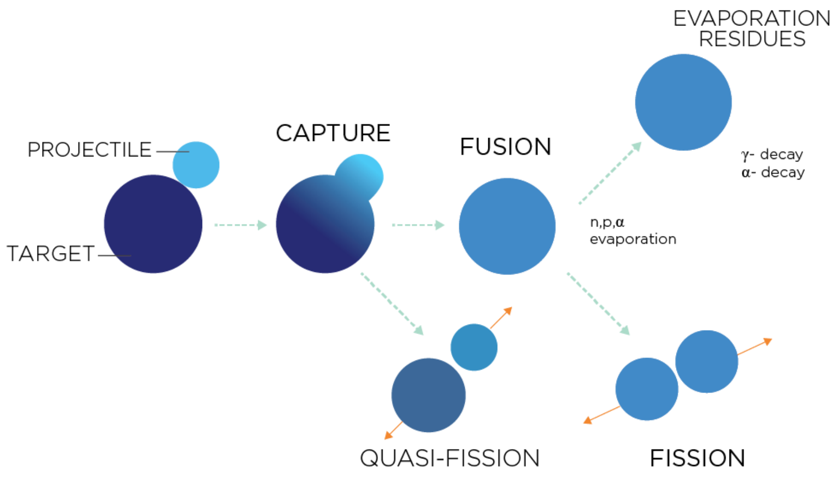
Benchmarking the Active Catcher Array to Study Multi Nucleon Transfer Reactions

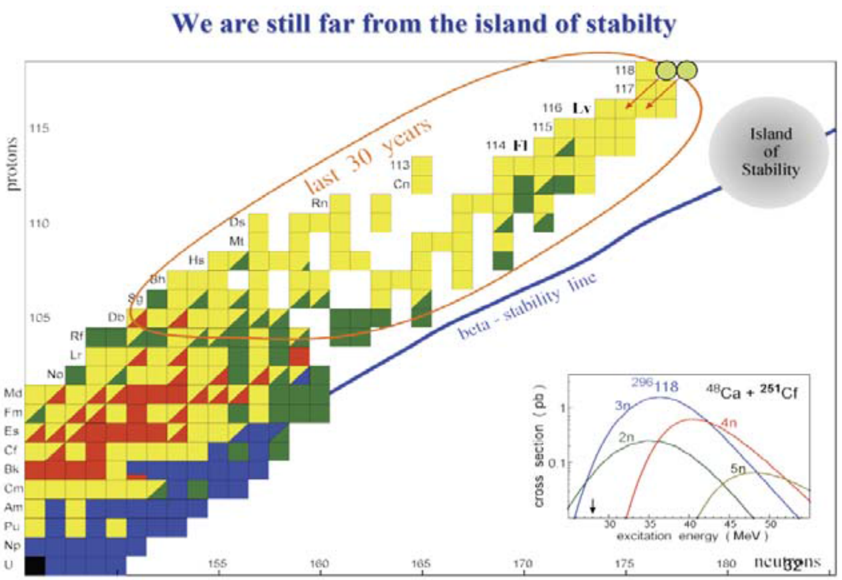
Aditya Wakhle

27th October 2018

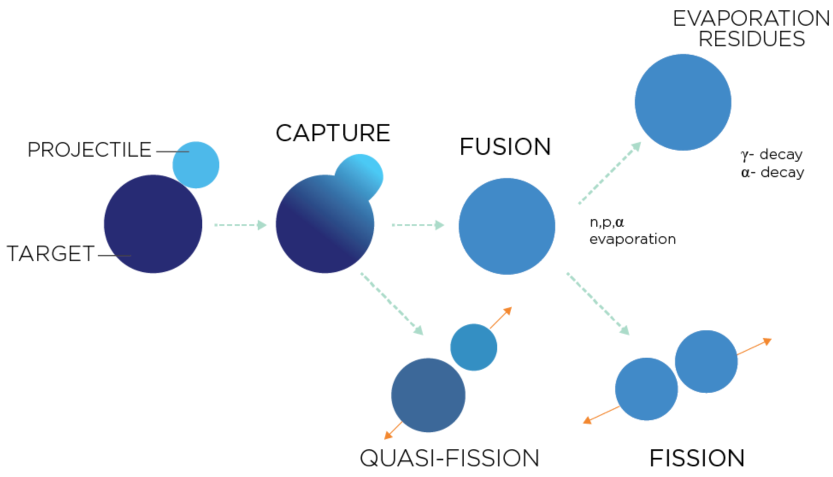
Cyclotron Institute, Texas A&M University

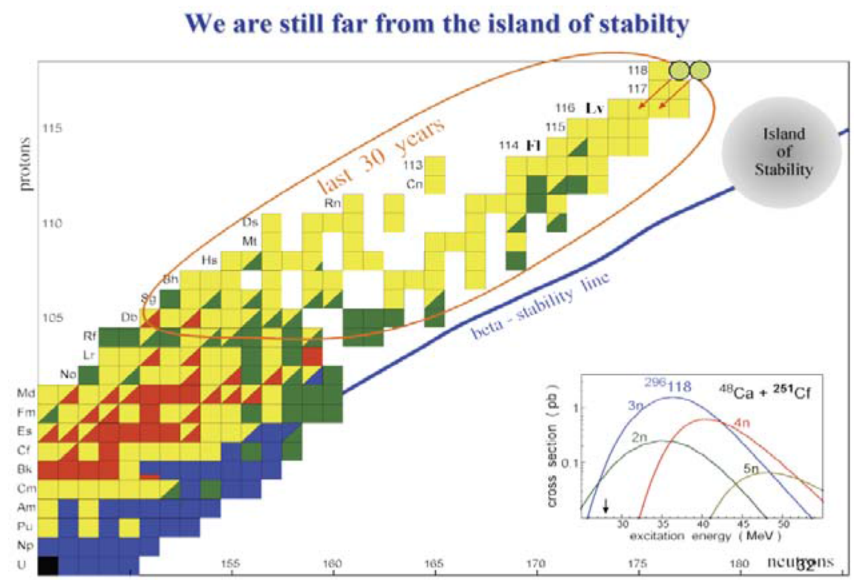
Heavy elements





Heavy elements – Heavy-ion Fusion





- All heavy elements to date have been synthesized by fusion.
- Quasi-fission and fusion-fission are competing channels.

- Limitation was target material -> move to radioactive targets
- Current limitation is beam -> transitioning to radioactive beams, current intensities are 10^5 pps. Need intensities above 10^10 pps.

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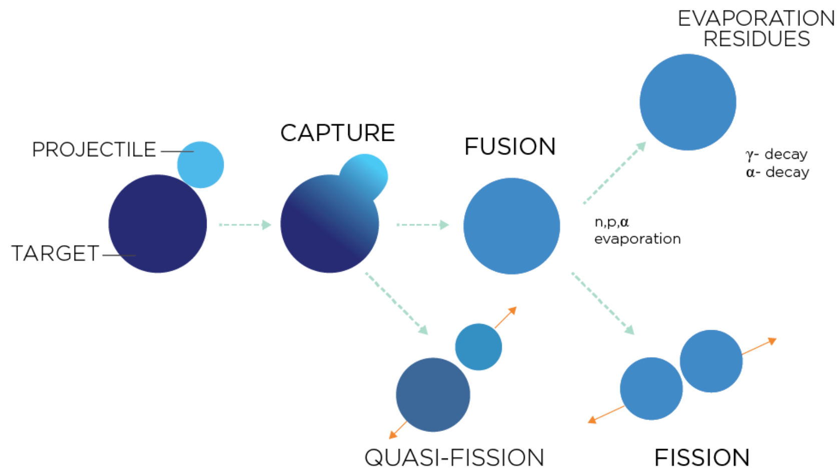

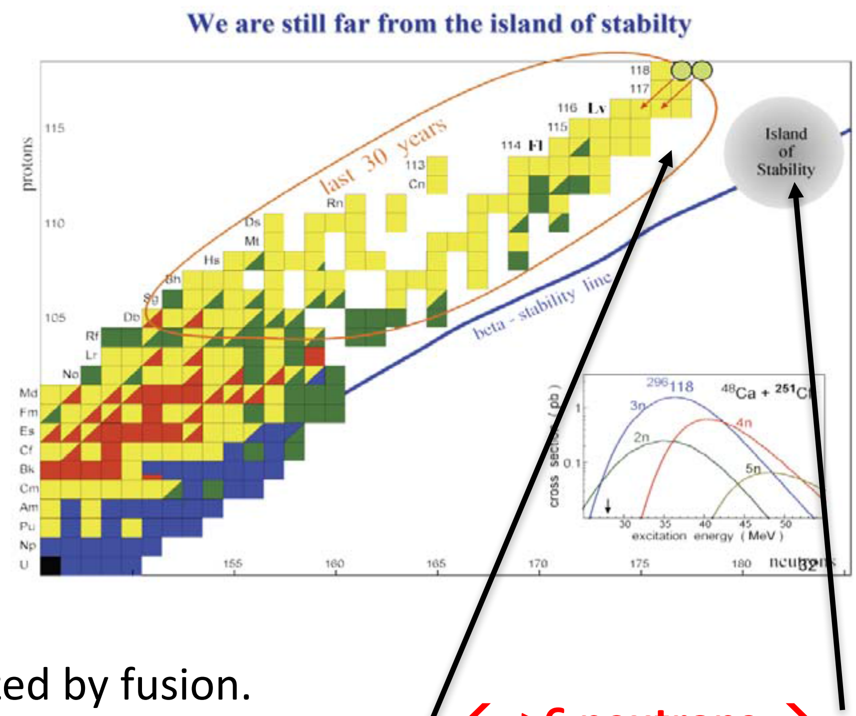

← >6 neutrons →

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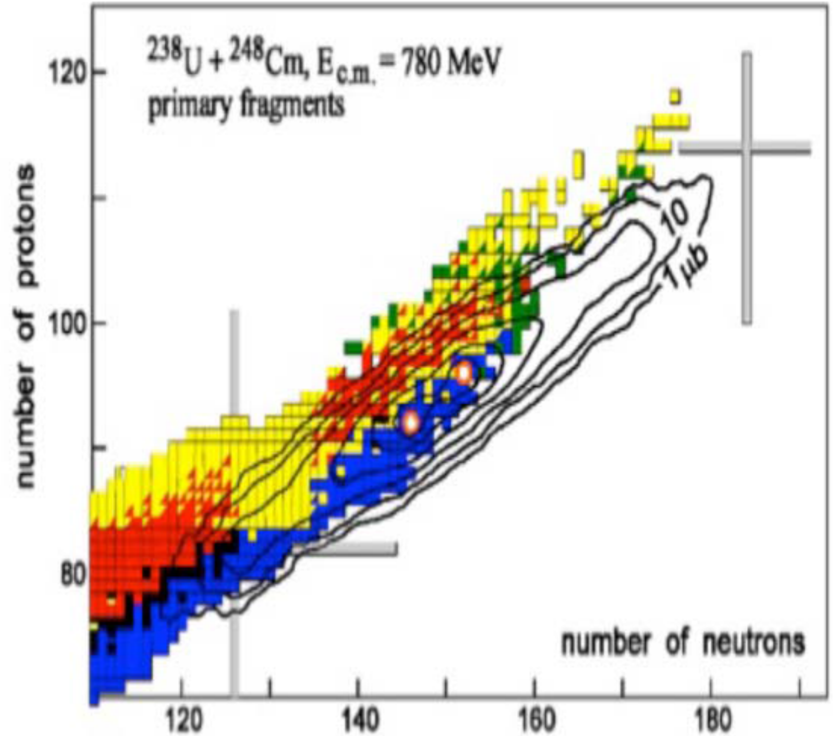
Heavy Elements - Multi-nucleon Transfer?

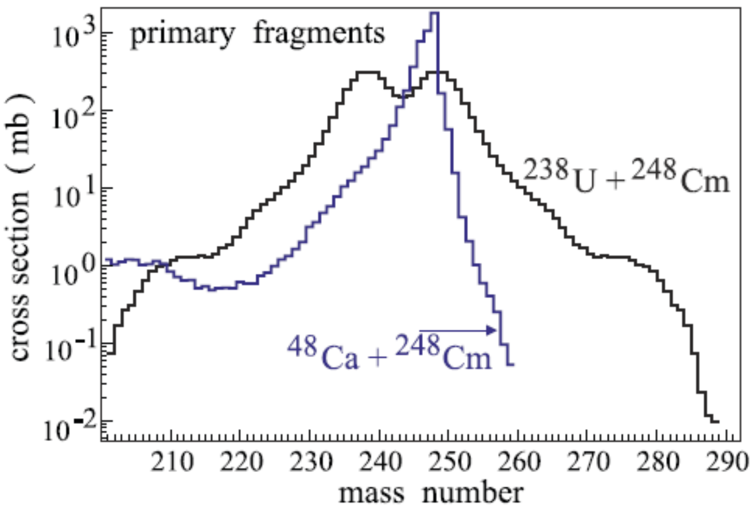
- Multi-nucleon transfer reactions between pairs of heavy nuclei – actinide+actinide
- Balance between:
  heavy residues – favour heavier pairs
  survival probability – favour lighter pairs

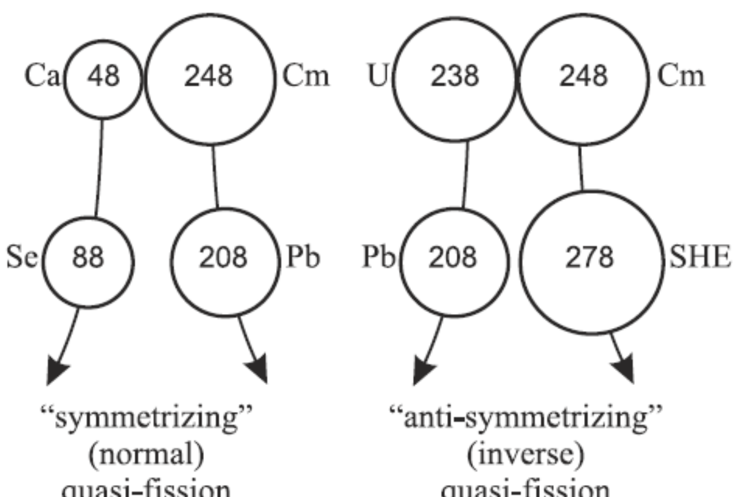
- Production of neutron rich, heavy and super-heavy isotopes with relatively higher cross section.
- Theoretical studies predicting fission rates indicate high survival probabilities around the island of stability via both **statistical models, and microscopic models**.

