Nuclear Physics at the Australian National University

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4th ANPhA Symposium, Adelaide, 3rd August 2012

Heavy Ion Accelerator Facility, ANU, Canberra

Canberra

– Capital city of Australia

– Named in 1913, in the middle of nowhere

- Population now 350,000

Australian National University (ANU)

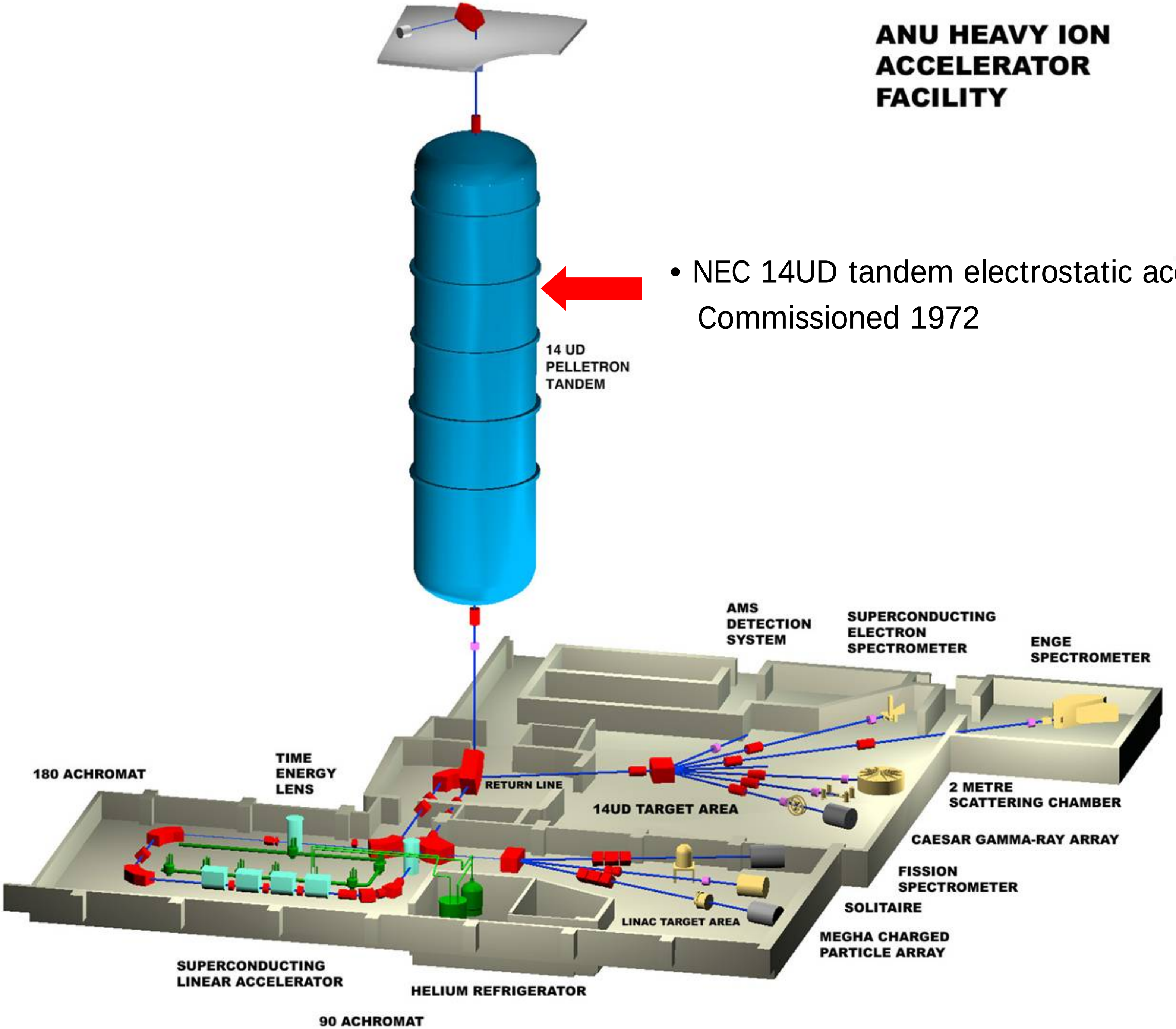
– Founded in 1949, still in the middle of nowhere

- Research University – originally no undergraduate students (10,000)

