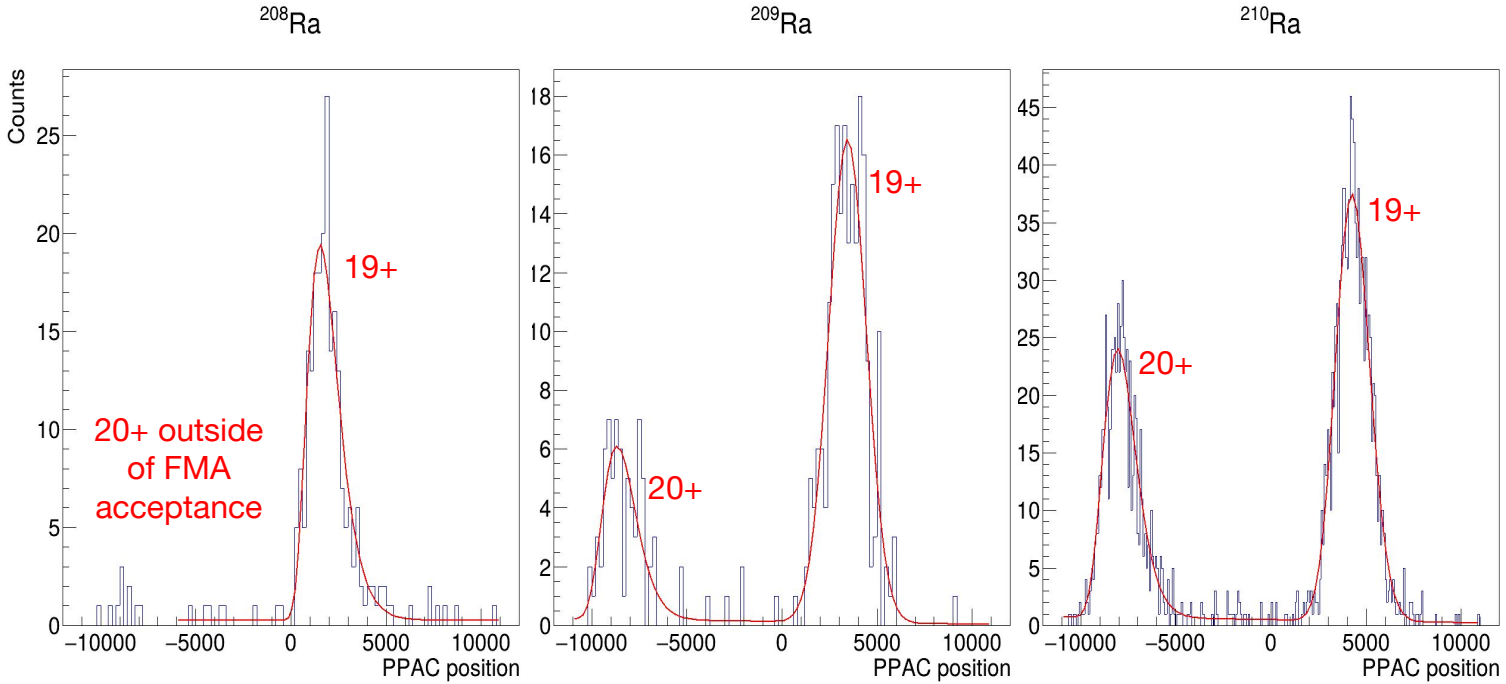
^{210}Ra



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

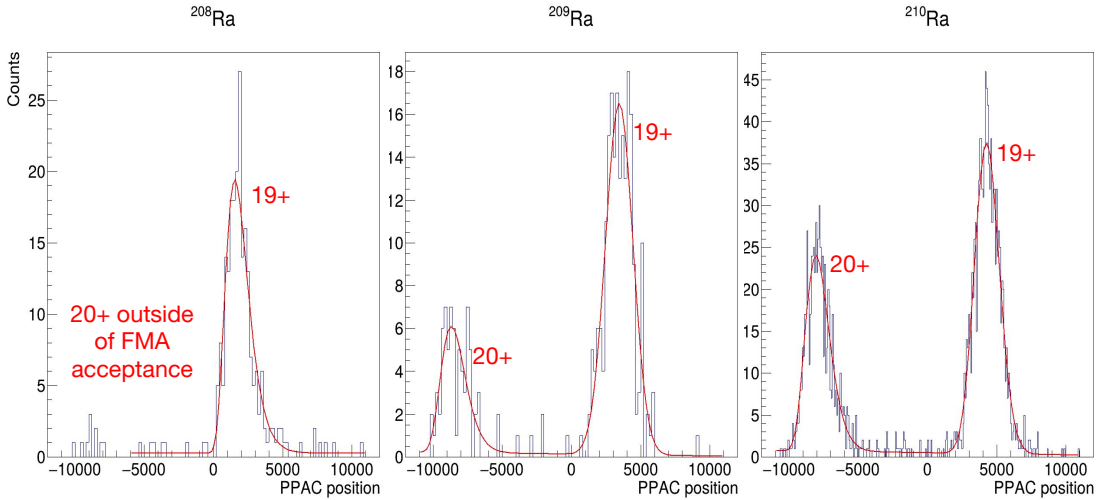
- Center position of the PPAC: A_0/Q_0 = 209/19.5

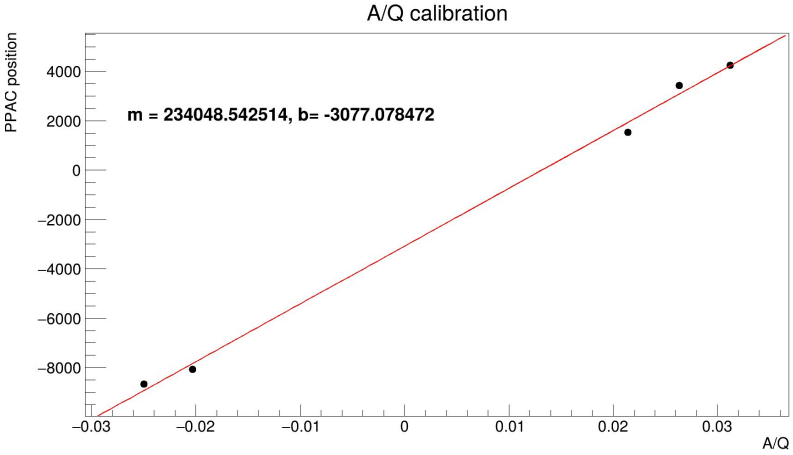
$$X = D \cdot \left(\frac{A/q - A_0/q_0}{A_0/q_0} \right) + X_0$$

Relation between the A/Q and PPAC position for a recoil