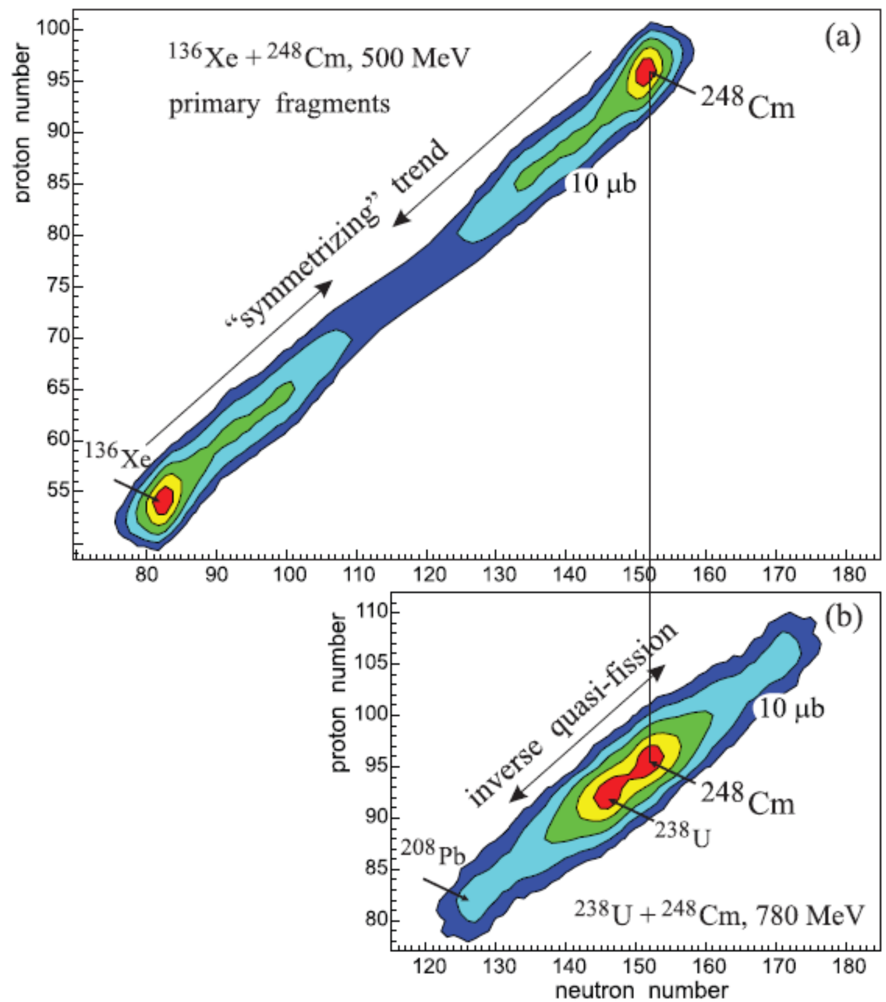


V.I. Zagrebaev and W. Greiner, Phys. Rev. C **87**, 034608 (2013)

Macroscopic Models, 'Inverse' Quasi-fission







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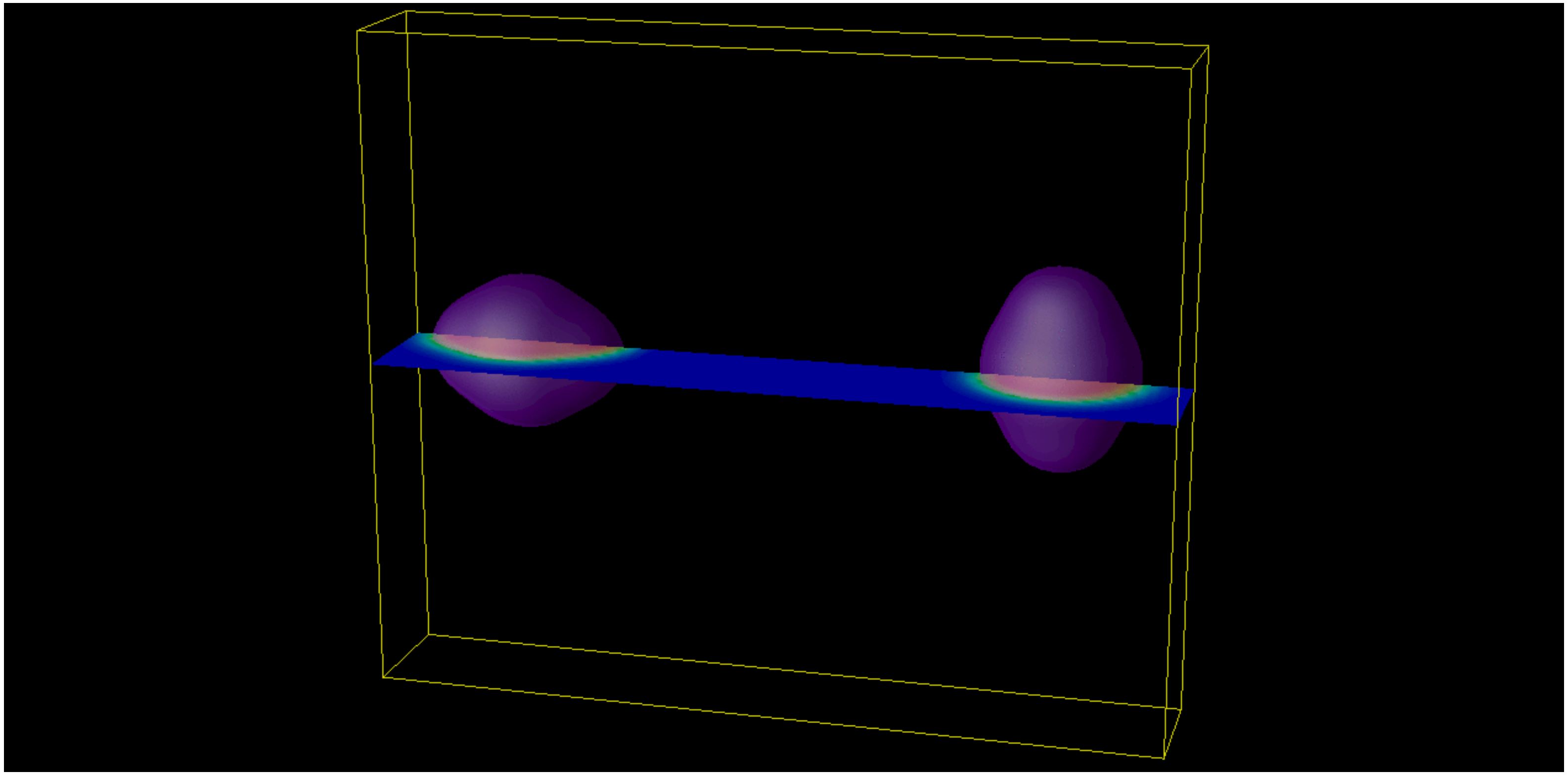
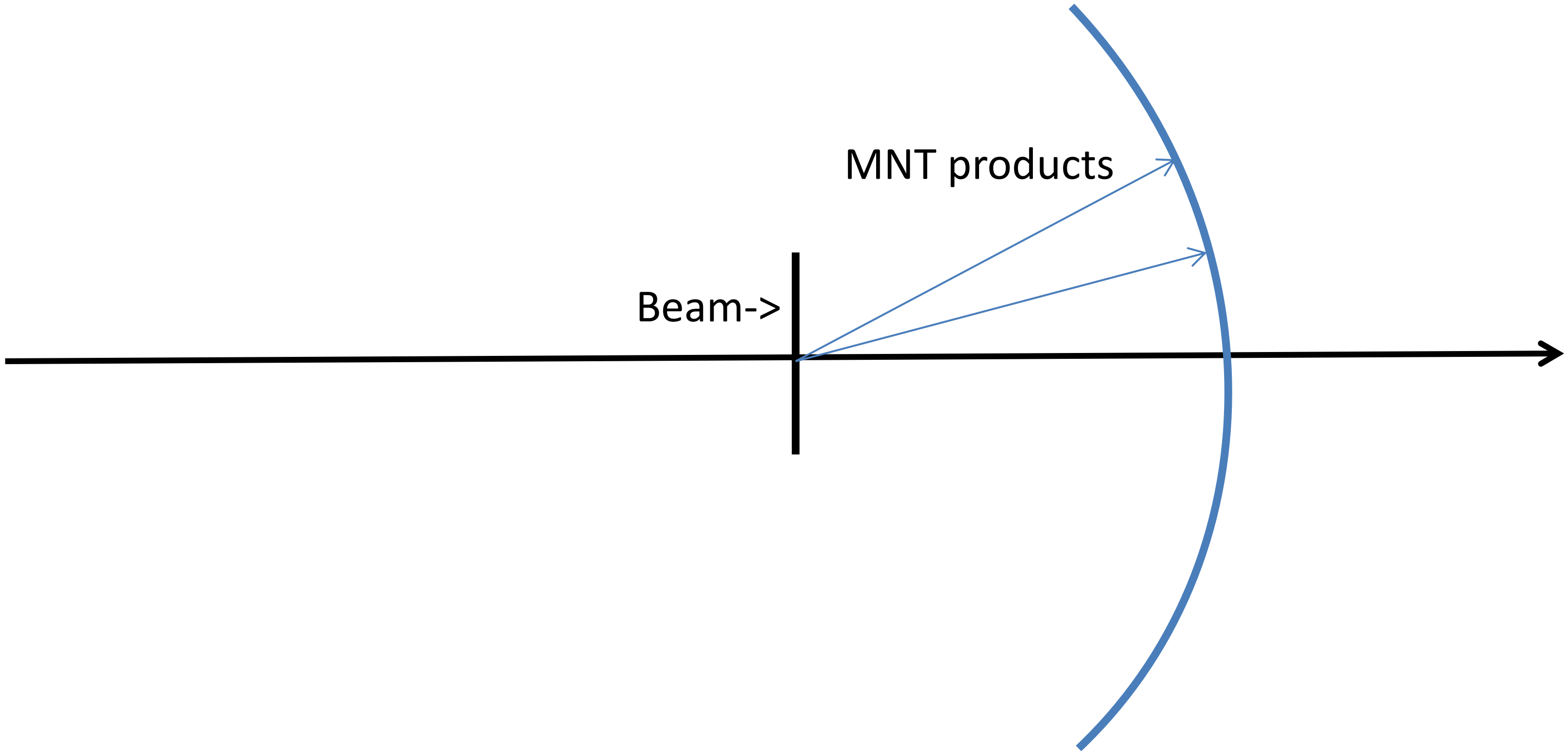
Microscopic Models, Multi Nucleon Transfer



MNT reactions in TDHF
Entrance channel $^{238}U + ^{232}Th$
Exit channel $^{220}Rn^* + ^{250}Cm^*$

Ian Jeanis – in preparation (2018) – See student poster session.
D. J. Kedziora and C. Simenel Phys. Rev. C **81**, 044613 (2010)

‘Passive’ Catcher Technique



H. Kumpf and E. D. Donets, Soviet Physics Jetp. 17, 3 (1963)

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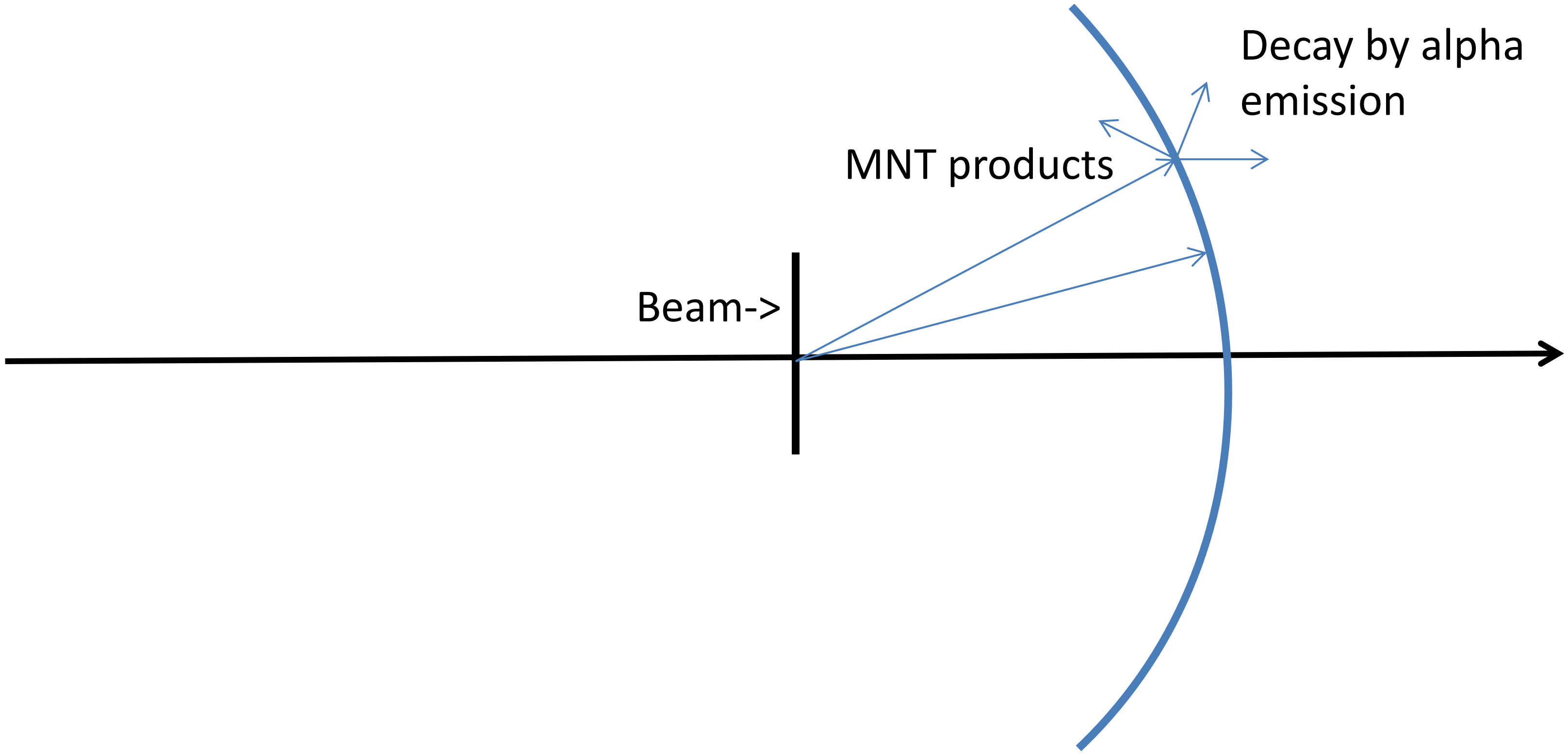

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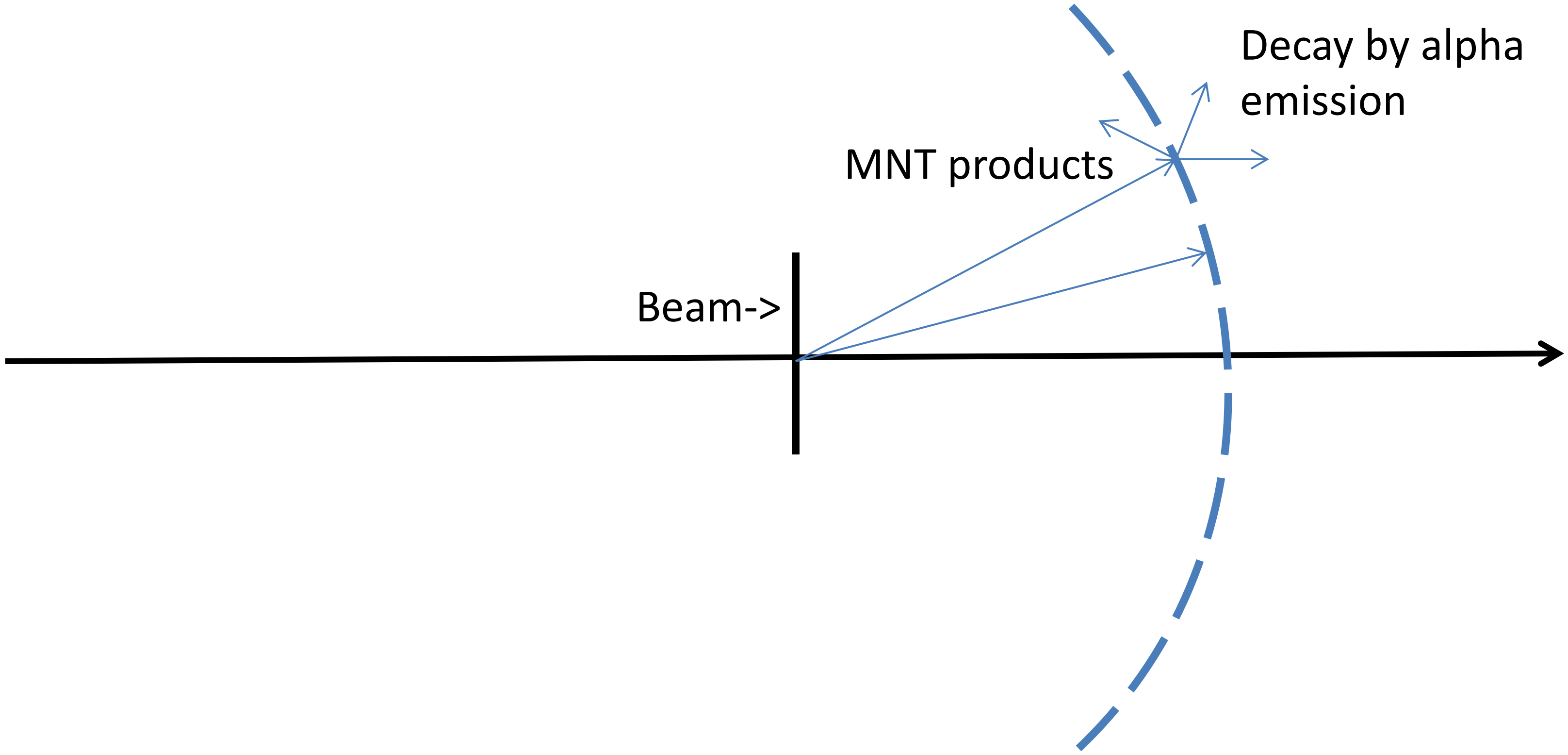