- RSPhysS one of founding divisions of ANU

- Department of Nuclear Physics one of original departments

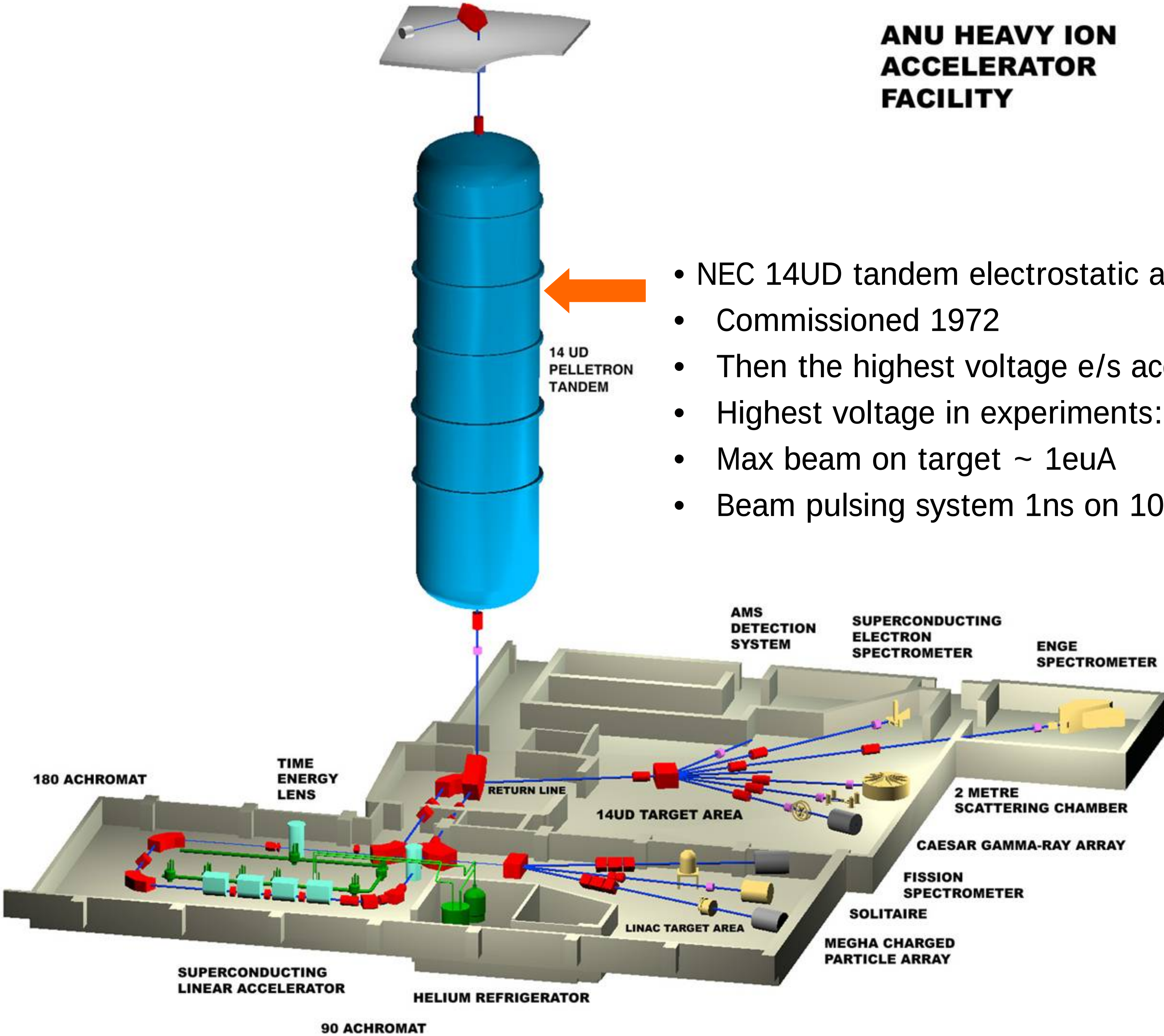
ANU HEAVY ION ACCELERATOR FACILITY



- NEC 14UD tandem electrostatic accelerator
  Commissioned 1972

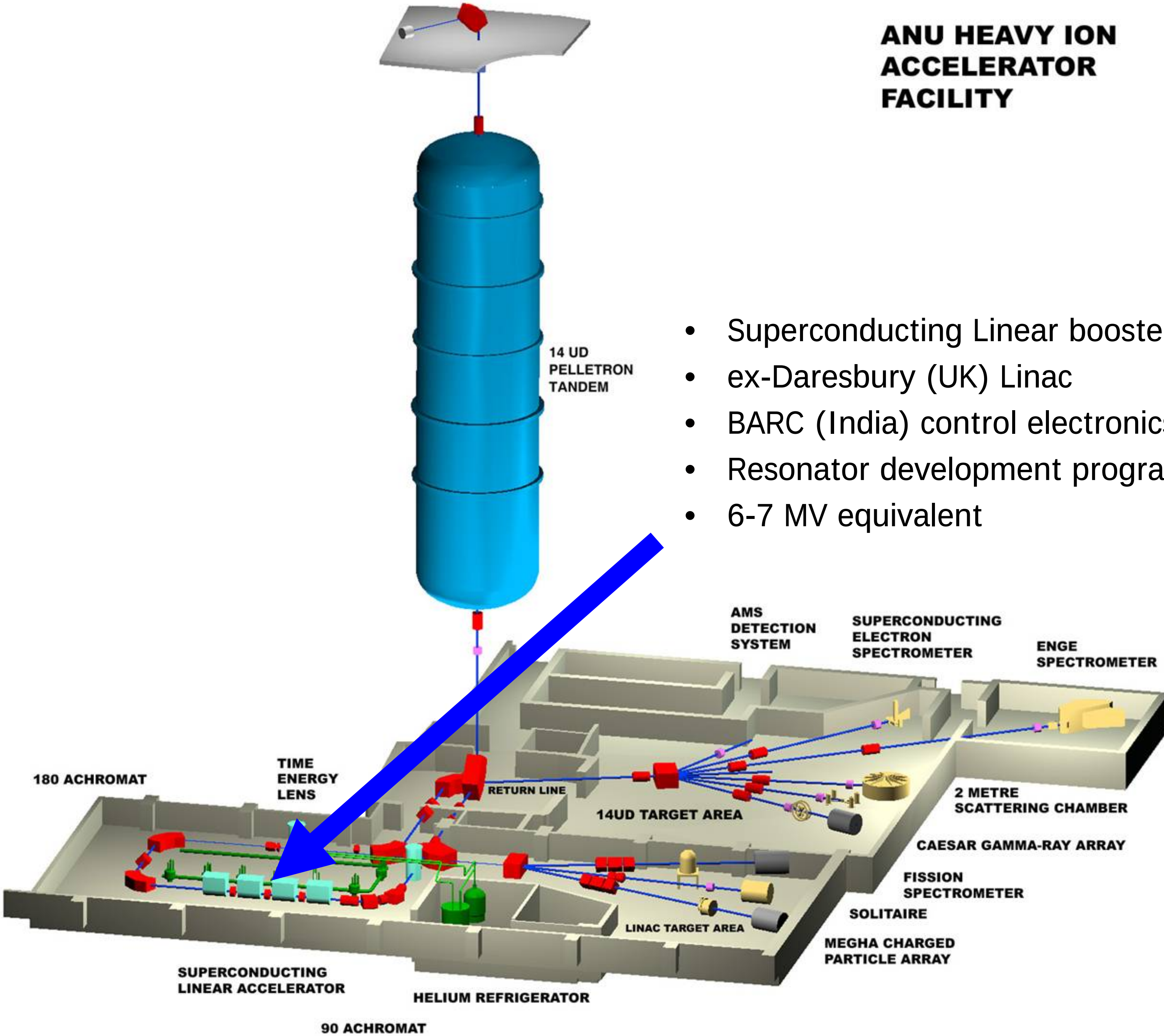
Heavy Ion Accelerator Facility, ANU, Canberra

ANU HEAVY ION ACCELERATOR FACILITY



- NEC 14UD tandem electrostatic accelerator
- Commissioned 1972
- Then the highest voltage e/s accelerator
- Highest voltage in experiments: 15.85 MV
- Max beam on target ~ 1euA
- Beam pulsing system 1ns on 107ns to 1s off

ANU HEAVY ION ACCELERATOR FACILITY



- Superconducting Linear booster accelerator
- ex-Daresbury (UK) Linac
- BARC (India) control electronics
- Resonator development program
- 6-7 MV equivalent

Accelerator enhancements (2010-2013)

- Australian Government response to 2009 Global Financial Crisis:
- EIF: $7.6M over 4 years for accelerator enhancement

Accelerator enhancements

- Beam pulsing update and upgrade – 200 ps pulses
- New beamline target stations
- Second dedicated s/c solenoid beamline (RIB, spectroscopy)
- Big upgrade of AMS capability – automation
- New EPICS-based accelerator computer control
- New data acquisition system
- Modern pumps and magnet power supplies

Heavy Ion Accelerator Facility, ANU, Canberra

Engineering/technical staff – enhance, maintain HIAF

- Staff numbers boosted by Accelerator Enhancement project (2009-2013)

- 4.5 accelerator, engineering and computing professional staff
  Accelerator manager Nikolai Lobanov (David Weisser)
- 9 technical + 1 administration staff
  Senior tech staff: Alan Cooper, Alistair Muirhead
  Technical staff exchanges ANSTO, Australian Synchrotron, U Melbourne
- Use of RSPE mechanical and electronic workshops (~16 staff)
- As yet no external source of tech/operating costs (user charges)

Heavy Ion Accelerator Facility, ANU, Canberra

Typical beams, energies used in experiments

Beam	V_B on Pb (MeV)	14UD energy (MeV, MeV/A)	Linac energy (MeV, MeV/A)
p,d	9	30, 30,15	-
^{9}Be	40	70, 7.8	-
$^{16,\mathbf{17},\mathbf{18}}$O	80	133, 8.4	165, 10.3
$^{32,34,\mathbf{36}}$S	166	210, 6.6	-
^{40,44}Ca	200	230, 5.8	325, 8.1
^{46,48,50}Ti	230	245, 5.1	300, 6.3
$^{58,\mathbf{64}}$Ni	290	280, 4.8	340, 5.3
^{197}Au	(ERDA)	200, 1.0	-

Near-barrier (E/A~5 MeV) - reactions, spectroscopy, AMS, Materials

14UD provides most experimental requirements

Heavy Ion Accelerator Facility, ANU, Canberra

Academic Staff – 3 research groups - operate accelerator

AMS – 3 continuing staff + 2 fixed term staff
Prof. Keith Fifield, Anton Wallner, Steve Tims

Nuclear reactions – 2 continuing staff + 5(7) fixed term staff
Prof. David Hinde, Prof. Nanda Dasgupta Cedric Simenel

Nuclear structure – 3(4) continuing staff + 1 fixed term staff
Prof. Andrew Stuchbery, Greg Lane, Tibor Kibedi
(+ Emeritus Prof. George Dracoulis)

Materials research – external users ANU, UNSW

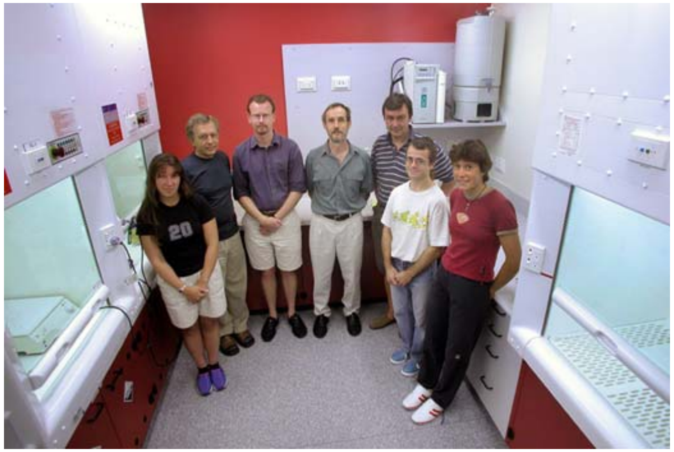
(13 of 19 researchers (2013) externally funded – ARC Disc, FF, LF; AMS)
~ 20 research students
~ 40 regular users outside department (NP, AMS, Materials)

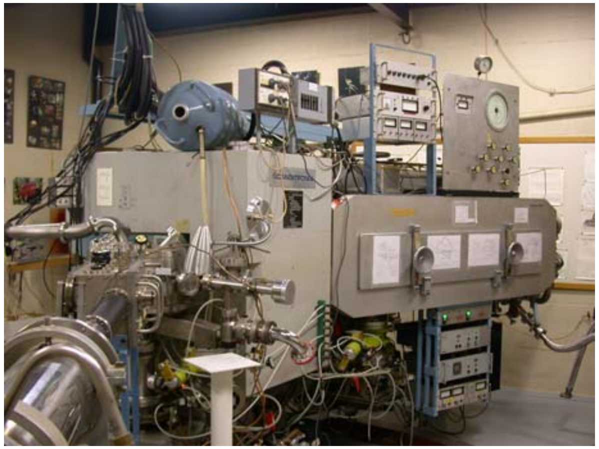
Accelerator Mass Spectrometry

Equipment

- Sample preparation/chemistry laboratory
- Multi-sample SNICS accelerator ion source
- Velocity Filters + Gas ionization ΔE-E detectors
- Gas-filled magnet (ENGE split pole)

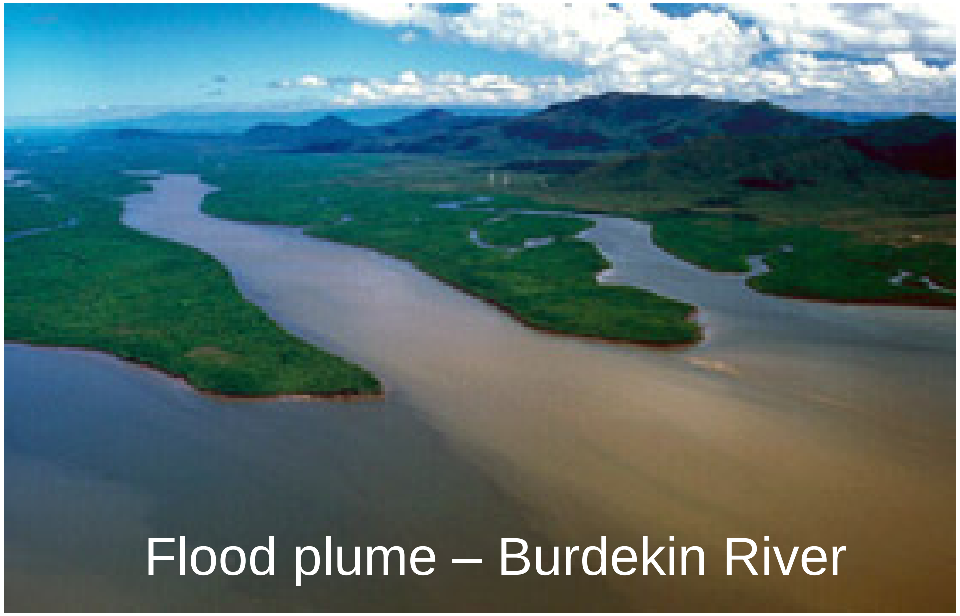
^{10}Be, ^{14}C, ^{26}Al, ^{32}Si, ^{36}Cl, ^{41}Ca, ^{53}Mn, ^{59}Ni, ^{99}Tc, ^{129}I, ^{236}U, ^{239}Pu,...