X_0: Position of central mass and charge state

D: Dispersion constant





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

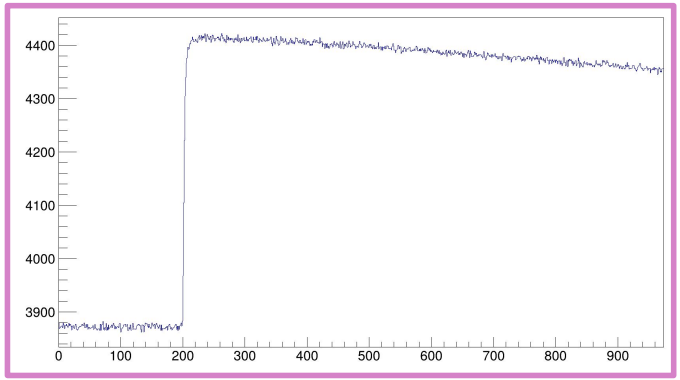
No traces for the Si-box

- Found one event matching the criteria

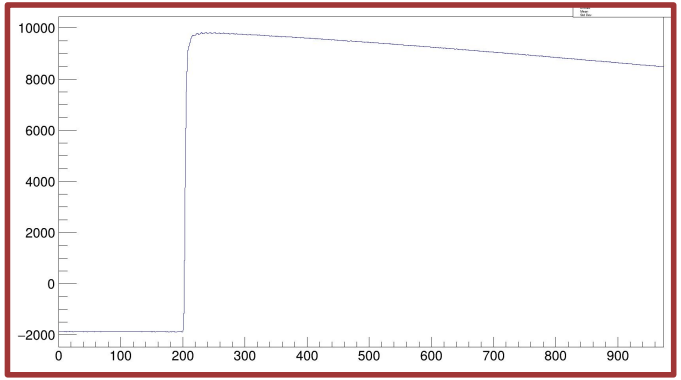
SF

E_{DSSD} = 117 MeV + $E_{Si\text{-}box}$ = 31 MeV
E_{ER} = 5.2 MeV
Δt = 74 µs
8 Ge events in coincidence
E_{Beam} = 210 MeV