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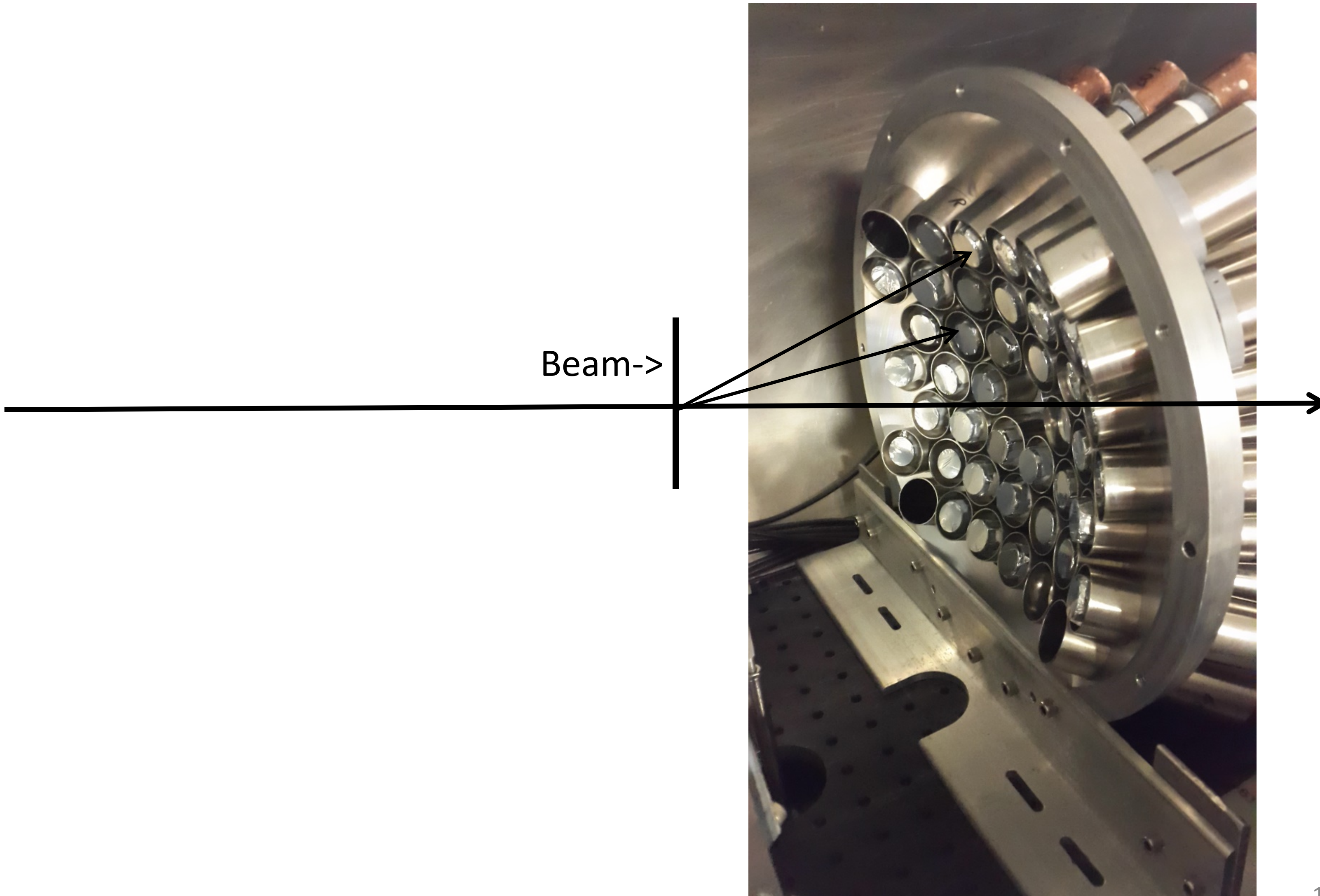
J. Natowitz Group - Active Catcher at Texas A&M



S. Wuenschel, et al. Phys. Rev. C **97**, 064602 (2018)

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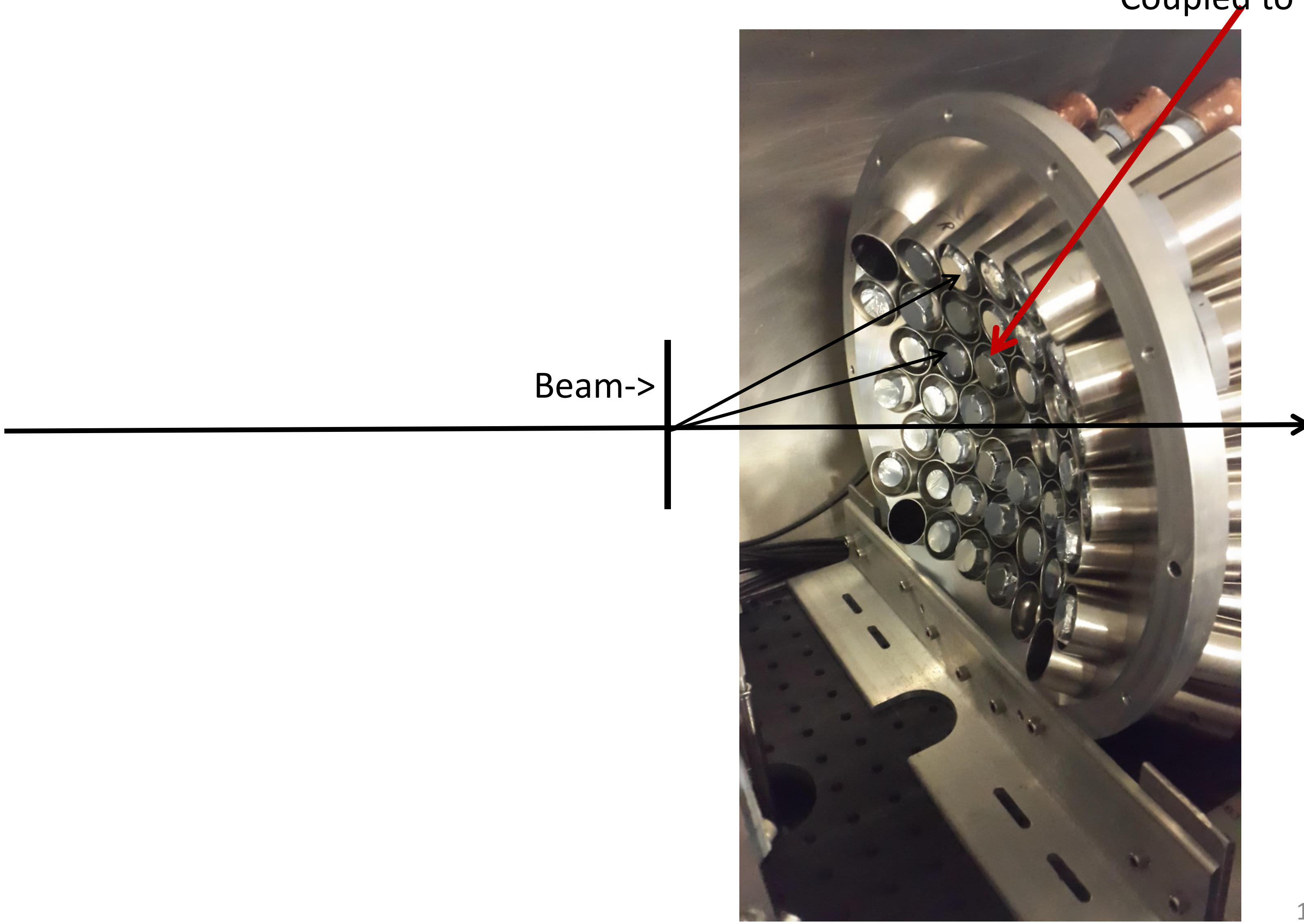

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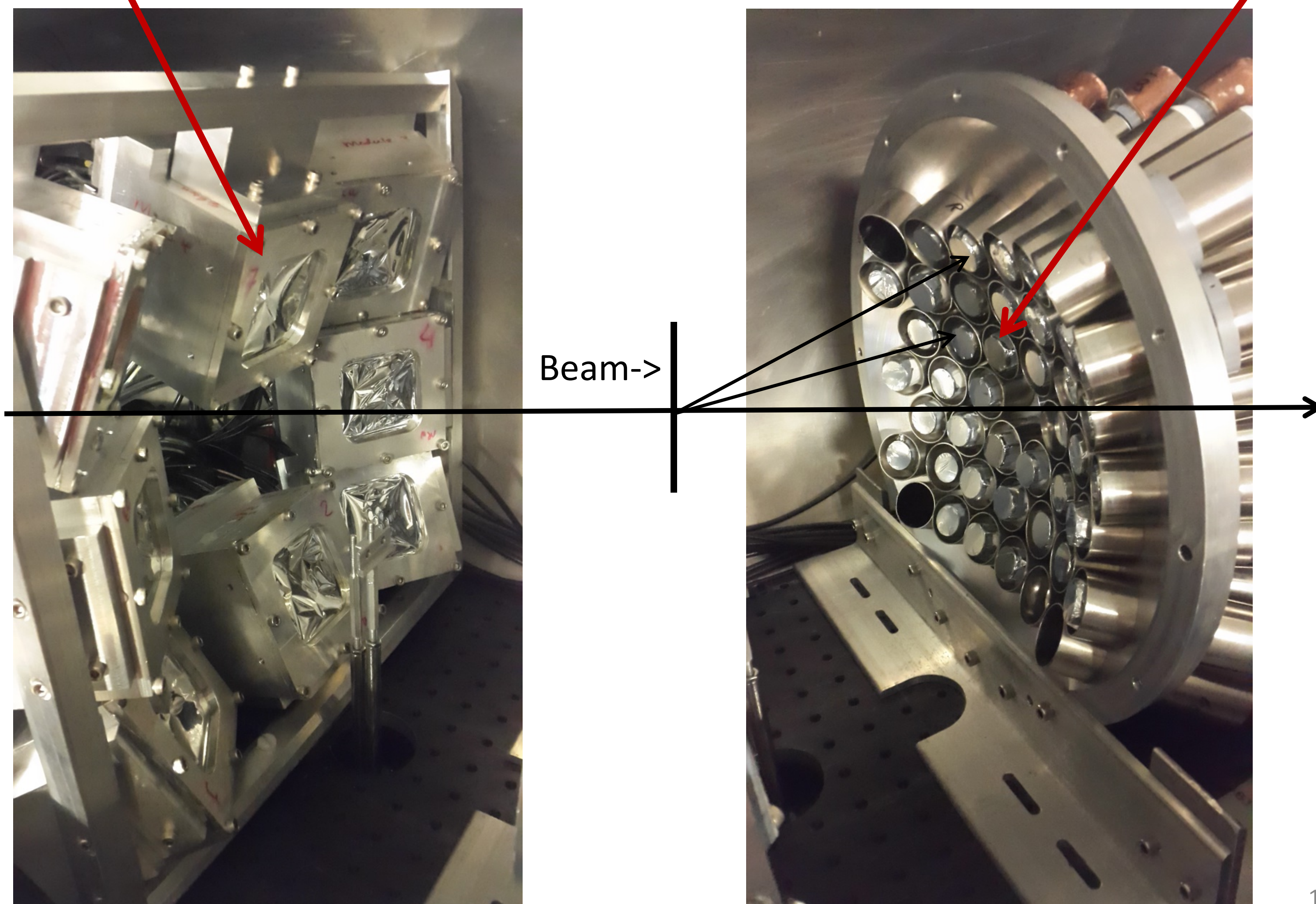
Backward angle:
8x IC + Si

40x YAP ($YAlO_3$)
Scintillators
Coupled to PMTs



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$^{238}U+^{232}Th$ Measurement with Active Catcher at TAMU

- 7.5 MeV/u ^{238}U beam, ^{232}Th 10 mg/cm2 target,
- Forward angle YAP scintillators (coverage from ~7^o to ~60^o, 22% geometric efficiency), radiation hard; provide pulse shape discrimination->Distinguish implants from subsequent alpha decay. Alpha detection efficiency >50% during beam 'OFF'
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Tested beam on/off combinations of 30/30 ms and 100/30ms.

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Acquisition system: Struck 3316 Digitizers @ 250 MHz -> important for fast decays.

K. H. Schmidt, et al. Z. Phys A **316**, 19 (1984)

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Extracted predicted decay time from universal function of KH Schmidt, for alpha particles in 400 keV energy bins.**-> Indicative of decay times of nuclei whose yields are dominant in the sampled energy range.**

Partial half-lives extracted using Viola-Seaborg systematics & fits to known isotopes.

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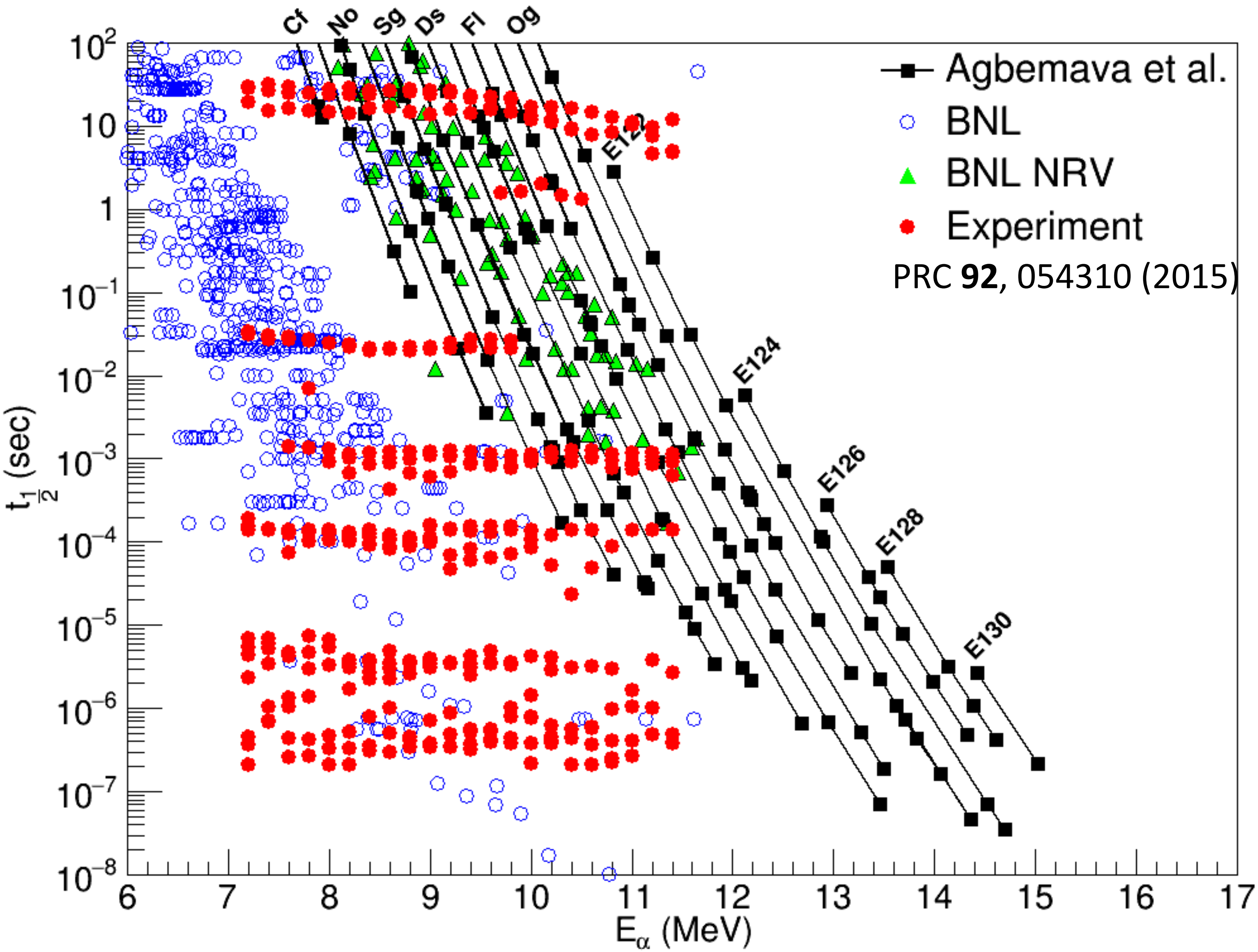
$^{238}U+^{232}Th$ – Geiger Nuttall Plot