Accelerator Mass Spectrometry

- ^{239}Pu - bomb pulse isotope: replacement for ^{137}Cs
  - Soil erosion, sedimentation
    - Herbert, Burdekin Rivers, QLD – Agriculture, Barrier Reef
    - Shanghai, China



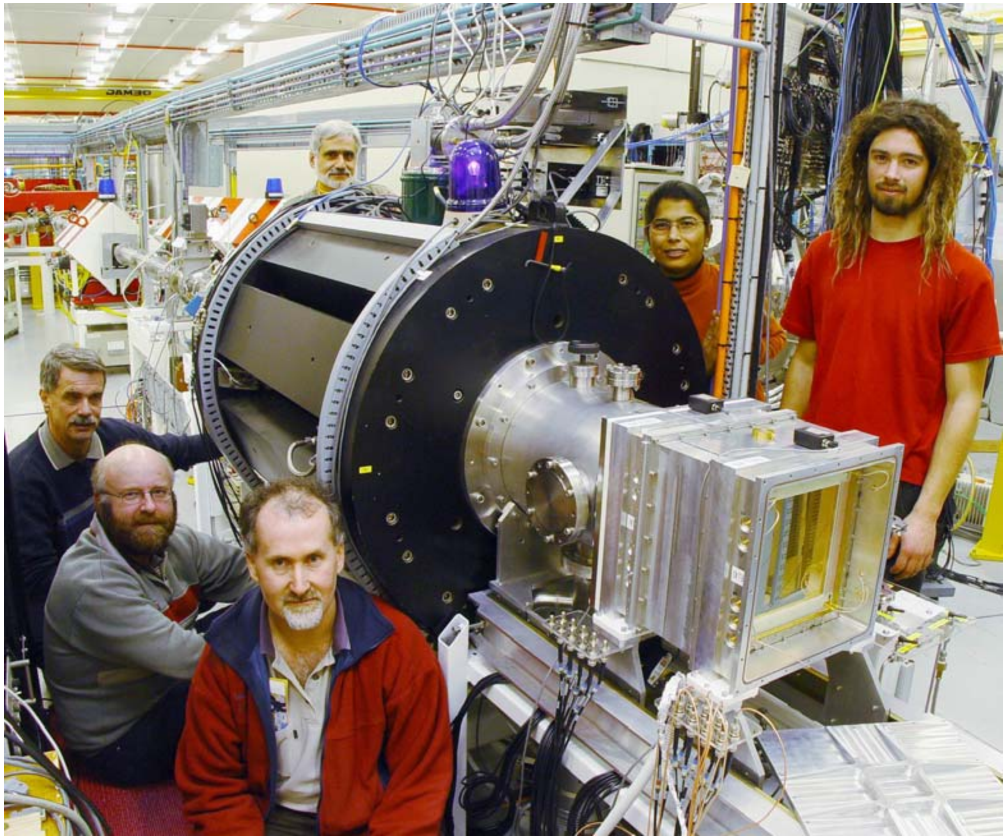
Flood plume – Burdekin River

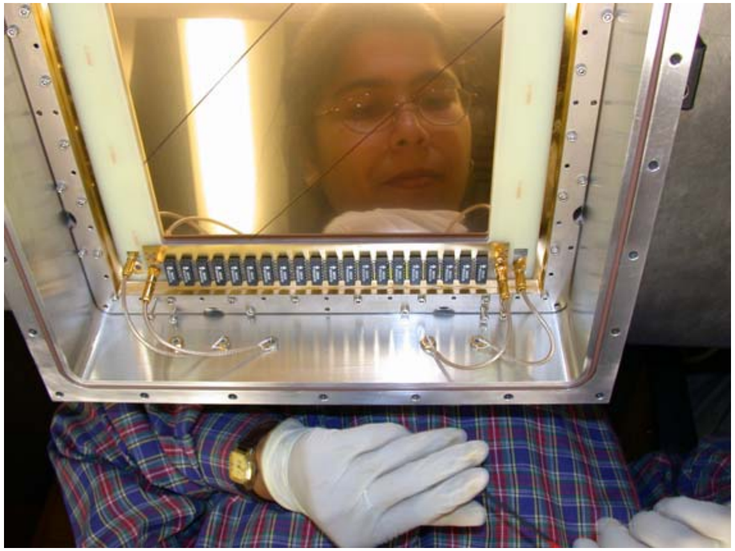
Nuclear Reaction Dynamics

Equipment

- **SOLITAIRE** superconducting 6.5 T solenoid: $\Delta\theta=9.5^{o}$ 86 msr
  - Heavy ion fusion: fusion barrier distributions, sub-barrier fusion
  - Radioactive beam production: ^{6}He
  - Nuclear structure - γ-ray spectroscopy: short-lived states
  - Materials characterization – implantation and PAC

SOLITAIRE

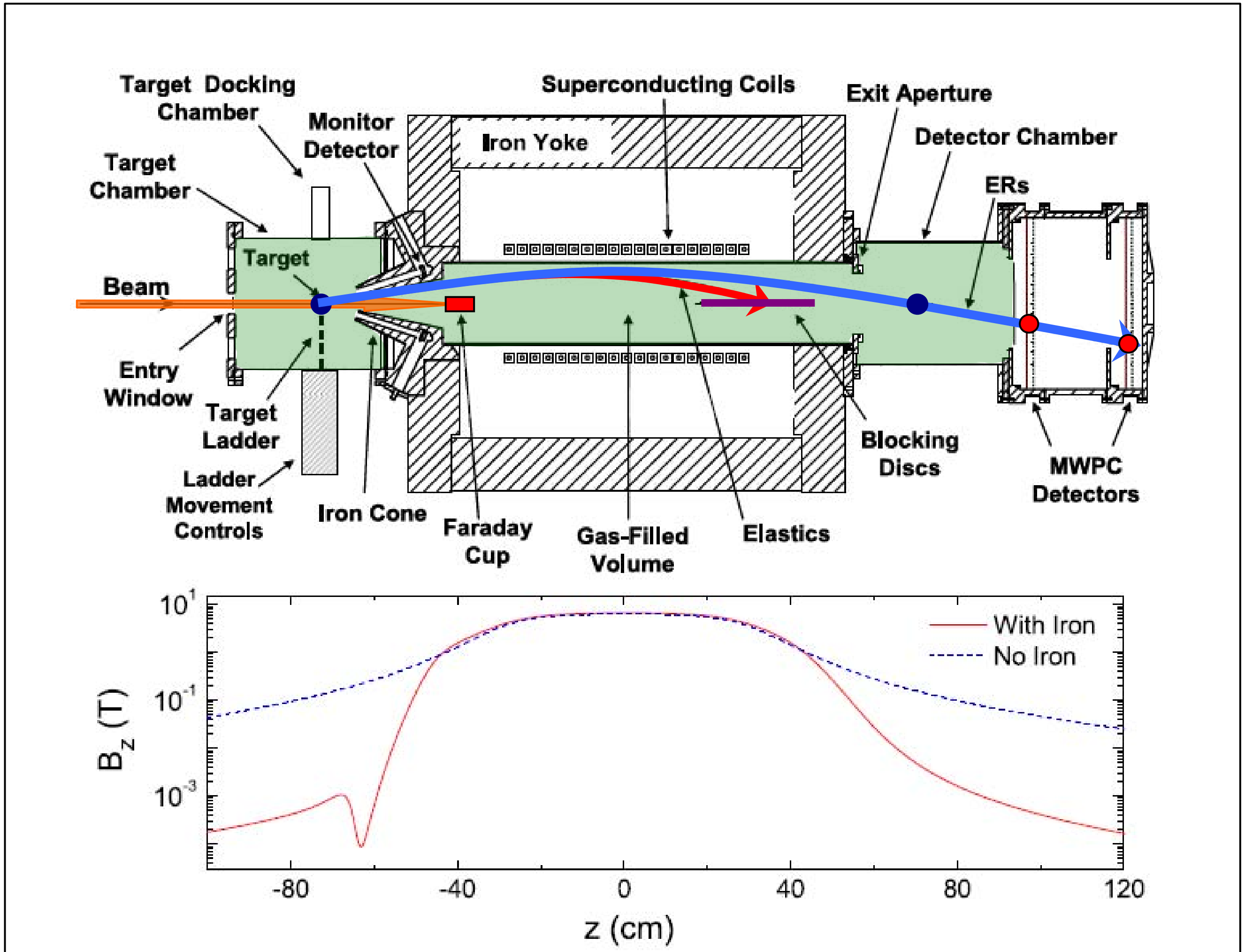




Separator and detector system allows precision measurements

Unique in the world – international users, interest (USA, Europe)