Trace for recoil



Trace for SF signal



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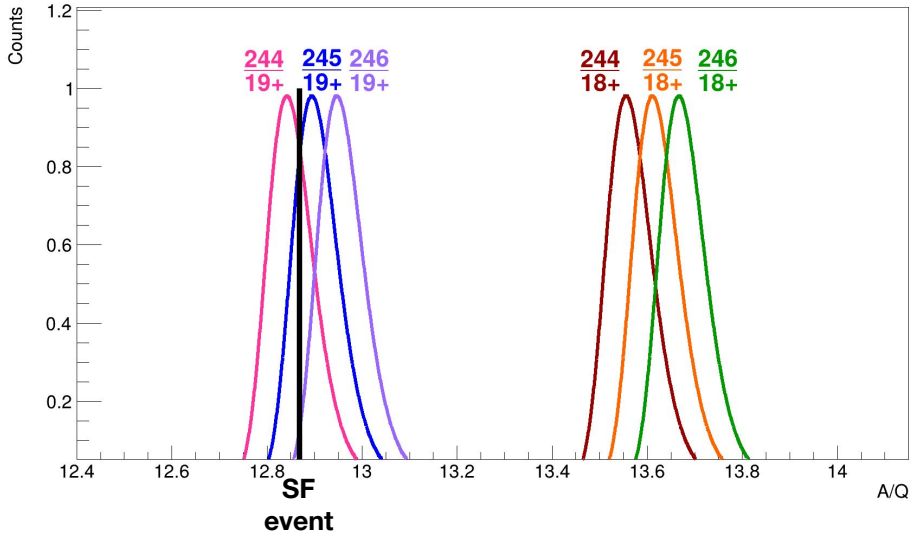
Calculated cross-section value of $0.14^{+0.32}_{-0.12}$ nb at 210 MeV



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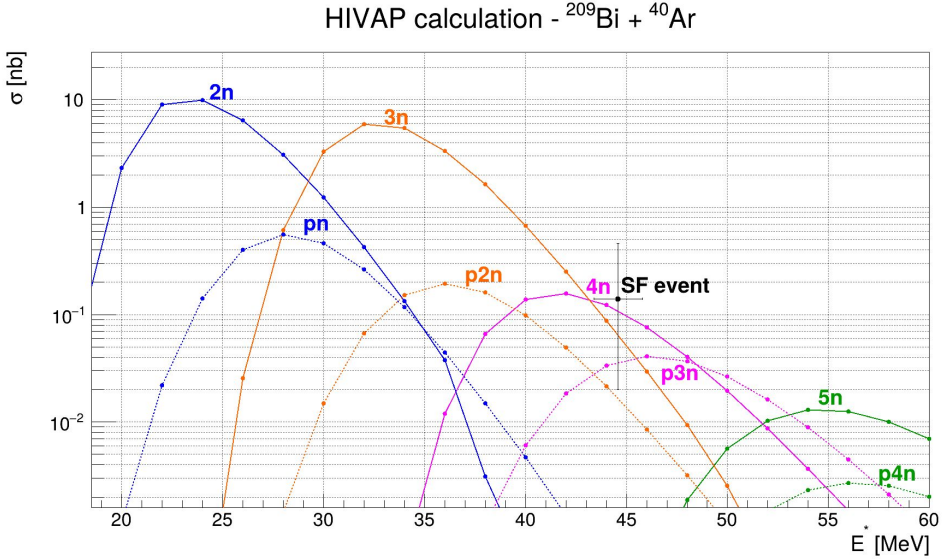
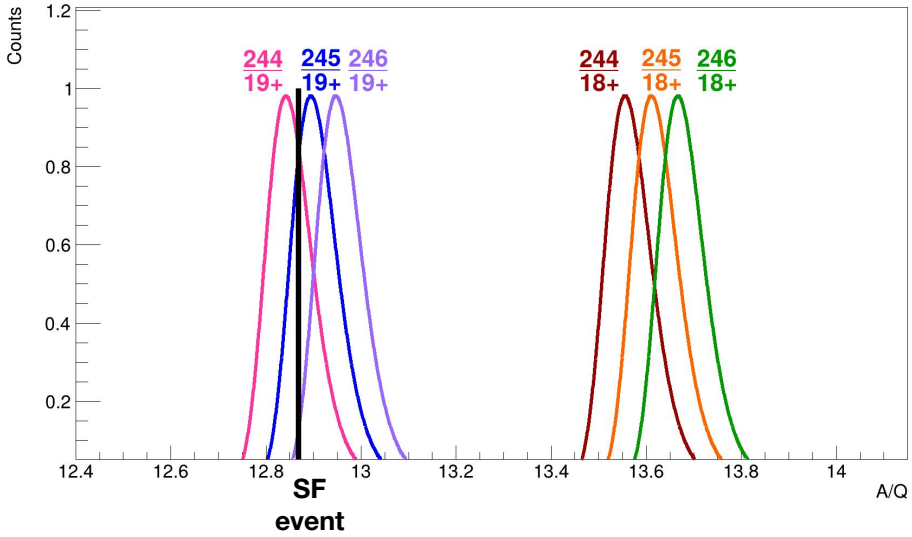
Calculated cross-section value of $0.14^{+0.32}_{-0.12}$ nb at 210 MeV