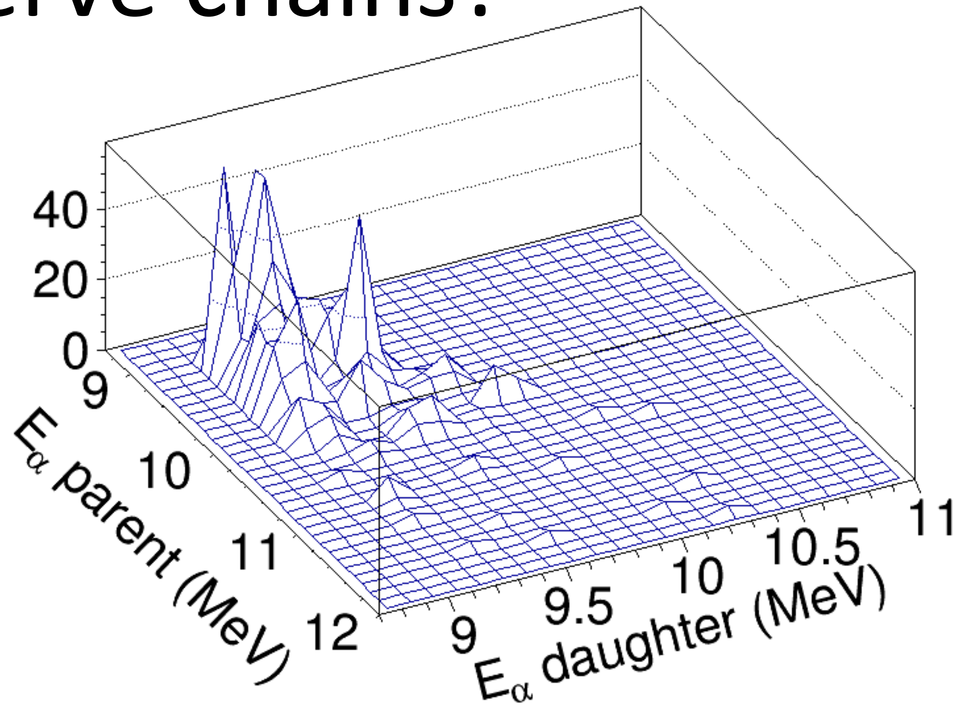


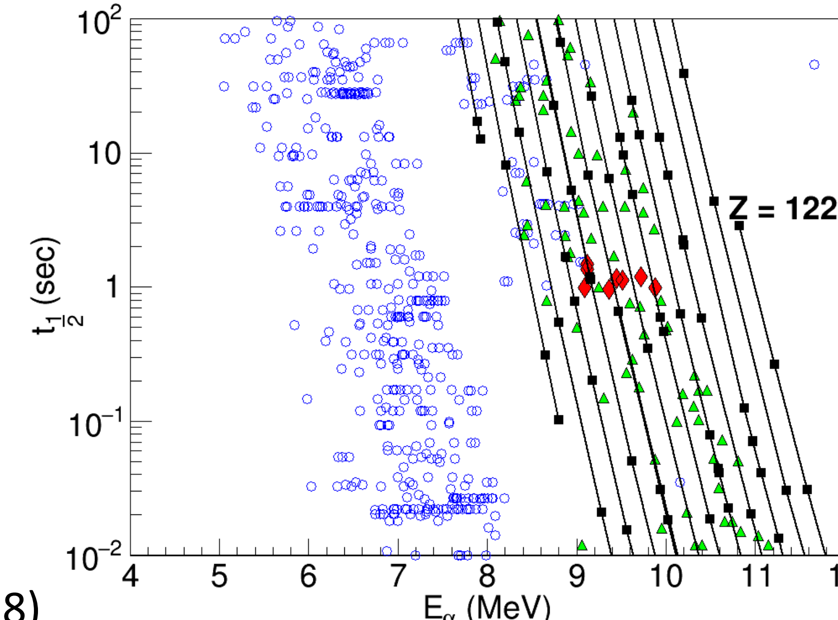
S. Wuenschel, et al. Phys. Rev. C **97**, 064602 (2018)

Can we observe chains?

- Correlation methods analogous to those used in gamma-decay spectroscopy + peak searching software package in ROOT

- Some evidence of daughters in the range of Z=106-114.





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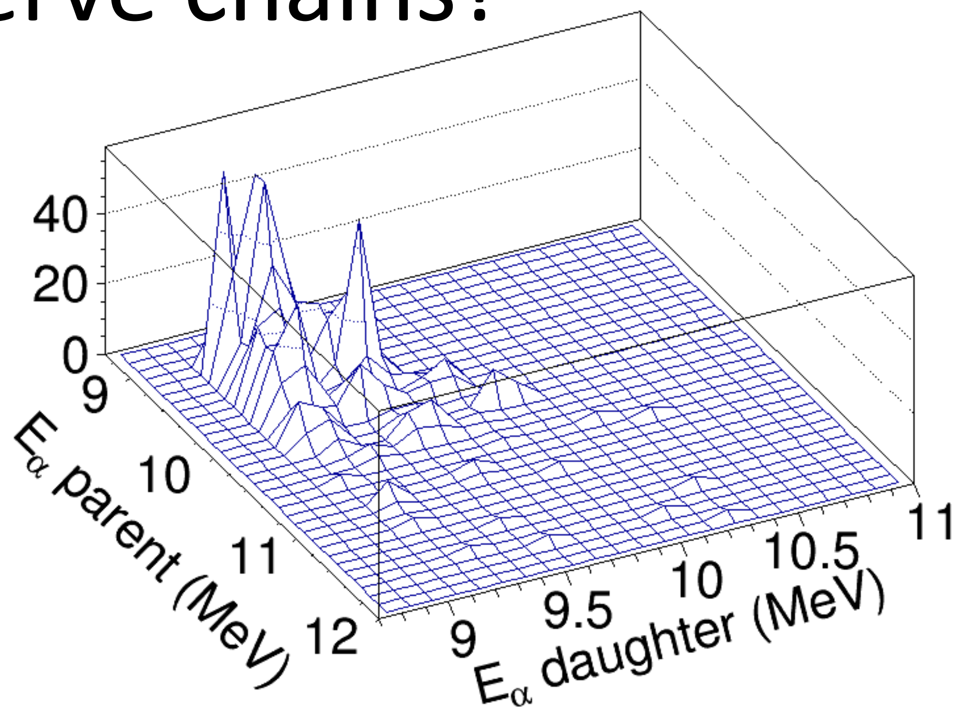
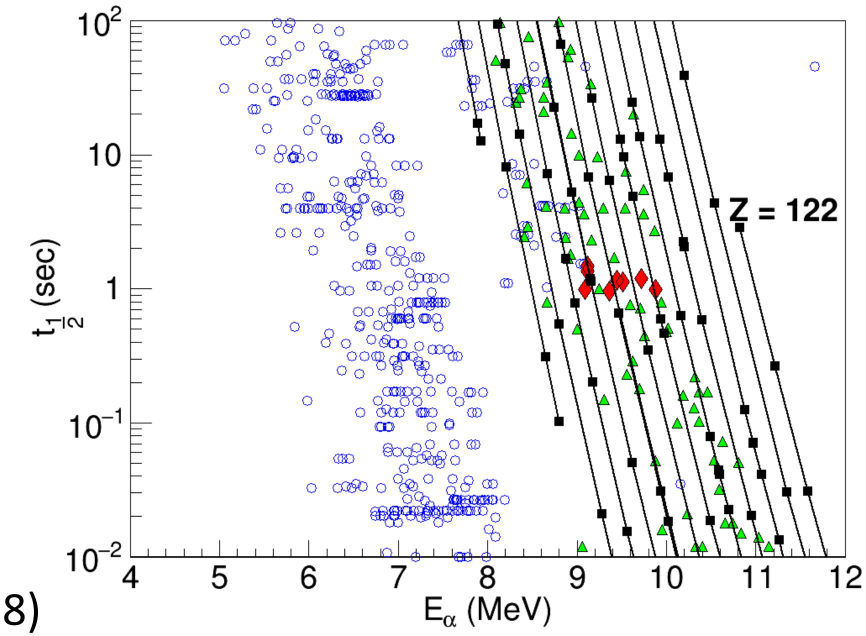
- Difficult because of:

- Large number of products from reaction "hostile landscape".

- Products in uncharted region

- New detector system-> needs benchmarking.





S. Wuenschel, et al. Phys. Rev. C **97**, 064602 (2018)

Benchmarking the Active Catcher

- **^{22}Ne + ^{232}Th:** -> Measurement completed June 2018

Suggested by Walter Loveland;

based on H. Kumpf and E. D. Donets, Soviet Physics Jetp. 17, 3 (1963)

- **^{208}Pb + ^{nat}Pb** -> Scheduled for 6th November 2018

^{22}Ne+^{232}Th Active Catcher Measurement

- **6.5 MeV/u ^{22}Ne + ^{232}Th target:** measure the production of ^{227}Th, ^{226}Ac, ^{225}Ac and ^{224}Ac All decay by either alpha, beta, or K-capture. Half lives from hours to days.
- End in decay of a Polonium isotopes, intermediate products have millisecond to microsecond half-lives

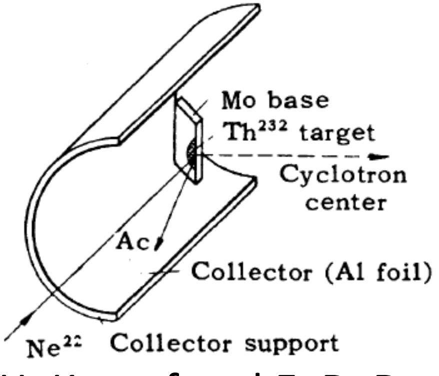


FIG. 3. Device for measurement of the angular distribution of recoil nuclei (in the angular range 180 to 40°).

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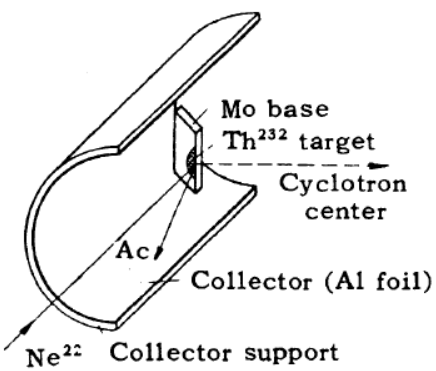
- Reaction products were implanted in the forward angle YAP Active Catcher; alpha counting in a backward angle Si+IC array.
- Offline counting for 21 days post beam.

Radioactive family	4n+3	4n+2	4n+1		4n	
Observed parent nucleus	Th^{227}	Ac^{226}	Ac^{225}	Ra^{225}	Ac^{224}	Ra^{224}
Periods determining the nucleus decay	18d, 11d	28 h	10d	14d, 10d	3 h 3.6d	3.6d
Energy of observed α line, MeV	7.35	7.68	8.35	8.35	8.78	8.78
Nucleons emitted from Th^{232}	5n	p5n	p6n	2p5n	p7n	2p6n, 4nα
Q-value estimate, MeV	—6	+3	+2	+15	—3	+18
Cross section σ at 143 MeV, 10^{-28} cm²	10	6.6	5.5	<1.5	5.3	<2



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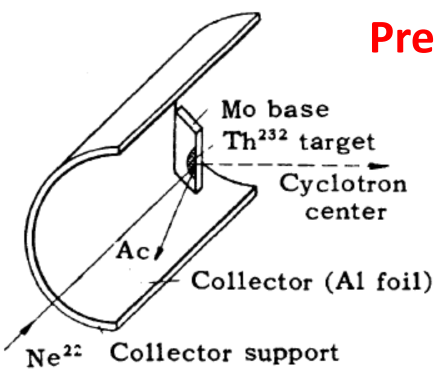
Preliminary Cross sections from AC:	>7.6	<8.7	5.5*	1.8	6.2	2.1



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$^{208}Pb+^{nat}Pb$ Measurement

- **10Mev/u ^{208}Pb beam + ^{nat}Pb target (PbS)**
- From Two Centre Shell Model based Adiabatic Potential Energy Surface Calculations (V. Zagrebaev, Y. Aritomo, W. Greiner):

Most extreme Multi-nucleon transfer products with ΔZ~10 and ΔA ~20

Higher cross sections for ΔZ~4 and ΔA ~8

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Higher cross sections for ΔZ~4 and ΔA ~8

- Decay by alpha emission with alpha energies between 7MeV and 10MeV
- Half-lives ranging from ~1s down to a few 100ns.
- 5 clean alpha chains – distinct alpha Energy and half-life
- Can we Identify alpha chains against known alpha chains in this region of the nuclear chart? Establish parent-daughter relationships?

$^{208}Pb+^{nat}Pb$ Measurement- Candidate alpha chains

Z	126	127	128	129	130	131	132	133	N
	212Rn 23.9 M α: 100.00% 6385	213Rn 19.5 MS α: 100.00% 8243	214Rn 0.27 μS α: 100.00% 9208	215Rn 2.30 μS α: 100.00% 8839	216Rn 45 μS α: 100.00% 8197	217Rn 0.54 MS α: 100.00% 7887	218Rn 35 MS α: 100.00% 7262.5	219Rn 3.96 S α: 100.00% 6946.1	220Rn 55.6 S α: 100.00% 6404.66
85	211At 7.214 H ε: 58.20% α: 41.80% 5982.4	212At 0.314 S α: 100.00% ε < 0.03% 7817.0	213At 125 NS α: 100.00% 9254	214At 558 NS α: 100.00% 8987	215At 0.10 MS α: 100.00% 8178	216At 0.30 MS α: 100.00% β- < 6.0E-3% 7950	217At 32.3 MS α: 99.99% β-: 7.0E-3% 7201.3	218At 1.5 S α: 99.90% β-: 0.10% 6874	219At 56 S α: 93.60% β-: 6.40% 6324
84	210Po 138.376 D α: 100.00% 5407.45	211Po 0.516 S α: 100.00% 7594.5	212Po 0.299 μS α: 100.00% 8954.12	213Po 3.72 μS α: 100.00% 8536	214Po 163.6 μS α: 100.00% 7833.46	215Po 1.781 MS α: 100.00% β-: 2.3E-4% 7526.3	216Po 0.145 S α: 100.00% 6906.3	217Po 1.53 S α 6662.1	218Po 3.098 M α: 99.98% β-: 0.02% 6114.68
83	209Bi STABLE 100% 3137.3	210Bi 5.012 D β-: 100.00% α: 1.3E-4% 5036.5	211Bi 2.14 M α: 99.72% β-: 0.28% 6750.3	212Bi 60.55 M β-: 64.06% α: 35.94% 6207.26	213Bi 45.61 M β-: 97.80% α: 2.20% 5982	214Bi 19.9 M β-: 99.98% α: 0.02% 5621	215Bi 7.6 M β-: 100.00% 5.30E+3	216Bi 2.25 M β-≤ 100.00% 5.00E+3	217Bi 98.5 S β-: 100.00% 4.52E+3
82	208Pb STABLE 52.4% 517.2	209Pb 3.234 H β-: 100.00% 2248	210Pb 22.20 Y β-: 100.00% α: 1.9E-6% 3792	211Pb 36.1 M β-: 100.00% 3.57E+3	212Pb 10.64 H β-: 100.00% 3.29E+3	213Pb 10.2 M β-: 100.00% 3.02E+3	214Pb 27.06 M β-: 100.00% 2.76E+3	215Pb 147 S β-: 100.00% 2.62E+3	216Pb >300 NS β-: 100.00% 2.3E+3