SOLITAIRE

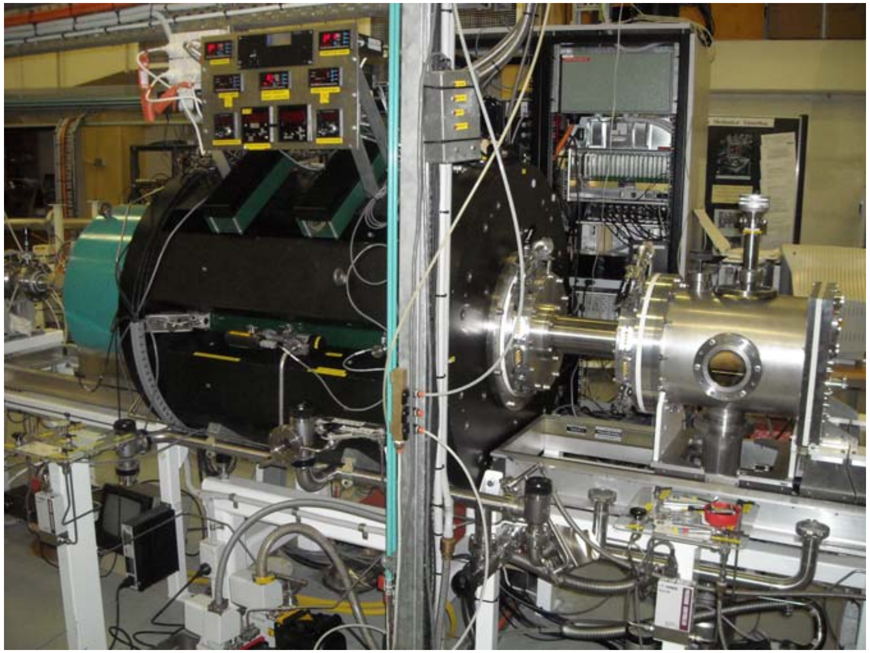


Target Docking Chamber
Superconducting Coils
Exit Aperture
Monitor Detector
Iron Yoke
Detector Chamber
Target Chamber
ERs
Target
Beam
Entry Window
Target Ladder
Blocking Discs
MWPC Detectors
Ladder Movement Controls
Iron Cone
Faraday Cup
Gas-Filled Volume
Elastics
With Iron
No Iron
B_z (T)
10^{1}
10^{-1}
10^{-3}
-80
-40
0
40
80
120
z (cm)