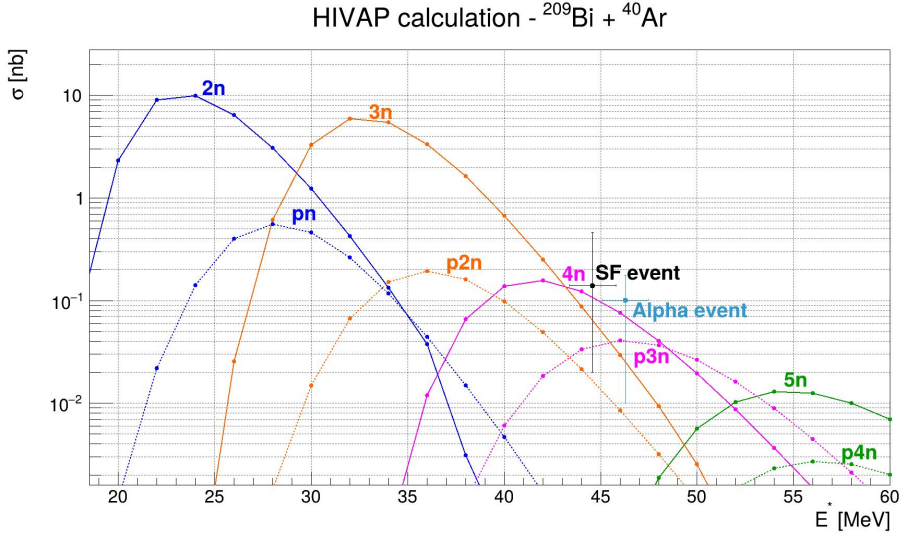
- The cross-section value is consistent with ^{245}Md