$^{208}Pb+^{nat}Pb$ Measurement- Candidate alpha chains

4p 3,4,5,6n

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4p 3,4,5,6n

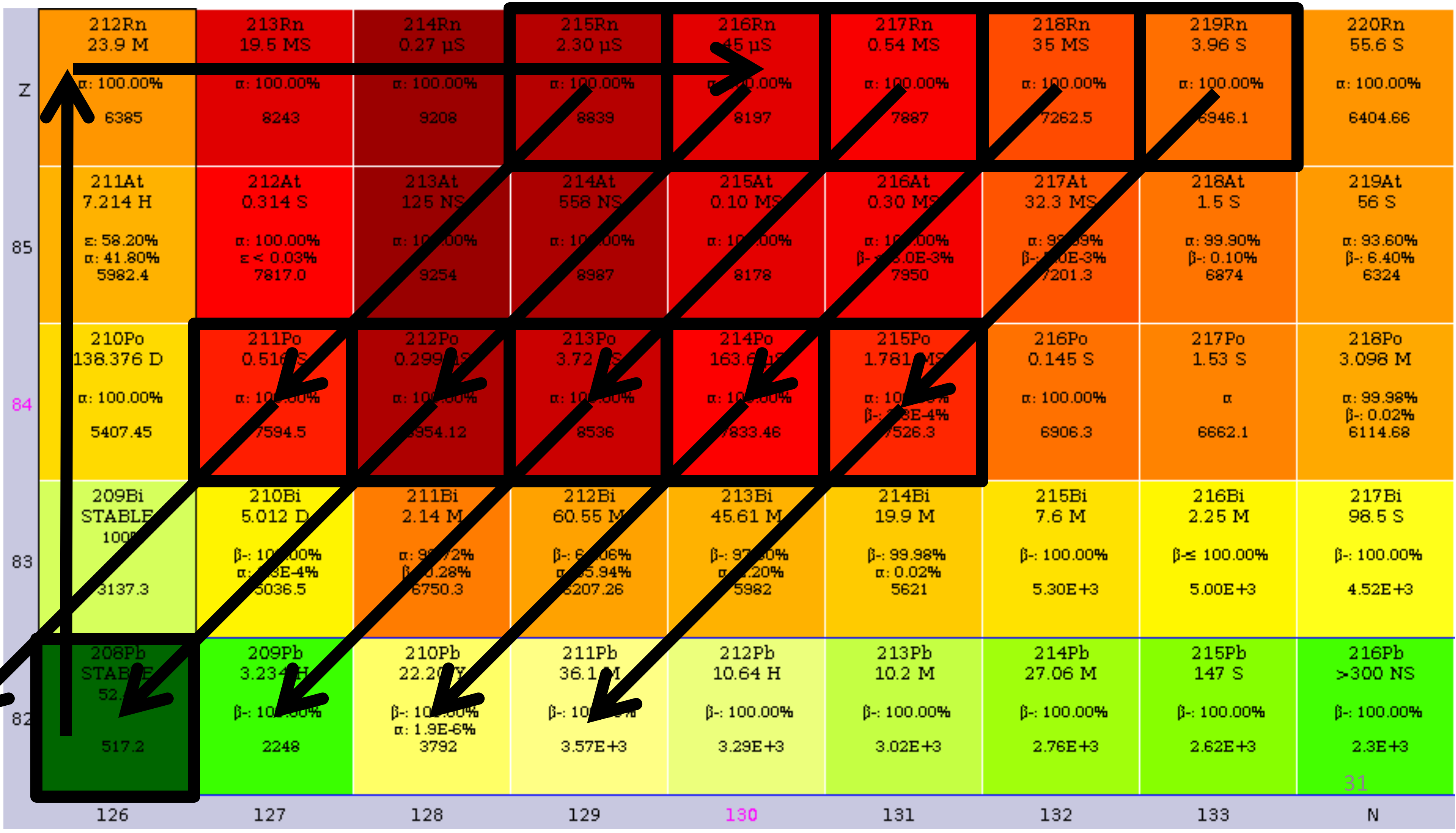
Z	212Rn 23.9 M α: 100.00% 6385	213Rn 19.5 MS α: 100.00% 8243	214Rn 0.27 µS α: 100.00% 9208	215Rn 2.30 µS α: 100.00% 8839	216Rn 45 µS α: 100.00% 8197	217Rn 0.54 MS α: 100.00% 7887	218Rn 35 MS α: 100.00% 7262.5	219Rn 3.96 S α: 100.00% 6946.1	220Rn 55.6 S α: 100.00% 6404.66
85	211At 7.214 H ε: 58.20% α: 41.80% 5982.4	212At 0.314 S α: 100.00% ε < 0.03% 7817.0	213At 125 NS α: 100.00% 9254	214At 558 NS α: 100.00% 8987	215At 0.10 MS α: 100.00% 8178	216At 0.30 MS α: 100.00% β- < 6.0E-3% 7950	217At 32.3 MS α: 99.99% β-: 7.0E-3% 7201.3	218At 1.5 S α: 99.90% β-: 0.10% 6874	219At 56 S α: 93.60% β-: 6.40% 6324
84	210Po 138.376 D α: 100.00% 5407.45	211Po 0.516 S α: 100.00% 7594.5	212Po 0.299 µS α: 100.00% 8954.12	213Po 3.72 µS α: 100.00% 8536	214Po 163.6 µS α: 100.00% 7833.46	215Po 1.781 MS α: 100.00% β-: 2.3E-4% 7526.3	216Po 0.145 S α: 100.00% 6906.3	217Po 1.53 S α 6662.1	218Po 3.098 M α: 99.98% β-: 0.02% 6114.68
83	209Bi STABLE 100% 3137.3	210Bi 5.012 D β-: 100.00% α: 1.3E-4% 5036.5	211Bi 2.14 M α: 99.72% β-: 0.28% 6750.3	212Bi 60.55 M β-: 64.06% α: 35.94% 6207.26	213Bi 45.61 M β-: 97.80% α: 2.20% 5982	214Bi 19.9 M β-: 99.98% α: 0.02% 5621	215Bi 7.6 M β-: 100.00% 5.30E+3	216Bi 2.25 M β-≤ 100.00% 5.00E+3	217Bi 98.5 S β-: 100.00% 4.52E+3
82	208Pb STABLE 52.4% 517.2	209Pb 3.234 H β-: 100.00% 2248	210Pb 22.20 Y β-: 100.00% α: 1.9E-6% 3792	211Pb 36.1 M β-: 100.00% 3.57E+3	212Pb 10.64 H β-: 100.00% 3.29E+3	213Pb 10.2 M β-: 100.00% 3.02E+3	214Pb 27.06 M β-: 100.00% 2.76E+3	215Pb 147 S β-: 100.00% 2.62E+3	216Pb >300 NS β-: 100.00% 2.3E+3
	126	127	128	129	130	131	132	133	N

^{208}Pb+^{nat}Pb Measurement- Candidate alpha chains

4p 3,4,5,6n

$^{208}Pb+^{nat}Pb$ Measurement- Candidate alpha chains

4p 3,4,5,6n



$^{208}Pb+^{nat}Pb$

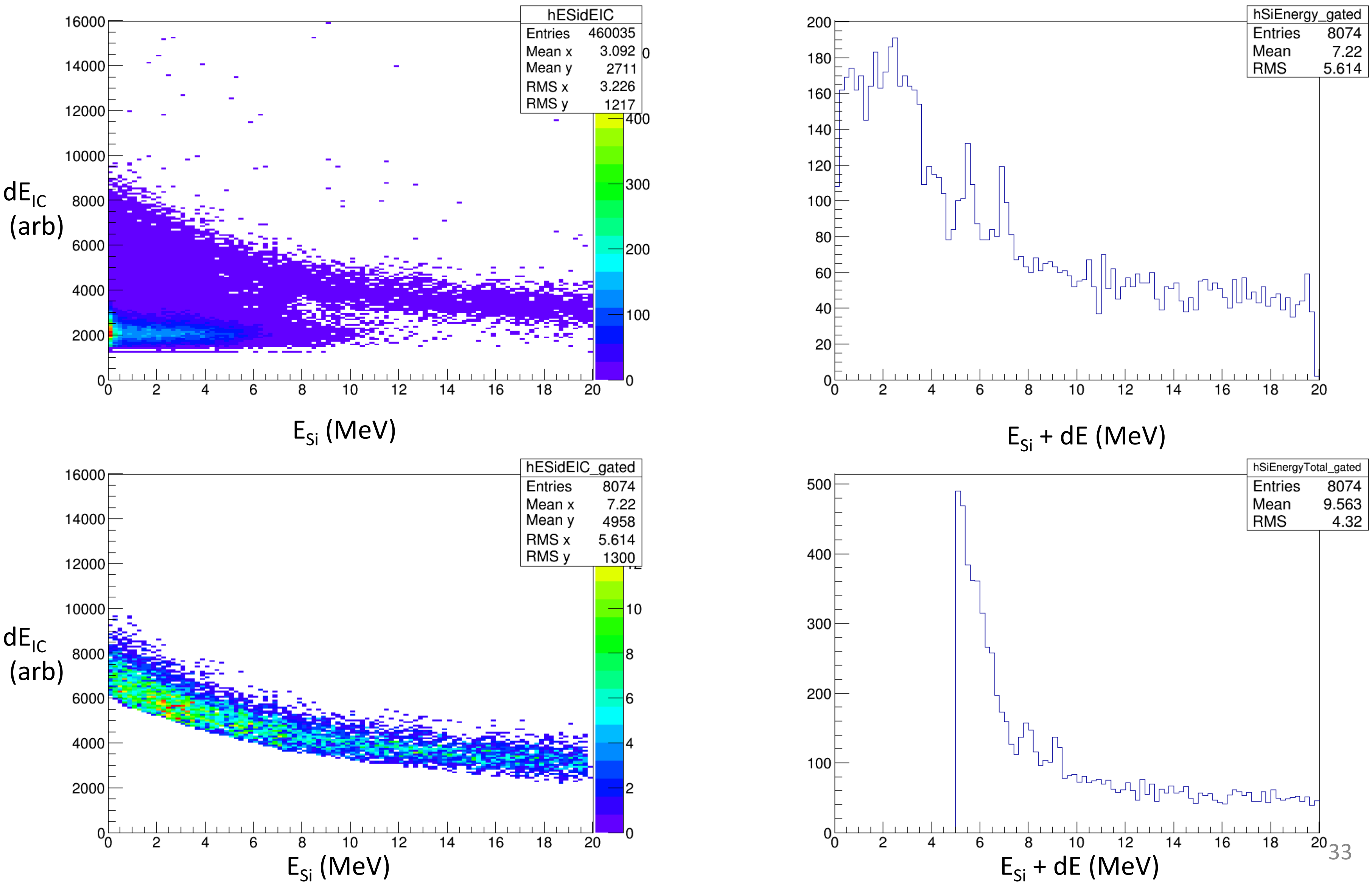
- **10Mev/u ^{208}Pb beam + ^{nat}Pb target (PbS)**
- Most extreme Multi-nucleon transfer products with ΔZ~10 and ΔA ~20 have low cross-section.
- Decay by alpha emission with alpha energies between 7MeV and 10MeV
- half-lives ranging from ~1s down to a few 100ns.
- Can we Identify alpha chains against known alpha chains in this region of the nuclear chart?
- Establish parent-daughter relationships?
- 'Cleaner' region alpha active products, compared to reactions with U, Th targets

Side note on Pb targets – Thanks to John Greene

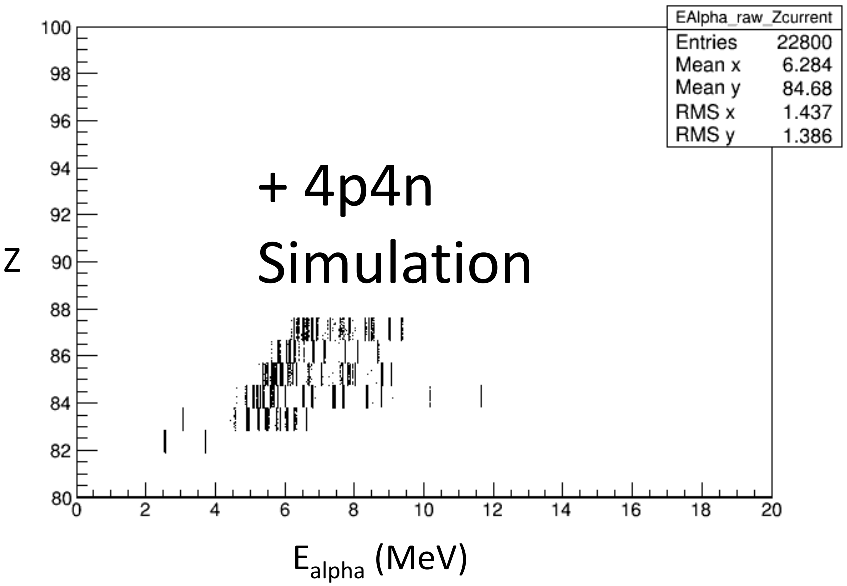
- Currently have PbS targets of thickness 2mg/cm^2. Ideally 5mg/cm^2
- Limitation is melting point of Pb (328^{o}C) vs. PbS (1114^{o}C)
- PbS is difficult to work with in thick configurations. Amorphous; thick foils crack during evaporation.

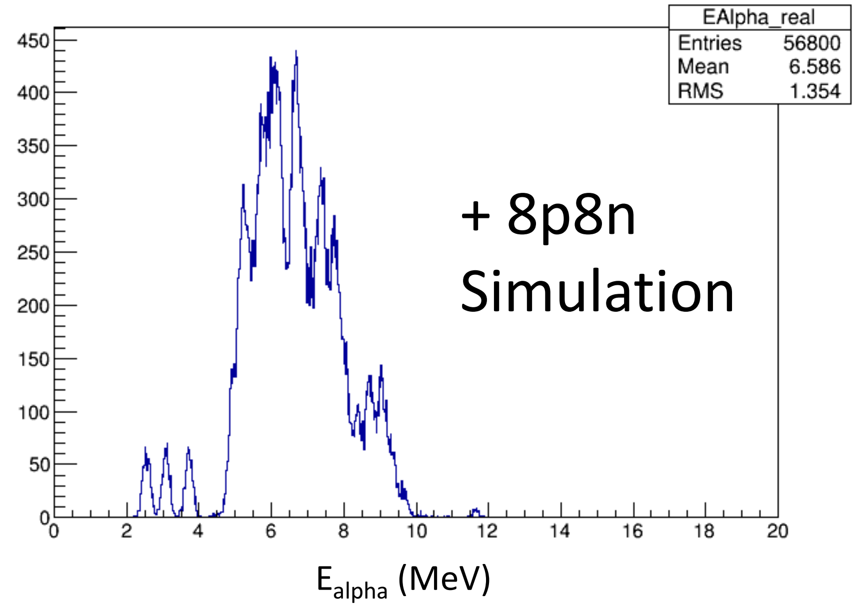
- Preliminary measurement on 15th of July 2018, with ^{197}Au beam and PbS targets.