SOLITAIRE

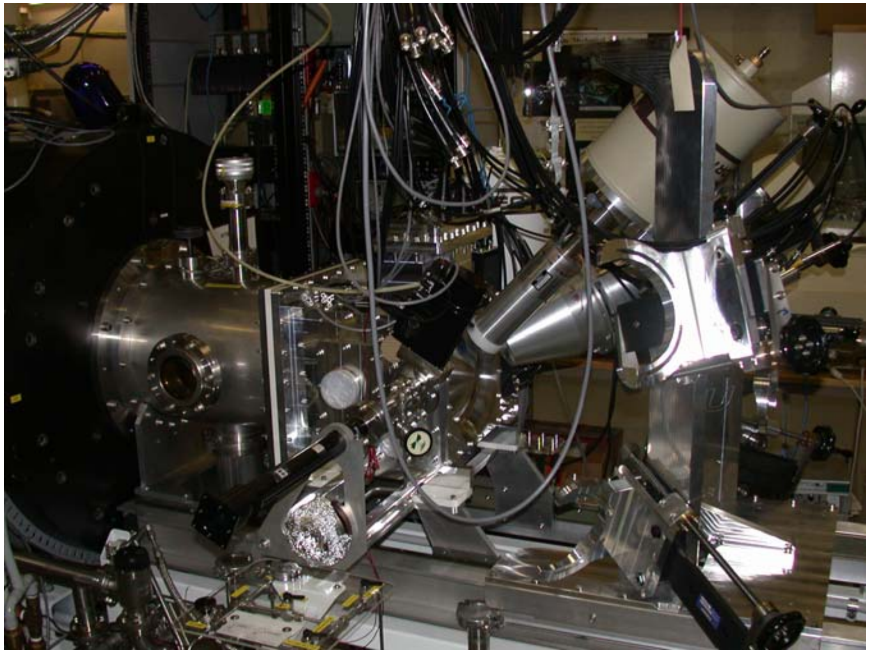
RIB

^{6}He



NUCLEAR STRUCTURE

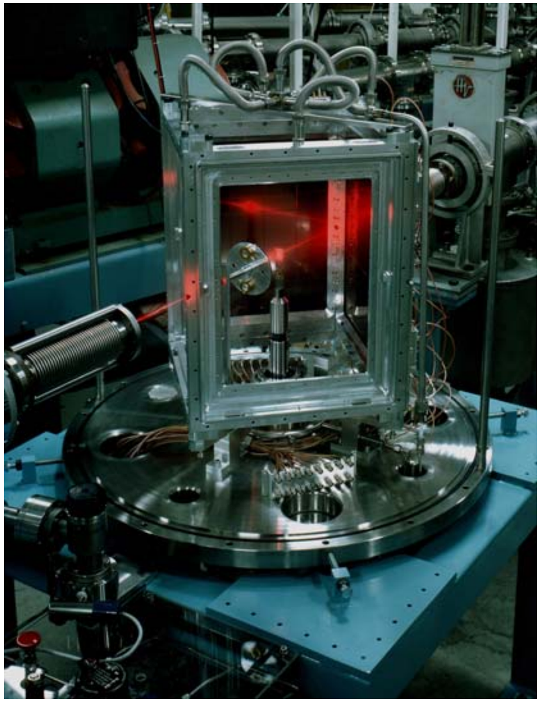
SOLENO-GAM

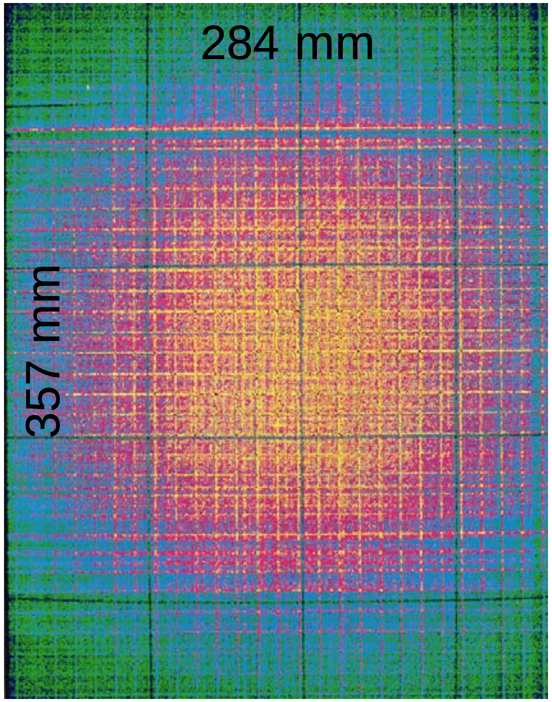


Nuclear Reaction Dynamics

Equipment

- **CUBE - ** MWPC detectors for fission: heavy element formation

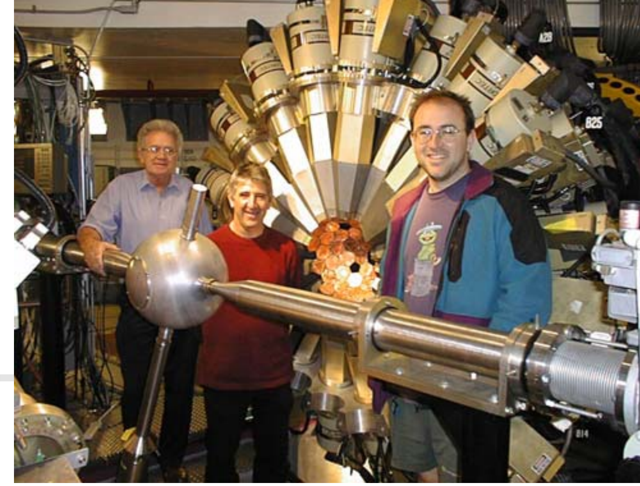




$\Delta\theta = 70^o$

$\Delta\phi = 90^o$

Gammasphere
ANL



Nuclear Structure

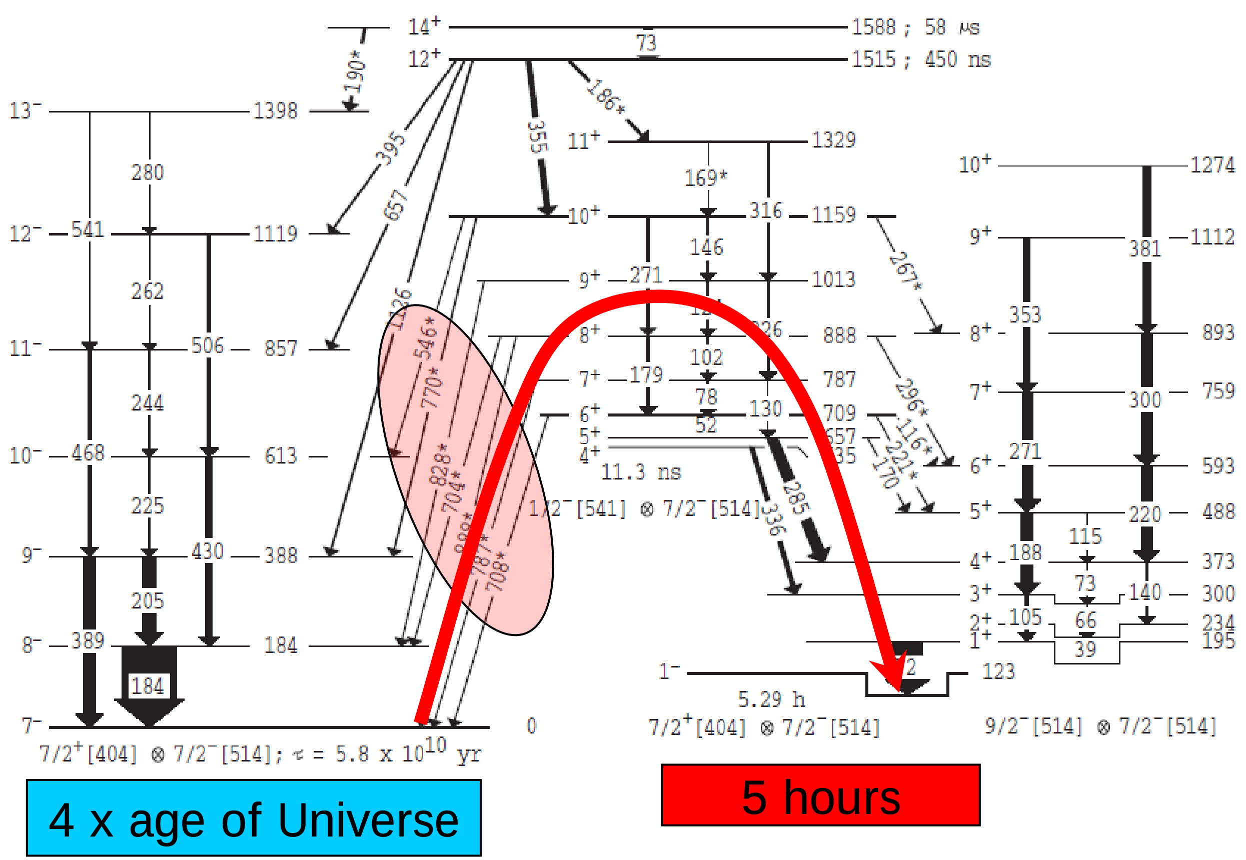
- CAESAR Ge γ-ray array: level schemes and lifetimes
- S/c electron spectrometer, upgraded with new electron detectors: conversion coefficients, Hoyle state of ^{12}C
- γ-ray angular correlation array; new γ detectors ordered; cryo-cooled target: magnetic moments, new techniques (RIB - MSU)
- SOLENO-GAM - γ-ray+electron module behind SOLITAIRE

CAESAR

Super-e

Nuclear Structure

^{176}Lu

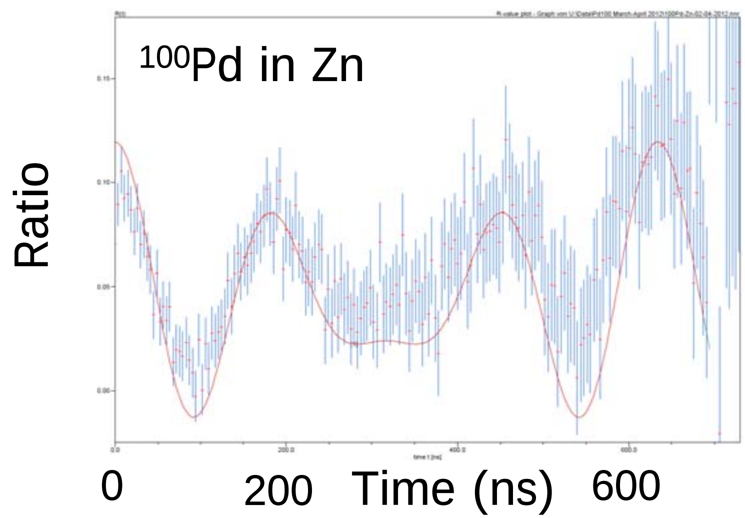


Materials modification and characterization

Equipment

- Beam rastering for material implantation/modification
- Large gas ionization ΔE-E detector for ERDA
- PAC arrays for γ-ray ang. correlation following implantation

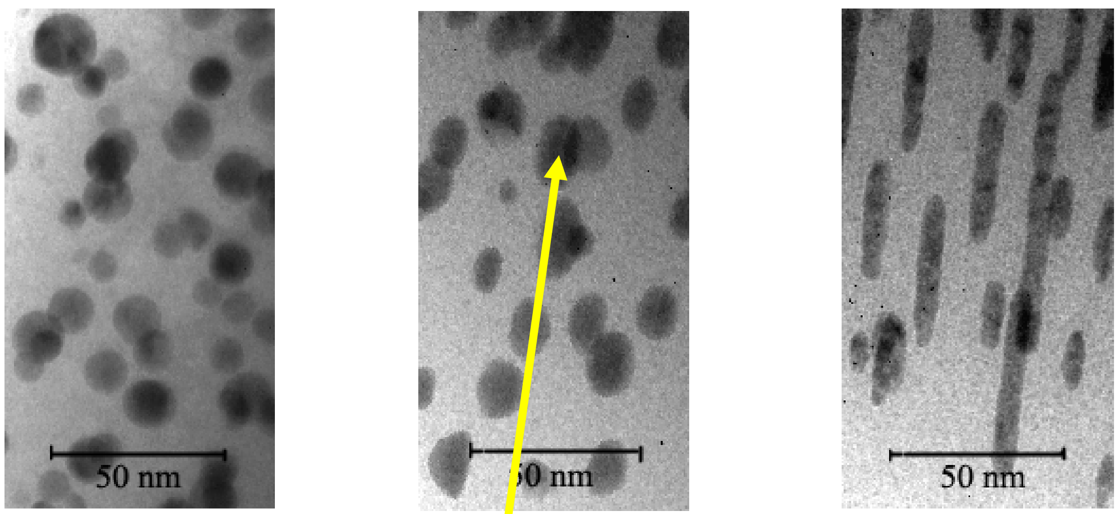
  Now using SOLITAIRE to eliminate scattered beam particles



Materials modification and characterization

Metal Nanoparticle Elongation by Ion Irradiation

unirradiated 2×10^{13} cm^{-2} 2×10^{14} cm^{-2}



Pt nanoparticles   185 MeV Au

- spherical to rod-like transformation

M. Ridgway et al. (EME, ANU)

Nuclear reaction dynamics

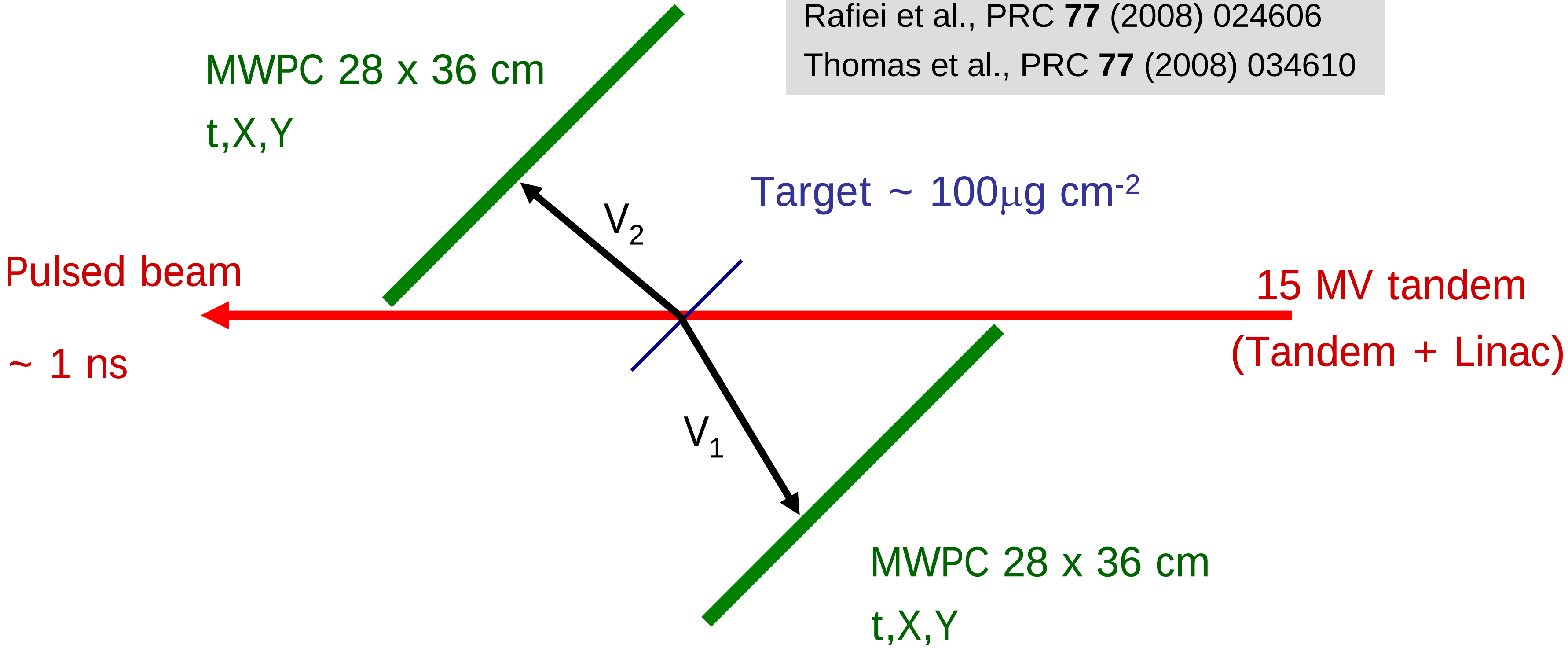
- Fusion barrier distribution
- Quantum decoherence in nuclear collisions
- Breakup of weakly-bound nuclei
- Superheavy element formation dynamics