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

SF and alpha events



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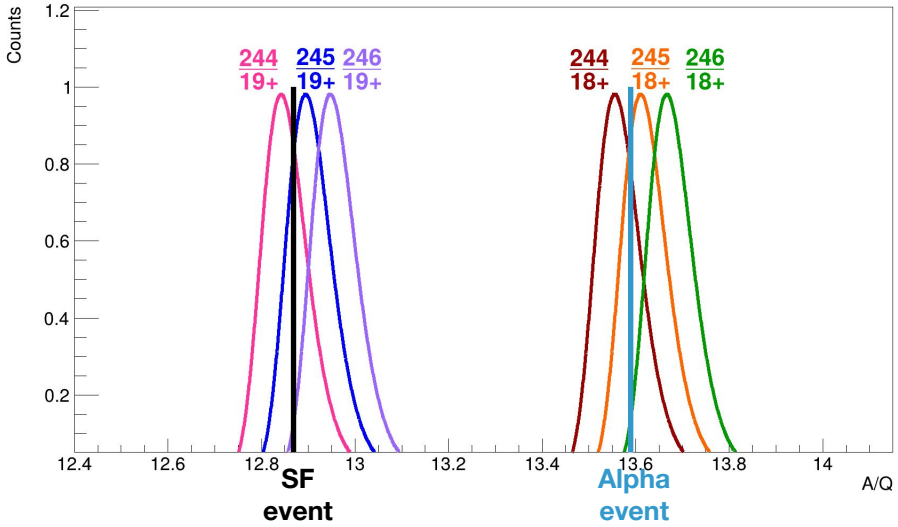

	A = 244	A = 245	A = 246
SF event	40.37 %	42.61 %	0.73 %
Alpha event	34.53 %	52.47 %	4.32 %

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

Comparison with literature

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

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

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→ 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

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

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

Conclusions

- The neutron-deficient ^{244,245}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

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- Superheavy elements: Synthesis methods, structure and chemistry
- Fission and quasi-fission dynamics
- Transfer and deep-inelastic collisions
- Near-barrier collisions with weakly bound and unstable nuclei
- Tunnelling and deep sub-barrier fusion
- Nuclear reactions relevant to astrophysics
- Facilities and instrumentation for reactions around the barrier
- Ground state and decay properties of atomic nuclei

https://indico.in2p3.fr/event/34700/

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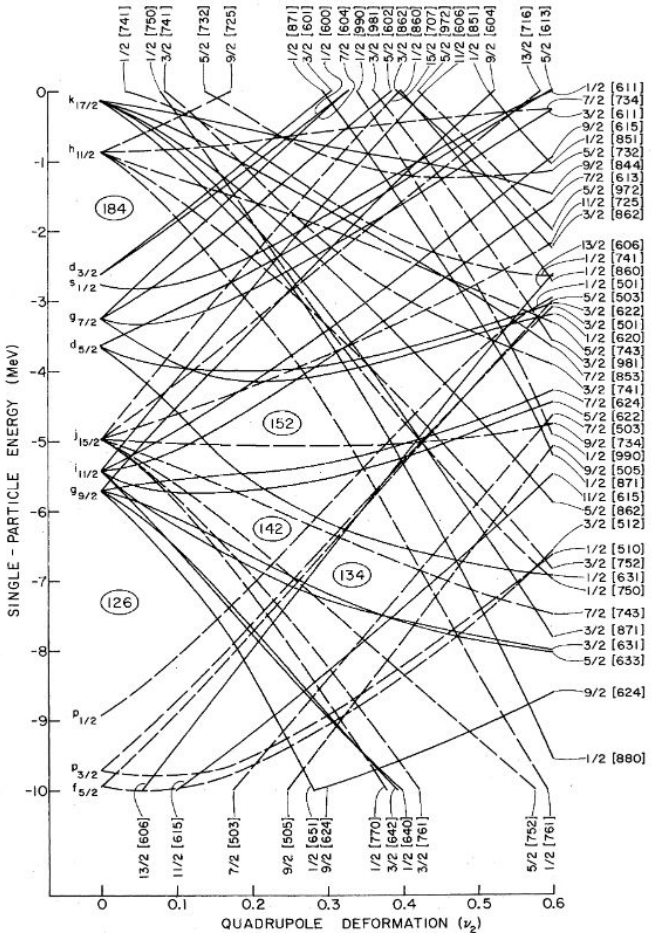
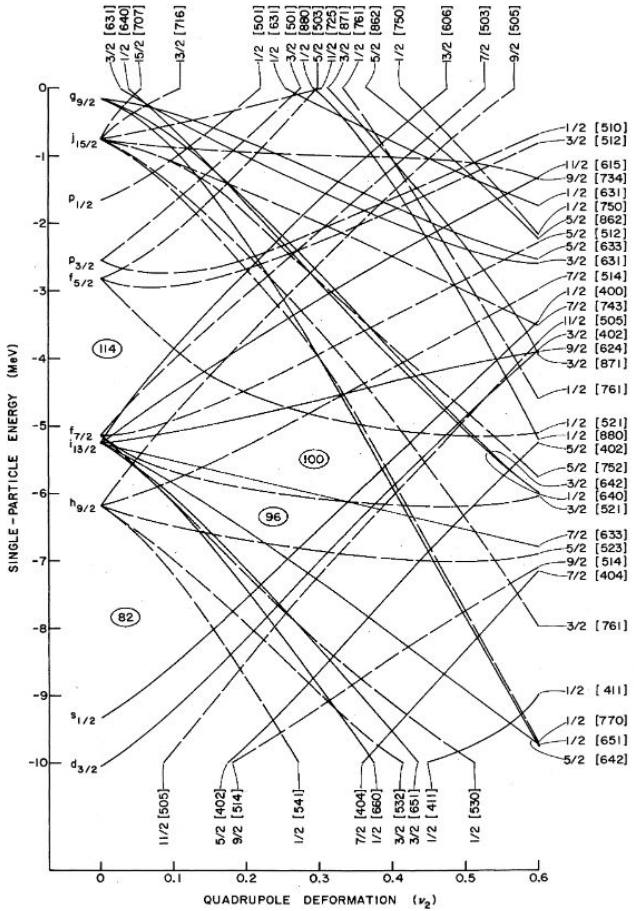
Back-up