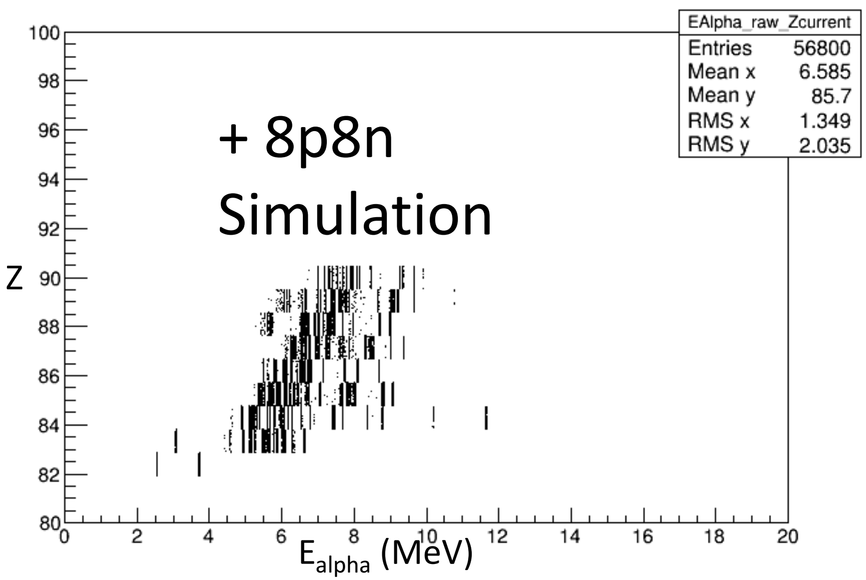
Test run with ^{197}Au beam on ^{nat}Pb target



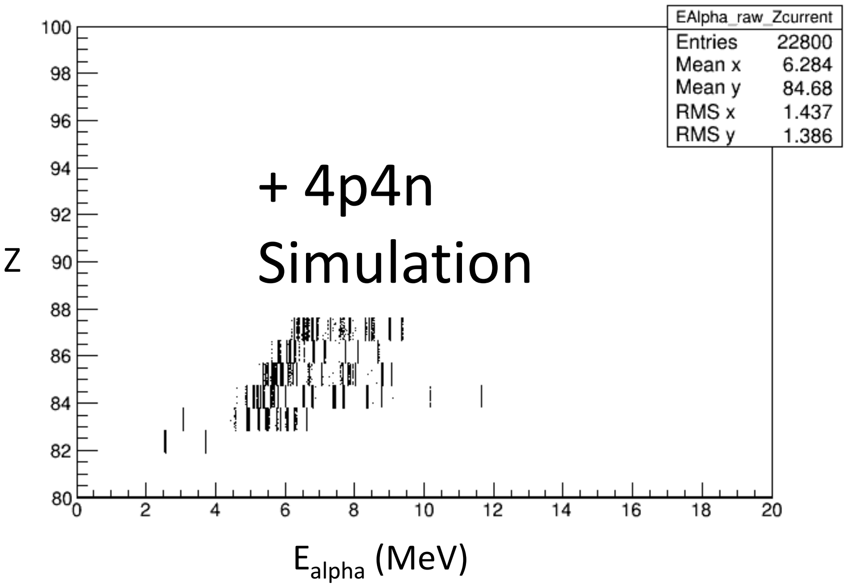
Test run with ^{197}Au beam on ^{nat}Pb target

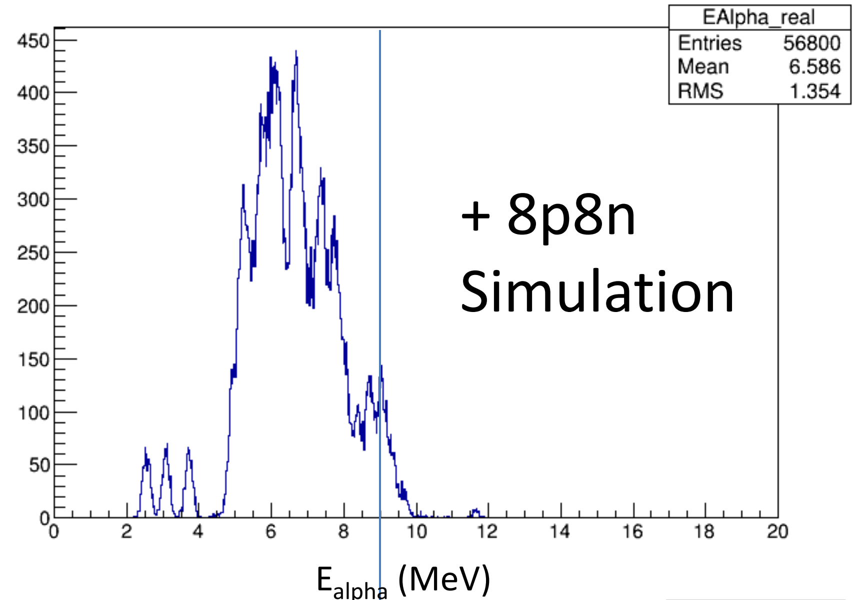


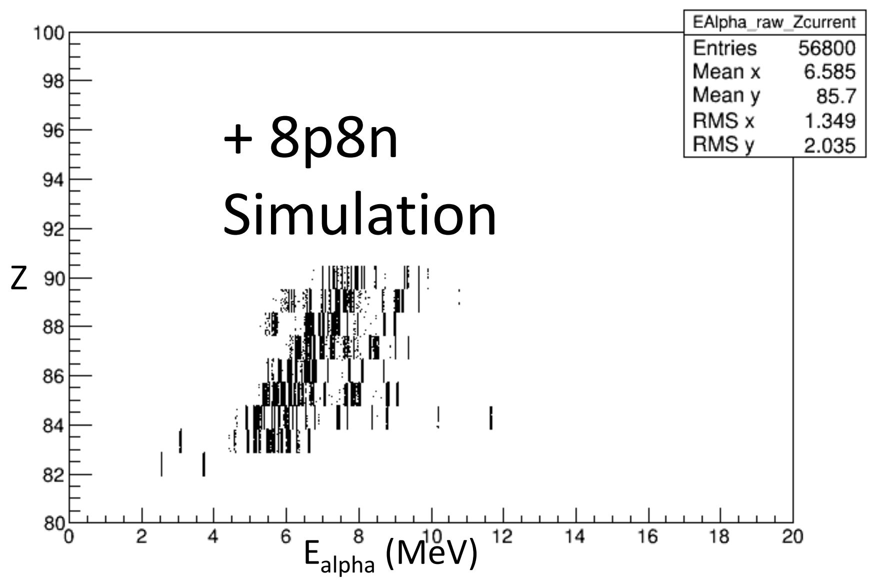


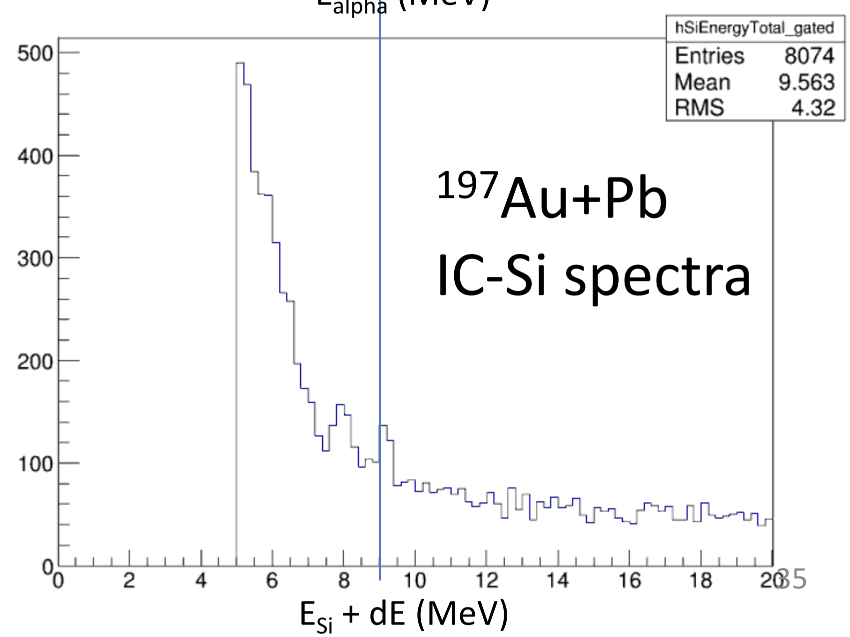


Test run with ^{197}Au beam on ^{nat}Pb target









Summary

- Multinucleon transfer reaction products implanted in forward angle scintillators
- Additionally used IC-Si to observe alpha decays of
- Using lifetime and energies and comparing to model calculations, signatures of Z<120 are observed in 238U + 232th measurement.
- Alpha Decay Chains difficult to observe because of large number of products and detector resolution.

- Current efforts focused on benchmarking AC, and identifying decay chains in known region of Segre chart.
- **^{208}Pb + ^{nat}Pb** -> Scheduled for 6th November 2018

- Ongoing program to incorporate diamond and SiC detectors -> improved granularity and resolution compared to scintillators, radiation hard.

Research team

- Initial R&D, ^{238}U+ ^{232}Th measurement & publication by J. B Natowitz's group: S. Wuenschel, **J. B. Natowitz, M. Barbui, J. Gauthier, K. Hagel**, X. G. Cao, **R. Wada**, E. J. Kim, Z. Majka, Z. Sosin, A. Weiloch, S. Kowalski, K. Schmidt,K. Zelga, C. Ma, G. Zhang

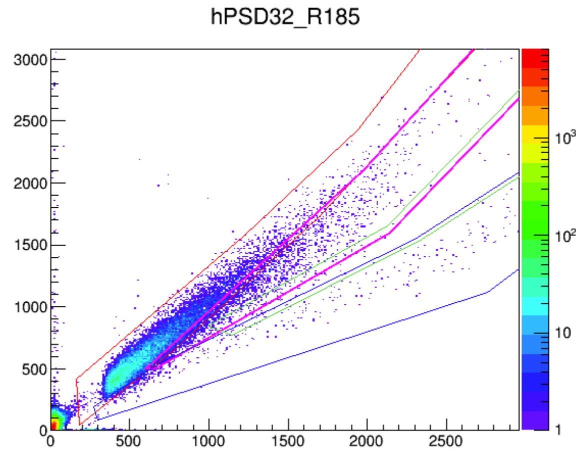
- Current work by S. J Yennello's group : A. Wakhle, A. B. McIntosh, K. Hagel, J. Gauthier, A. R. Manso, A. Jedele, A. Zarella, M. Youngs, I. Jeanis, B. M. Harvey, E. Salas, P. Hopkins, and S. J. Yennello.

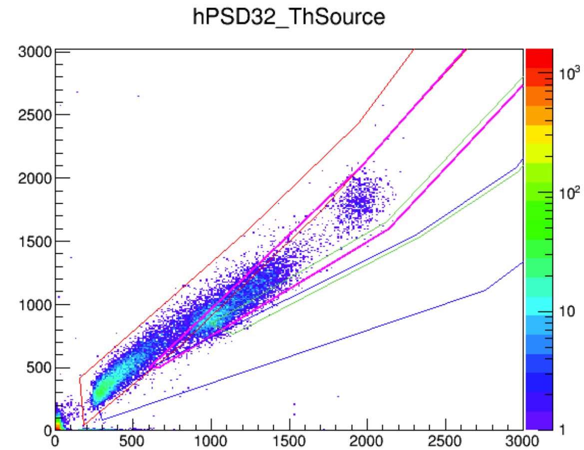
- Ongoing discussions with J. B. Natowitz and W. Loveland.

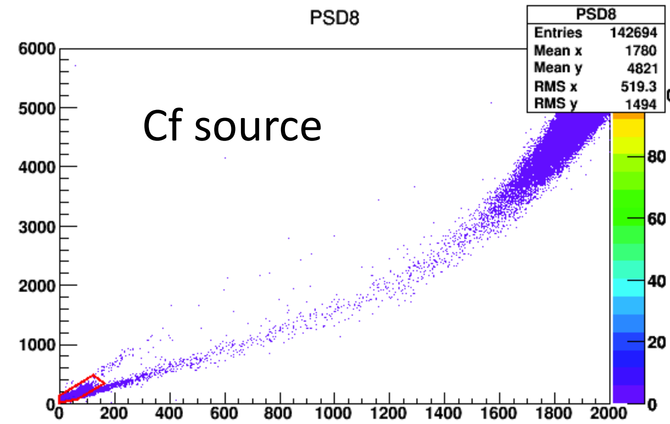
- PbS targets from J. Greene at Argonne National Laboratory.