ANU fission detector configuration

Hinde et al., PRC **53** (1996) 1290

Rafiei et al., PRC **77** (2008) 024606

Thomas et al., PRC **77** (2008) 034610



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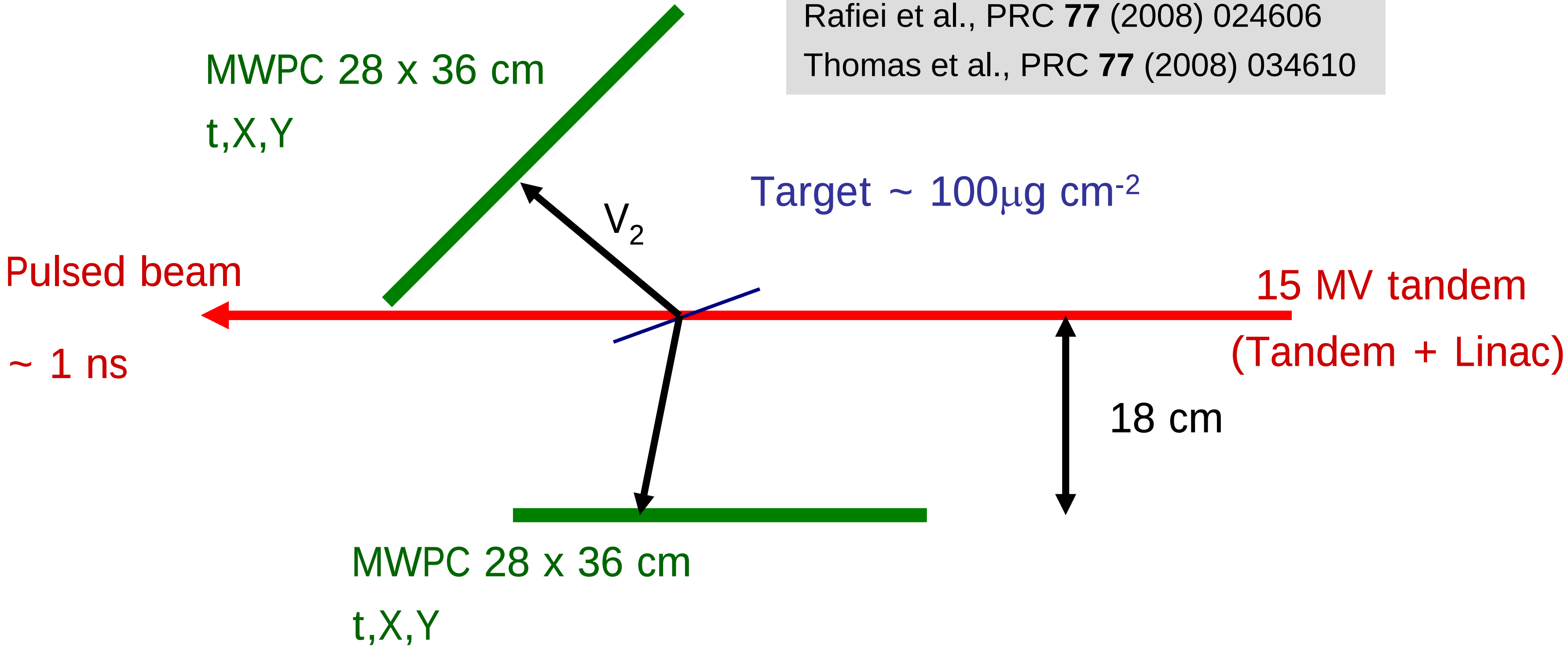
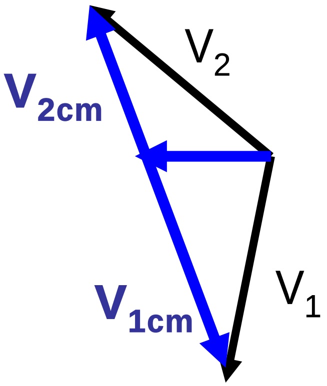


Binary fission kinematics

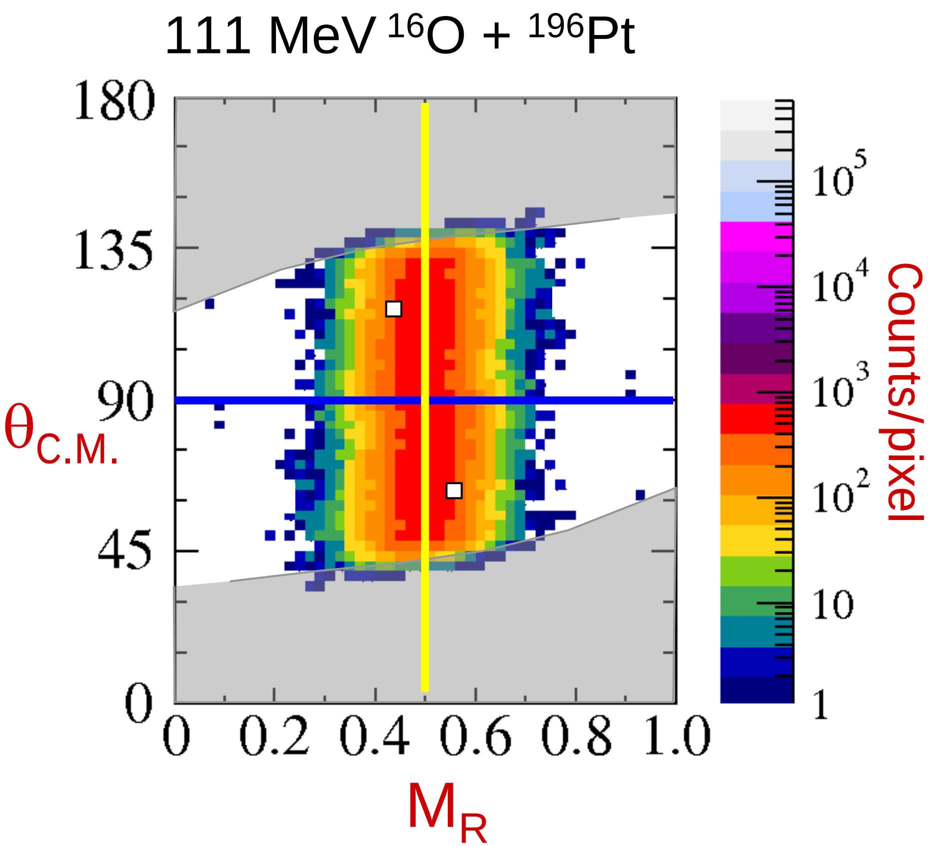
Hinde et al., PRC **53** (1996) 1290
Rafiei et al., PRC **77** (2008) 024606
Thomas et al., PRC **77** (2008) 034610



Kinematic coincidence:

Determine (binary) mass-ratio $M_{R1} = A_{F1}/(A_{F1}+A_{F2}) = V_{2cm}/(V_{1cm}+V_{2cm})$