Alpha event

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

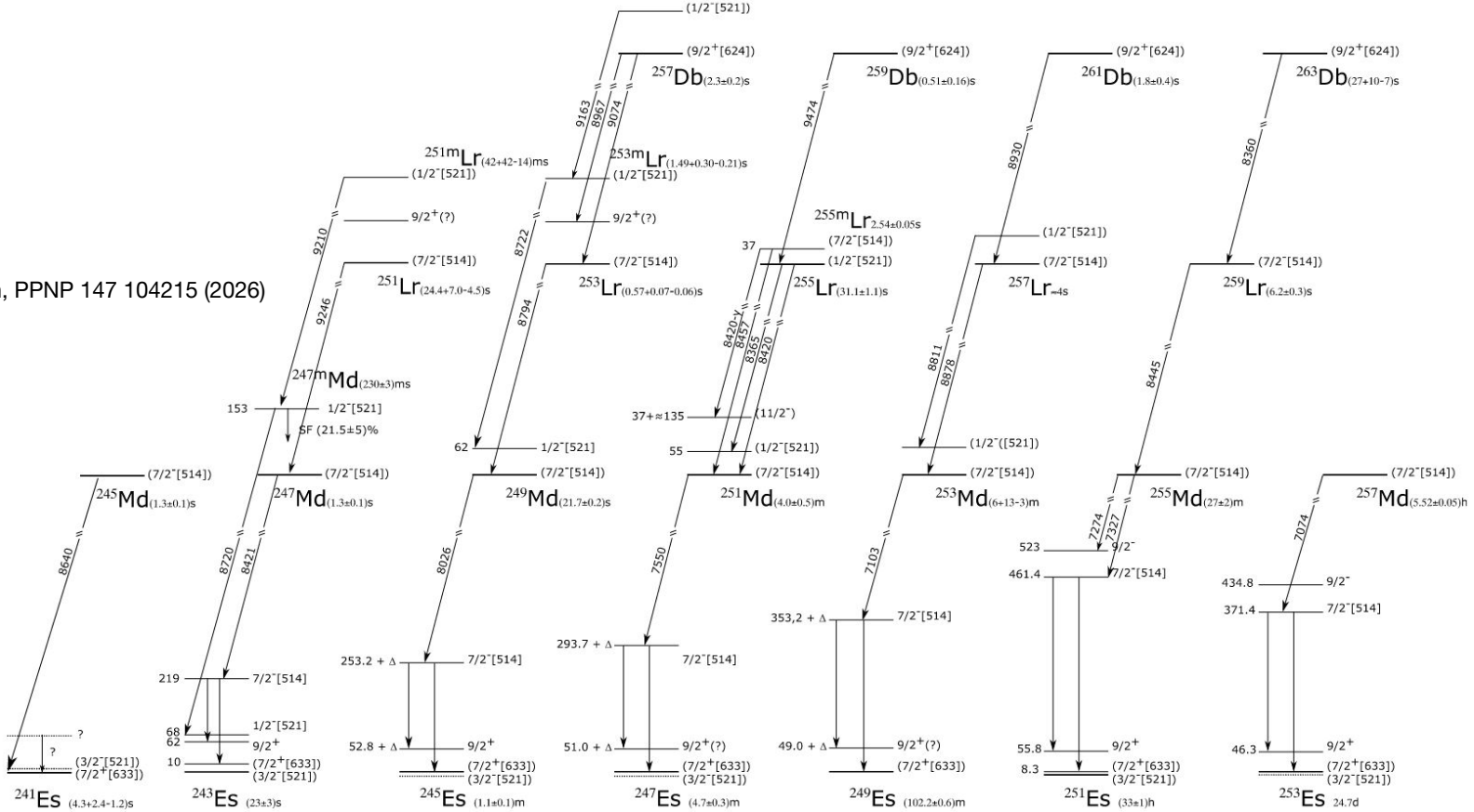
Taken from R. R. Chasman *et al.*, Rev. of Modern Physics, 49 4 (1977)