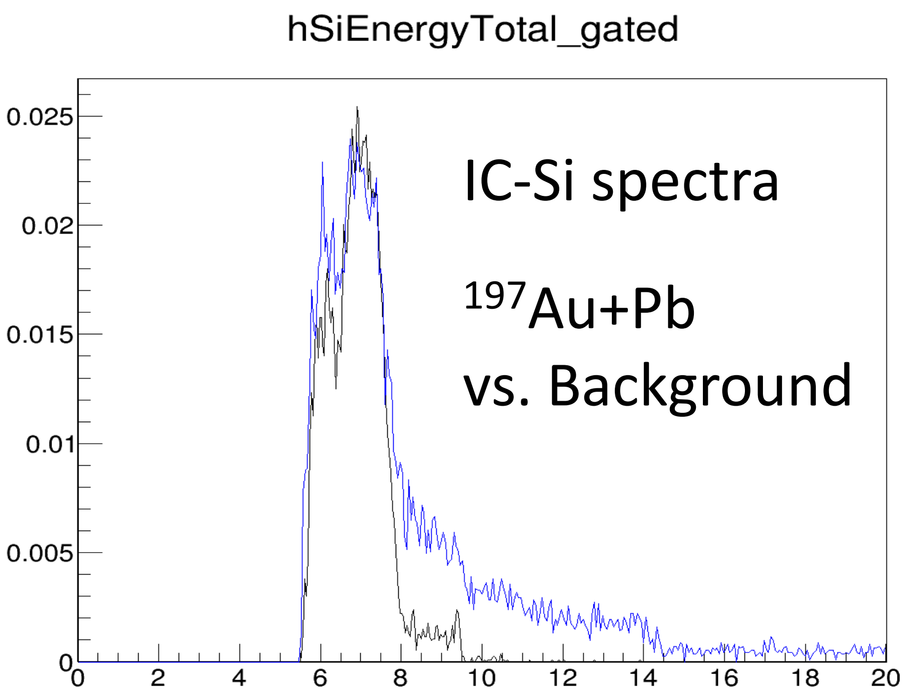
Extra Slides

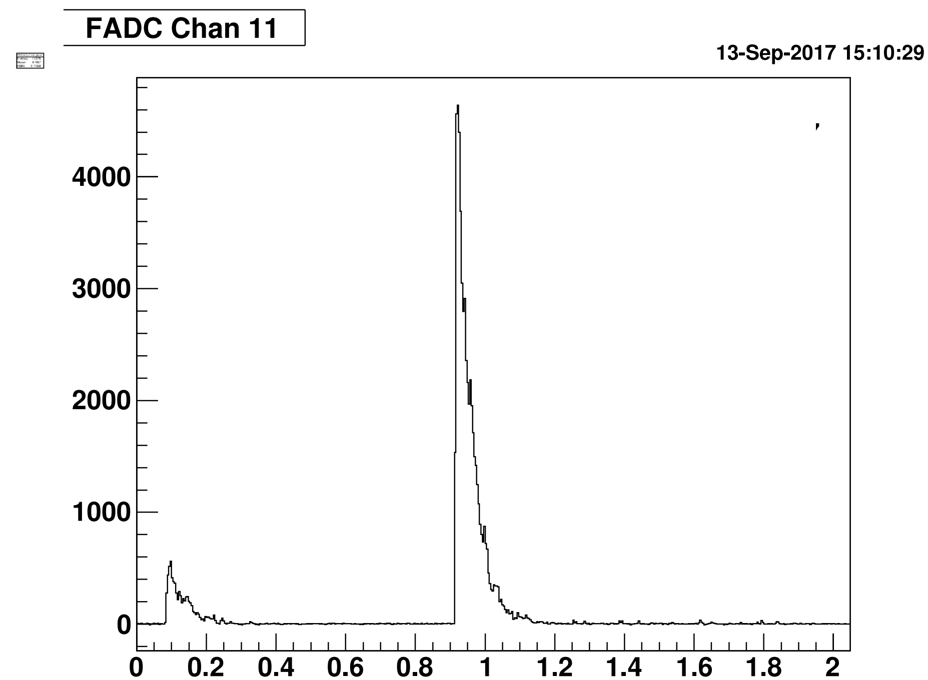
Detector Performance



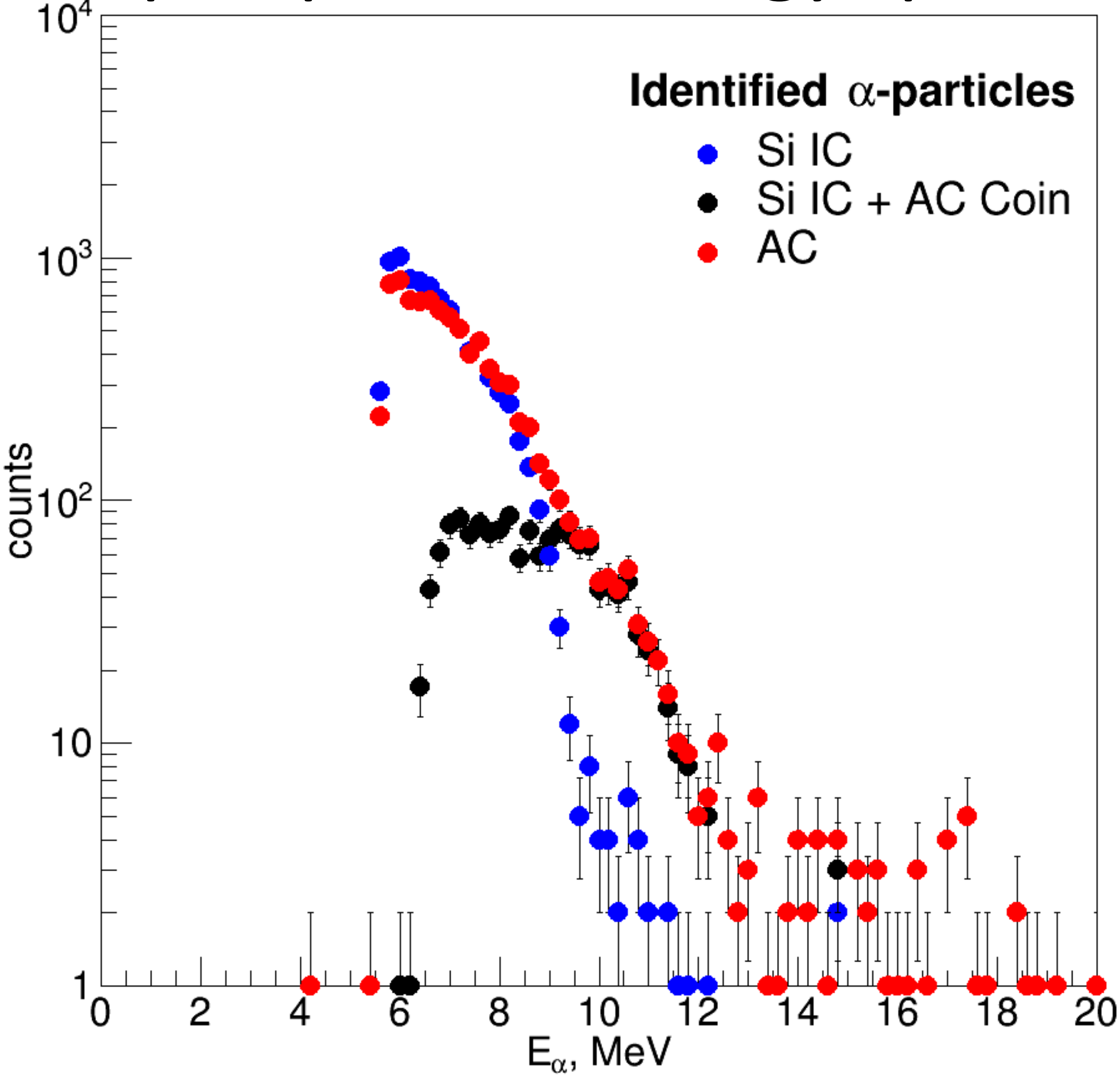






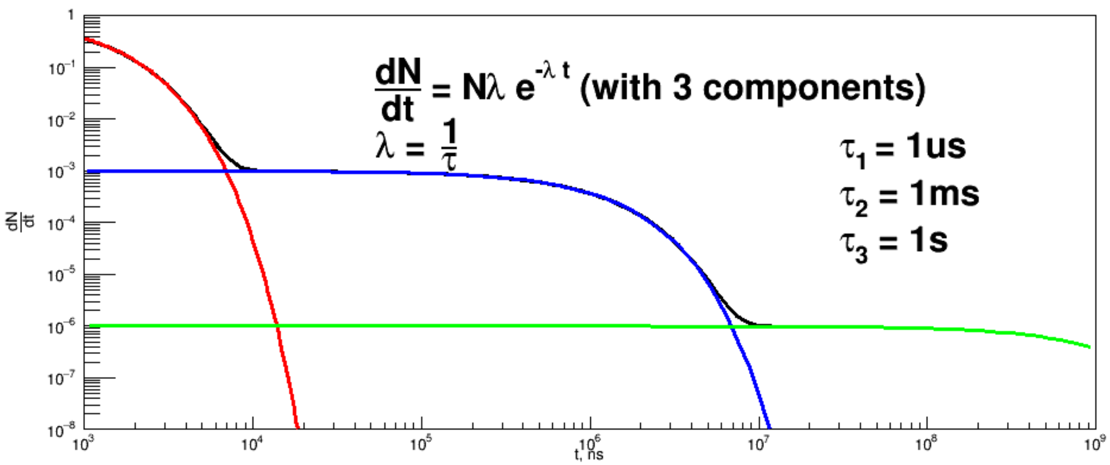


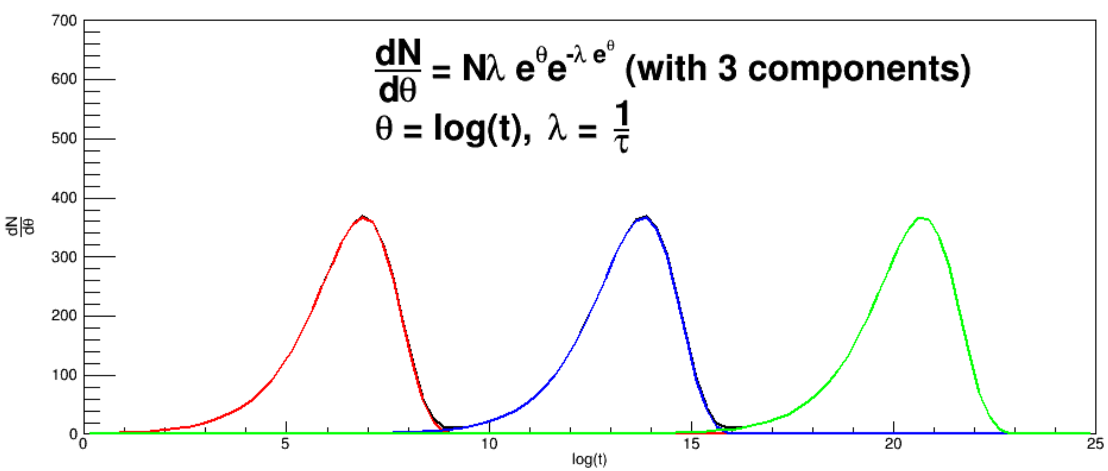
Alpha particle Energy spectra



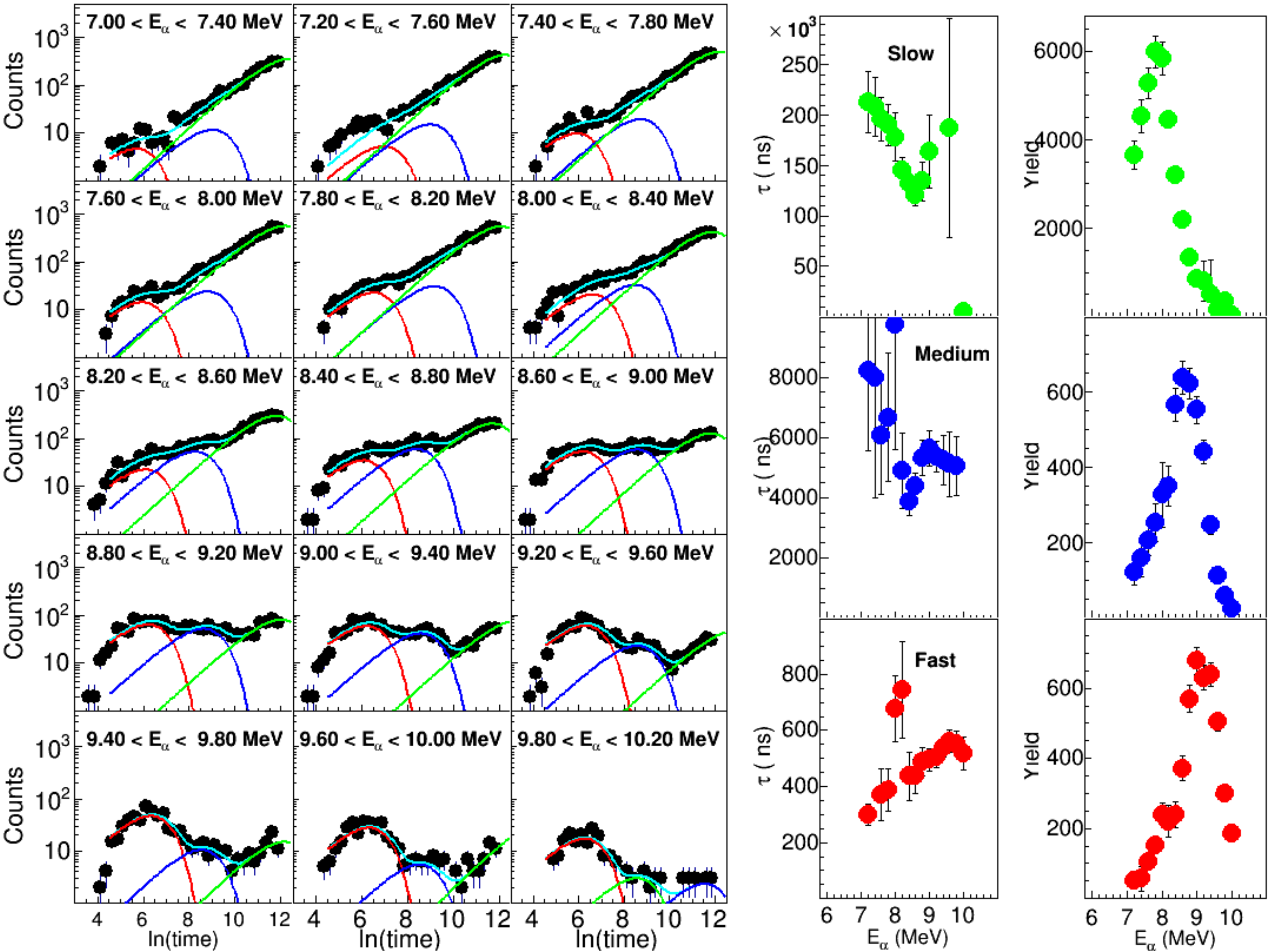
Fitting

- Fit decay curves in order to learn about lifetimes
- There can be a span of times over orders of magnitude (ns to s) leading to numeric problems in fitting.
- Introduce θ=log(t) and transform equation. (Z. Phys. A **316**, 19 (1984))
- Peaks of dN/dθ give mean time directly

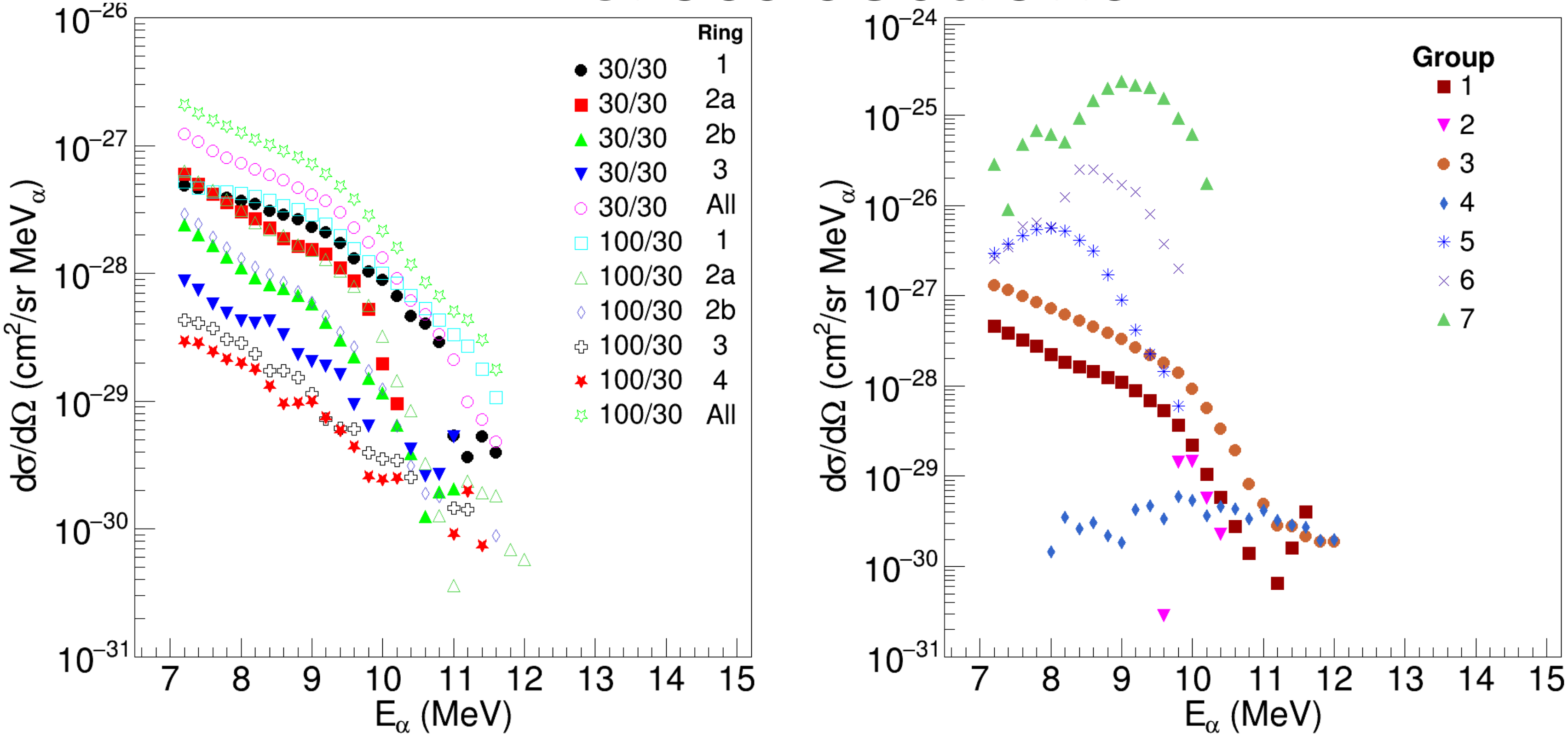




Lifetime Fitting



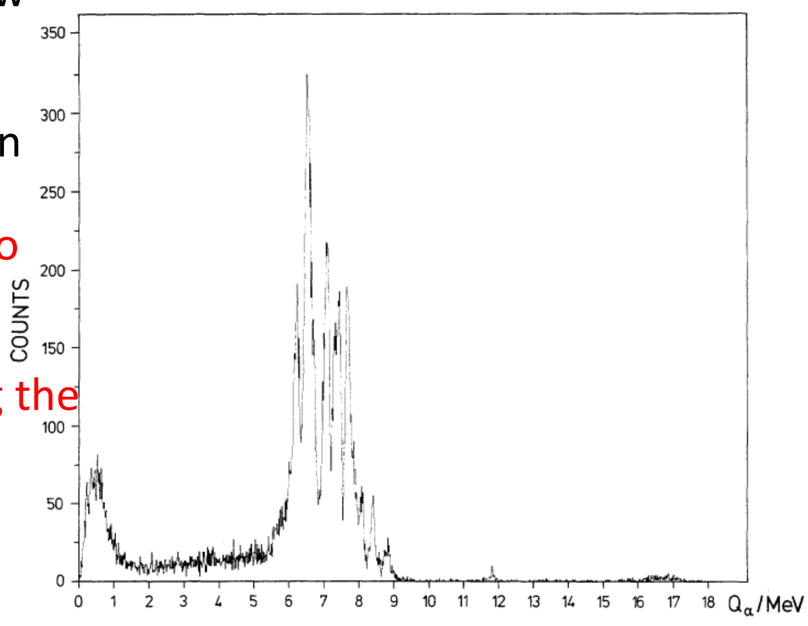
Cross sections

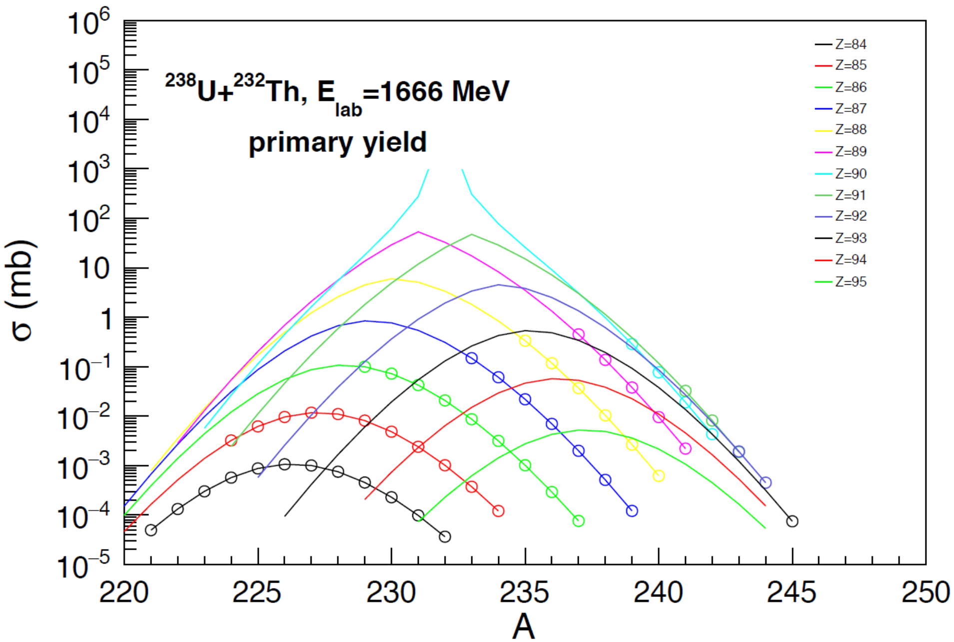


- Average cross sections derived assuming that entire energy range from incident energy to Coulomb barrier is contributing.
- More than one isotope in general contributes to energy windows.
- Decrease in cross section with increasing alpha energy is consistent with increase of alpha energy with increasing Z.
- Qualitatively consistent with trends predicted by multi-nucleon transfer models.