Mass-angle distribution – MAD



Kinematic coincidence

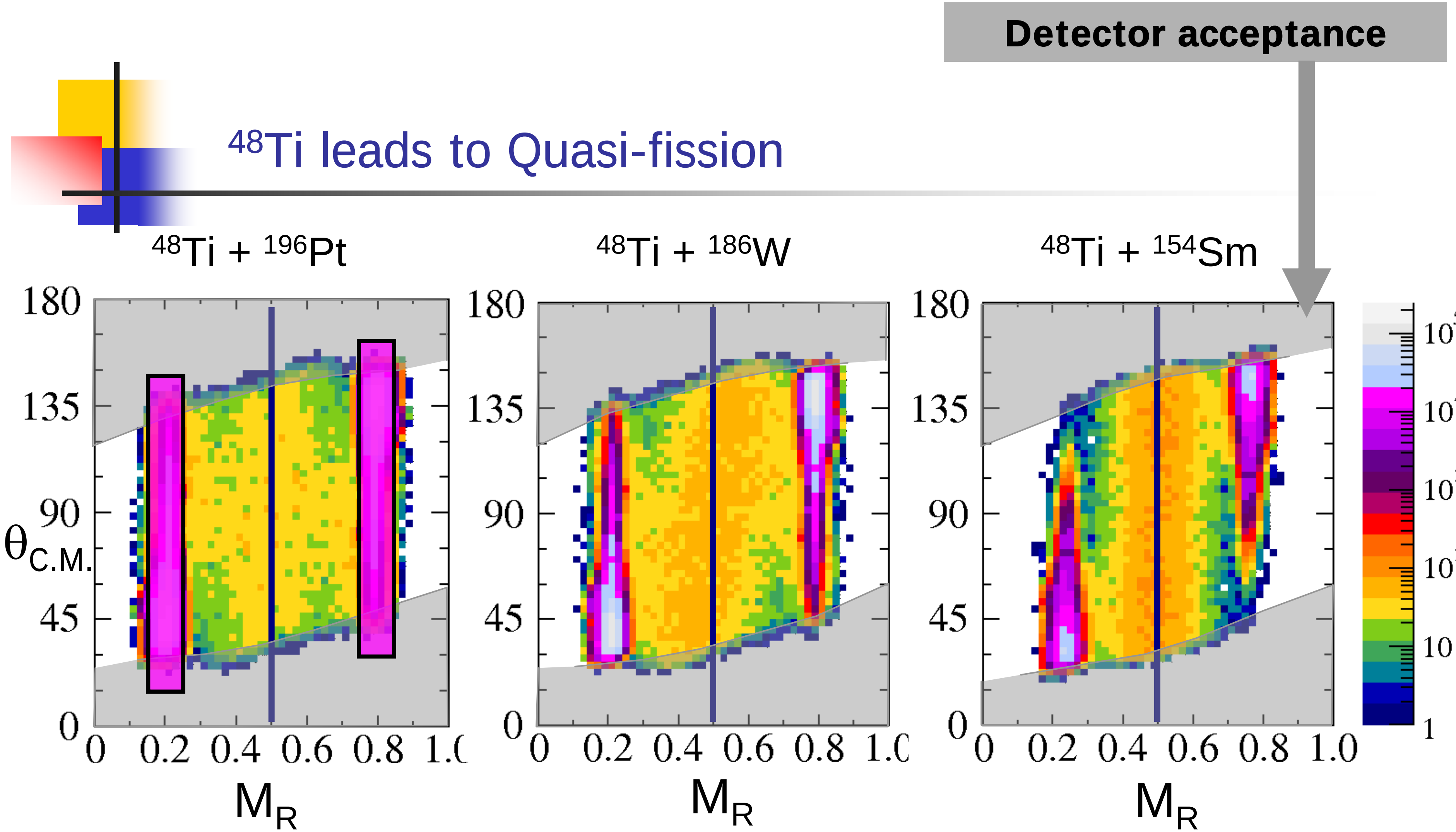
Detector angular acceptance

- Detect both fragments
- Populate matrix at M_R,θ_{CM}
- Also at $(1-M_R)$, $(\pi-\theta_{CM})$

Fusion-fission

- symmetric about $M_R = 0.5$
- <u>and</u> symmetric about $\theta_{CM} = 90^o$

^{48}Ti leads to Quasi-fission

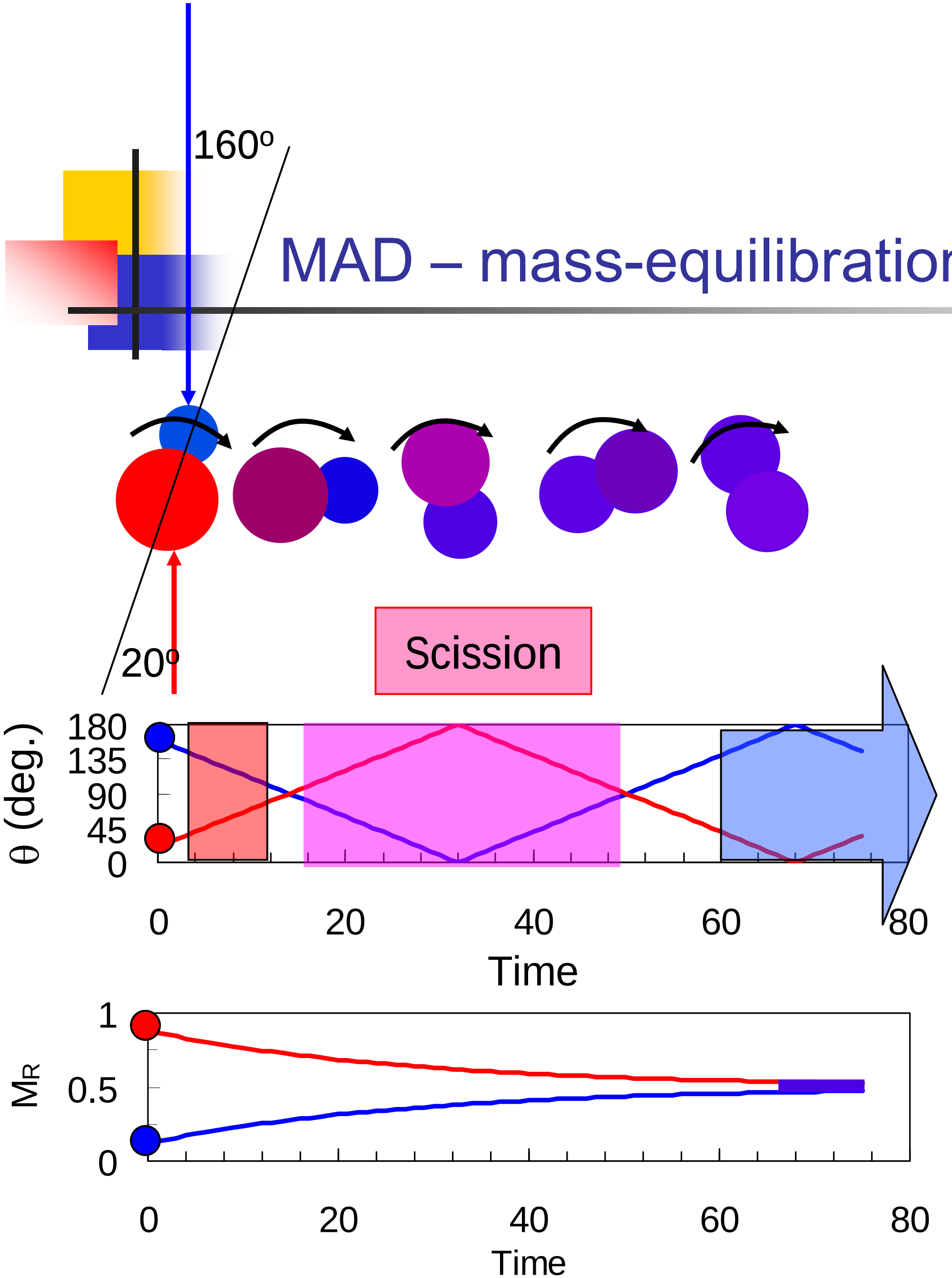


Elastic, quasi-elastic and deep inelastic events

Asymmetric features of MAD – what is physical origin?

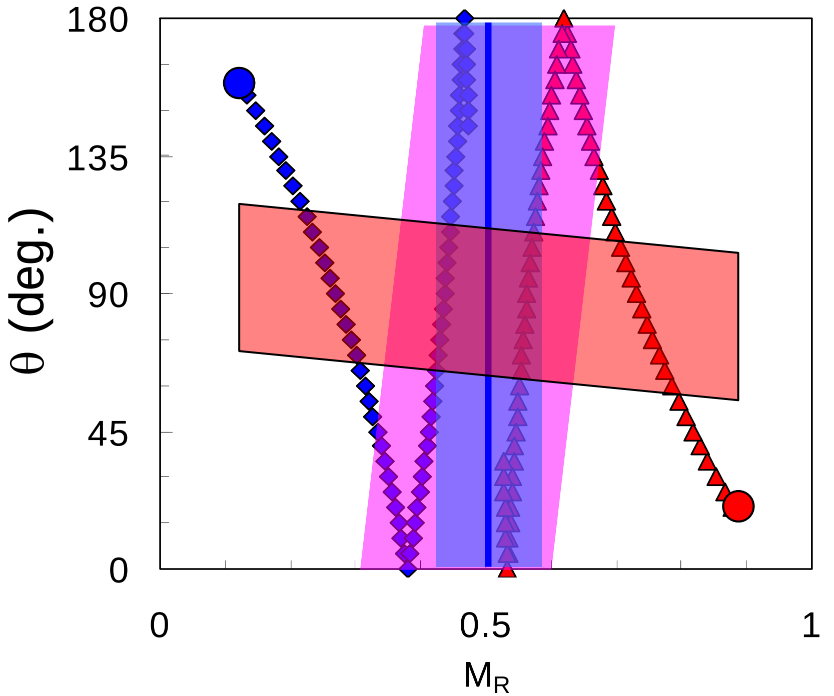
R. Bock et al., NP **A388** (1982) 334
J. Toke et al., NP **A440** (1985) 327
W.Q. Shen at al., PRC **36** (1987) 115
B.B. Back et al., PRC **53** (1996) 1734