Decay scheme close to the N=152 shell

Taken from D. Ackermann, PPNP 147 104215 (2026)



^{208,209,210}Ra decay energies

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

Parent Nucleus	Parent E(level)	Parent Jπ	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 Jπ	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 Jπ	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:

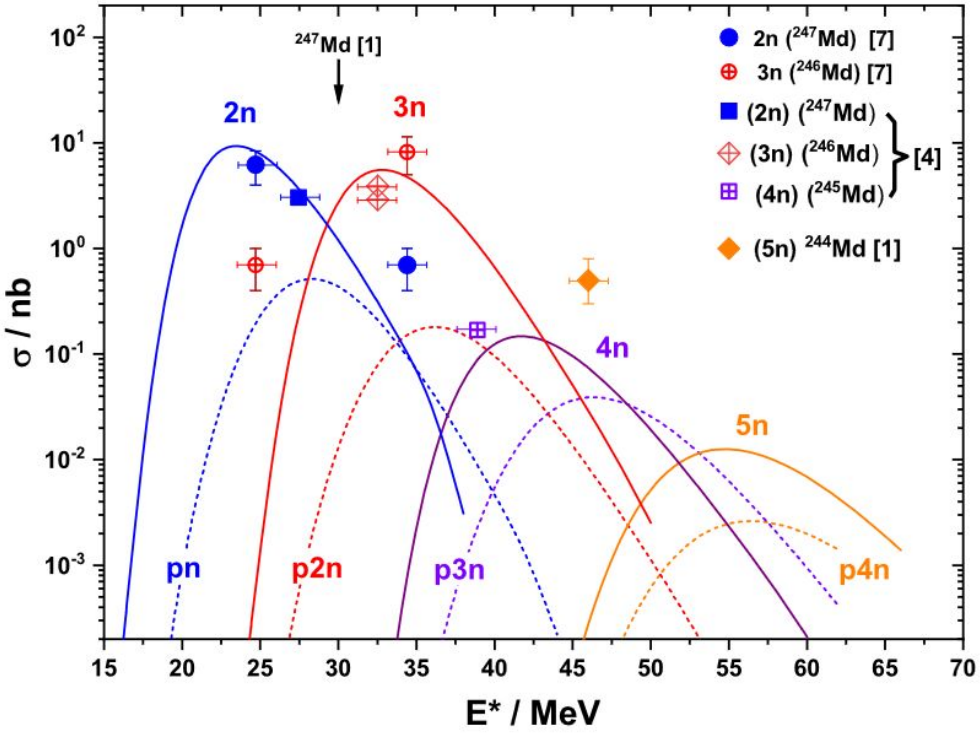
Energy (keV)	Intensity (%)	Dose (MeV/Bq-s)
6452 *3*	0.030 % *4*	0.0019 *3*
7014 *4*	100 % *14*	7.0 *10*

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 pnA
- Irradiation time - 19 hours
- FMA efficiency - 6%
- Detection efficiency - 55%

HIVAP - ^{40}Ar + ^{209}Bi



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