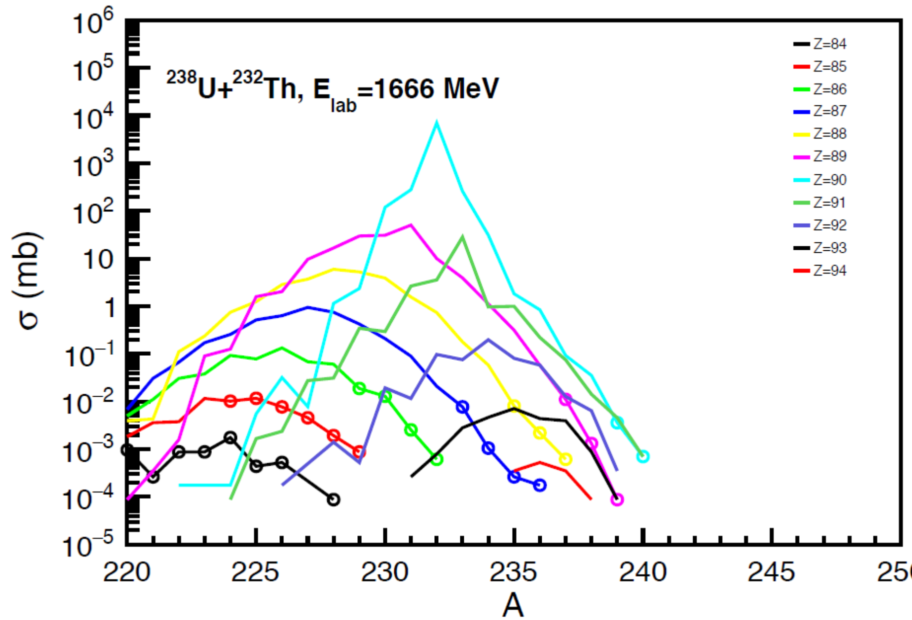
Why not observed before?

- Experiments ^{238}U with ^{238}U in the late 1970s
  - In beam detection and radiochemical studies
  - Time delay inherent in radiochemical and gas jet techniques
- Rotating wheel collection experiment
  - Only spontaneous fission activities were searched for
  - Implanation depths of products
- Freiseleben et al. (Z. Phys. A 292,171 (1979))
  - In beam experiment
  - Thin target, so reaction energy was a very narrow window near 7.42 MeV/u
  - A few high energy signals were observed, but discounted because of inadequate discrimination against pile up events.
  - Present experiment measures from 7.5 MeV/u to around 6 MeV/u because of thicker target
  - Present experiment employed Flash ADCs which allowed for about 16ns time resolution reducing the possibility of pileup.
  - Recording of individual detector signal traces allowed inspection of individual detector signals





$^{238}U+^{232}Th$, E_{lab}=1666 MeV
primary yield
σ (mb)
A
Z=84
Z=85
Z=86
Z=87
Z=88
Z=89
Z=90
Z=91
Z=92
Z=93
Z=94
Z=95



$^{238}U+^{232}Th$, E_{lab}=1666 MeV
σ (mb)
A
Z=84
Z=85
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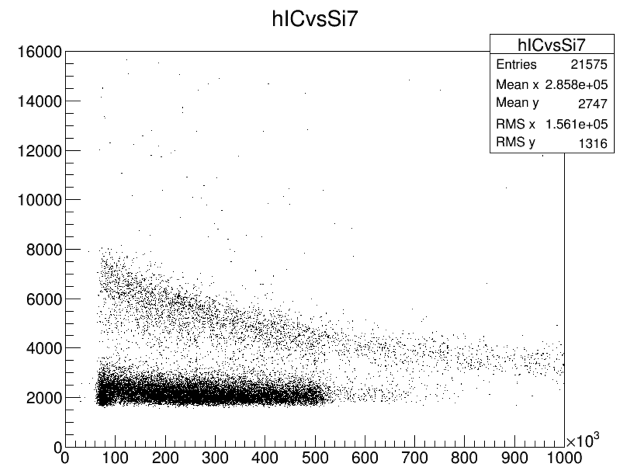
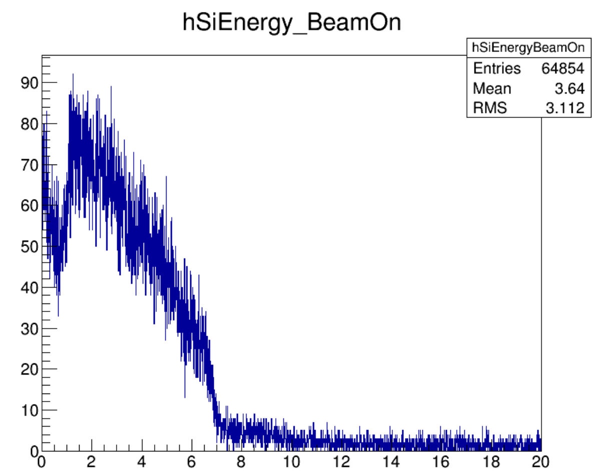
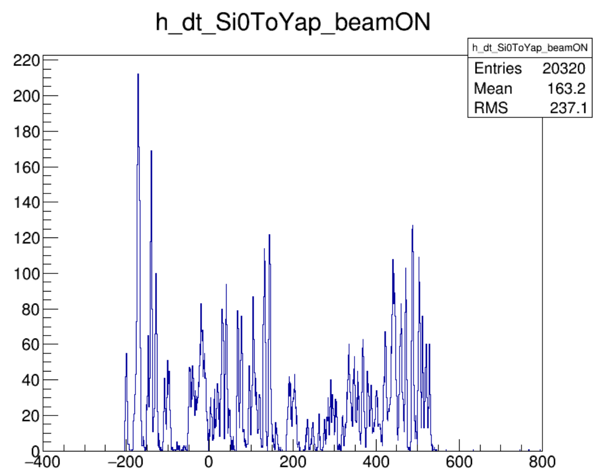
Z=87
Z=88
Z=89
Z=90
Z=91
Z=92
Z=93
Z=94

Detector performance

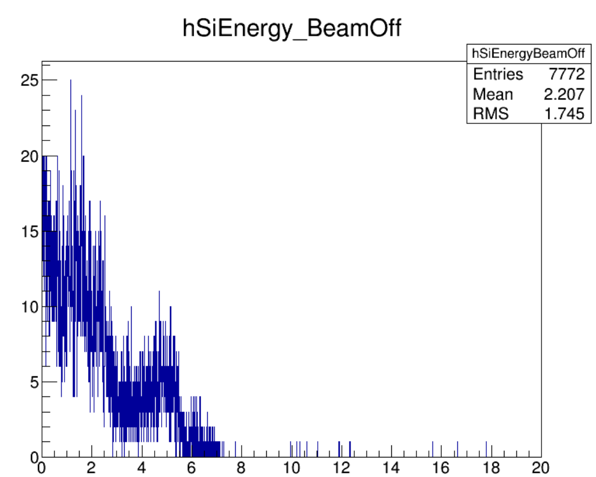


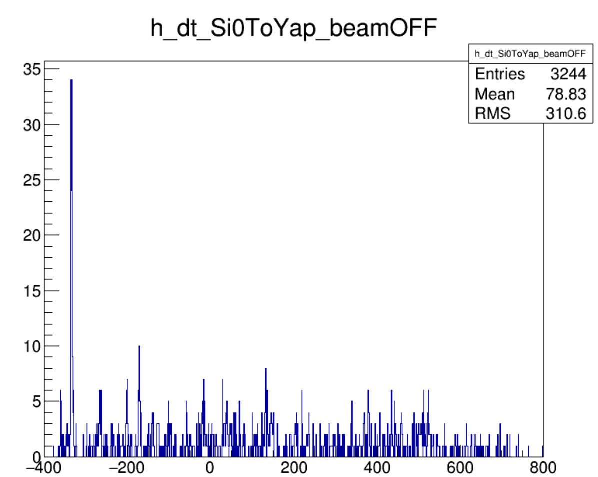




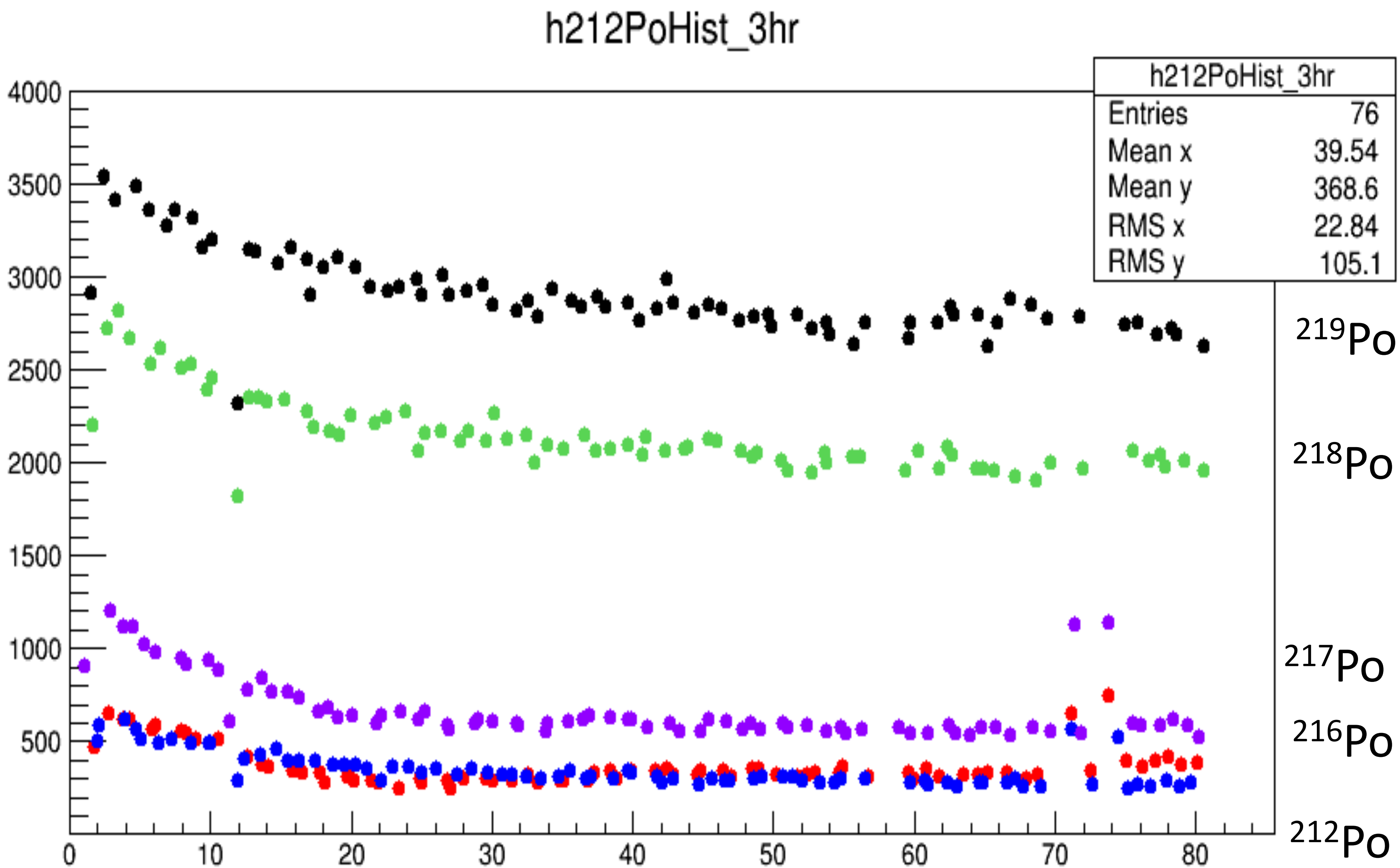
Next:

- Gate out elastics w. time diff.
- Alpha energy selection,
- Angular distributions,
- Look for 2+ alphas from one decayer.
- Look for long lived products in offline spectra





Preliminary “Decay Curves” from offline counting



^{219}Po

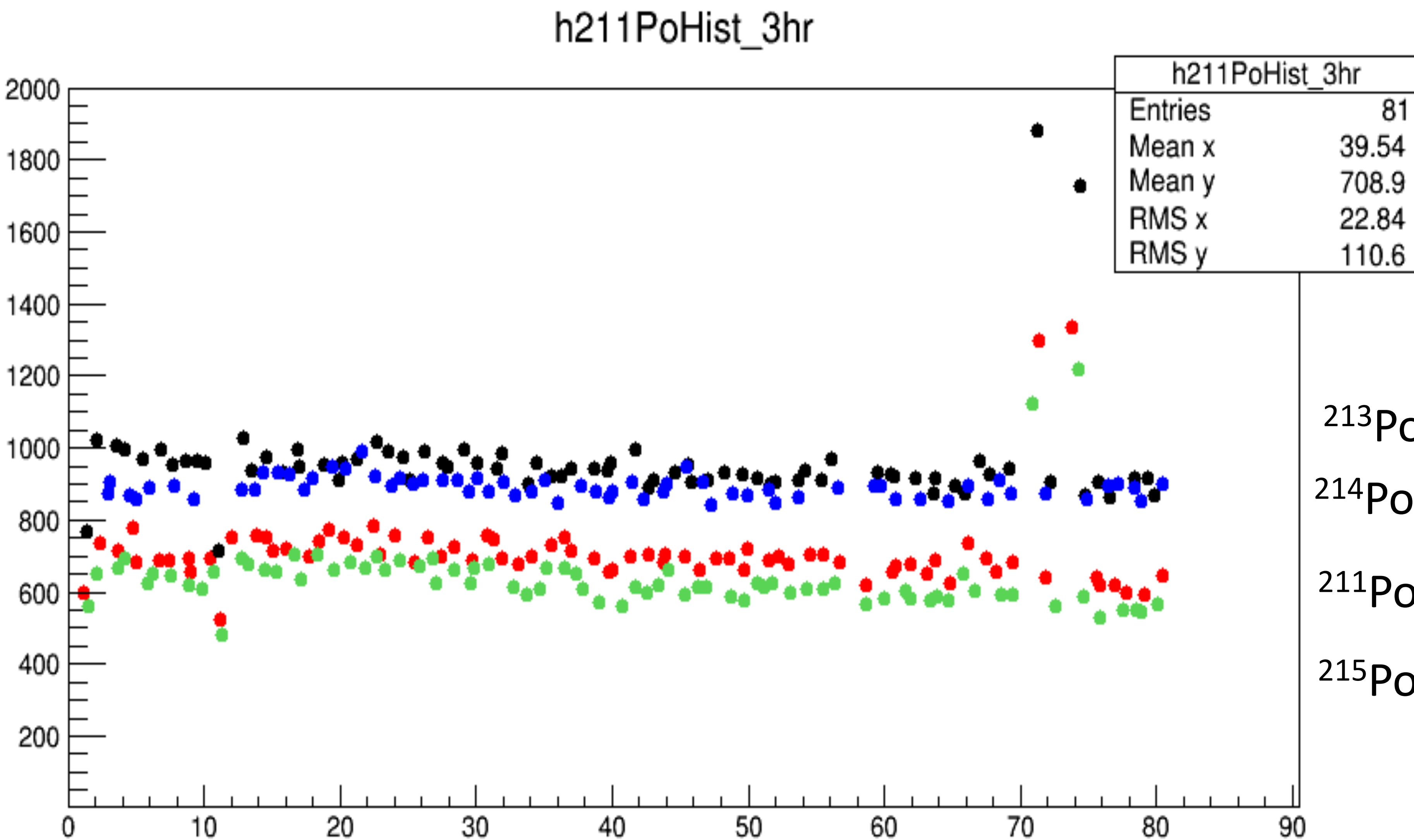
^{218}Po

^{217}Po

^{216}Po

^{212}Po

Preliminary "Decay Curves" from offline counting



^{213}Po
^{214}Po
^{211}Po
^{215}Po