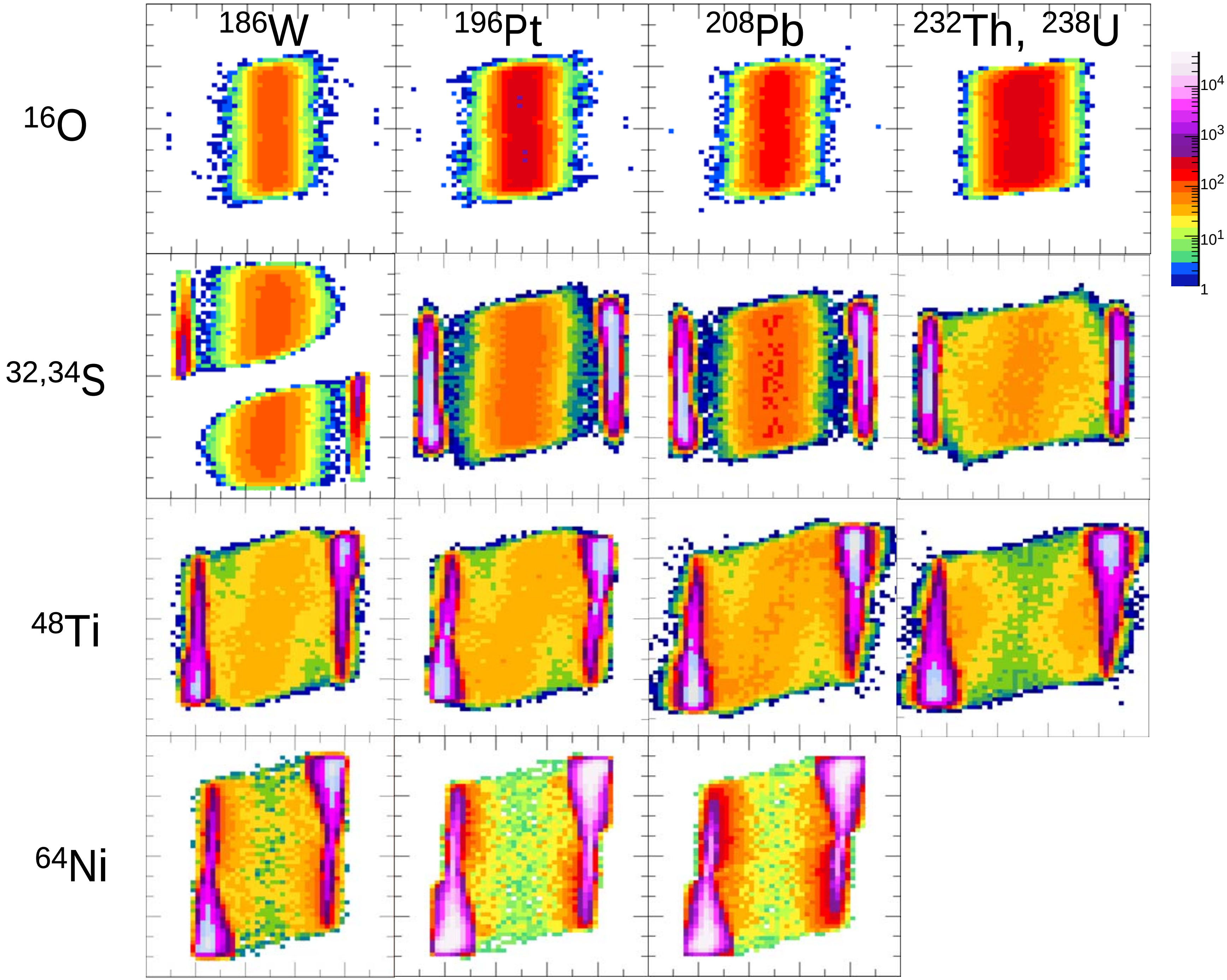
MAD – mass-equilibration and rotation



Miminal mass-angle correlation

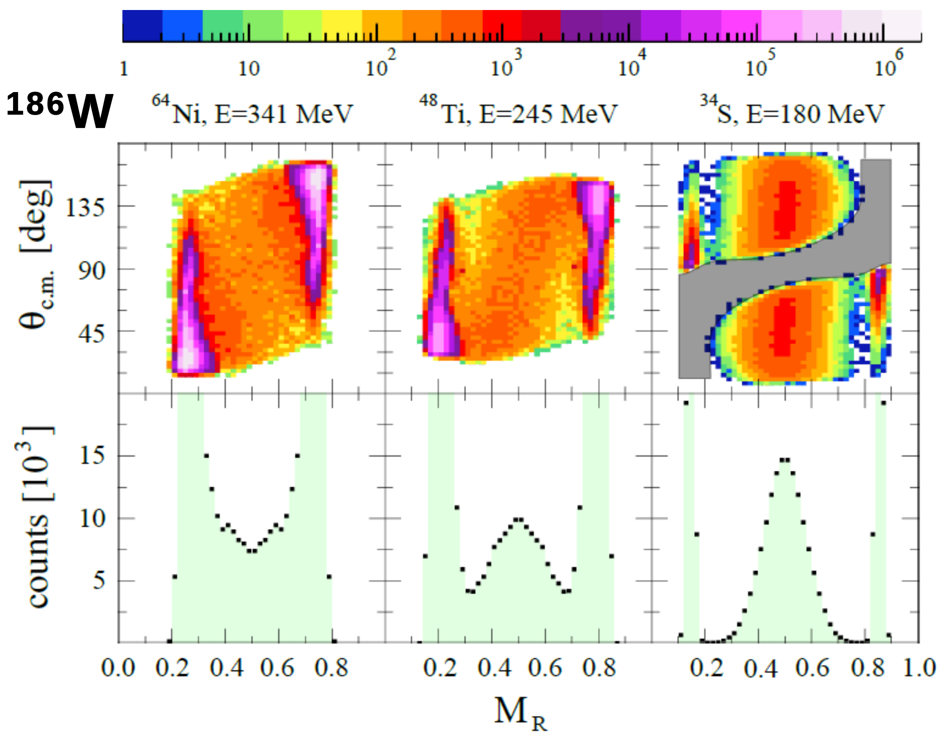
Strong mass-angle correlation

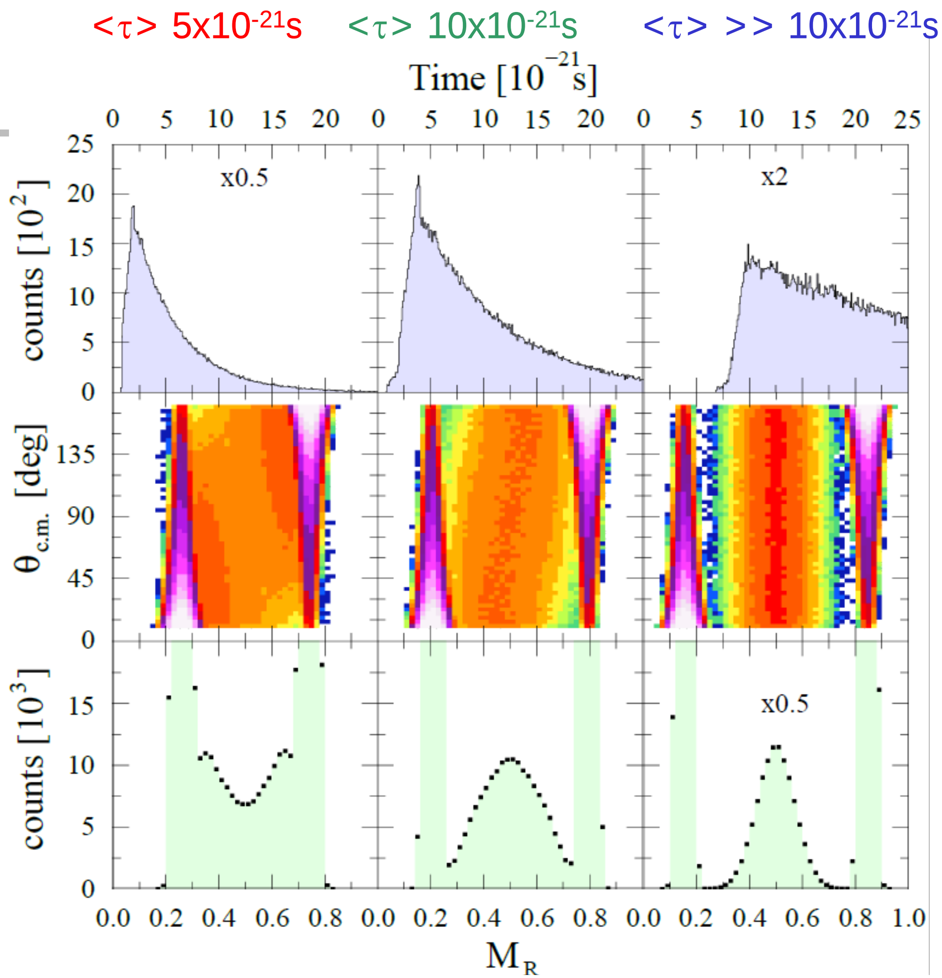




186W
196Pt
208Pb
232Th, 238U
16O
32,34S
48Ti
64Ni
1
10^1
10^2
10^3
10^4

MAD timescales

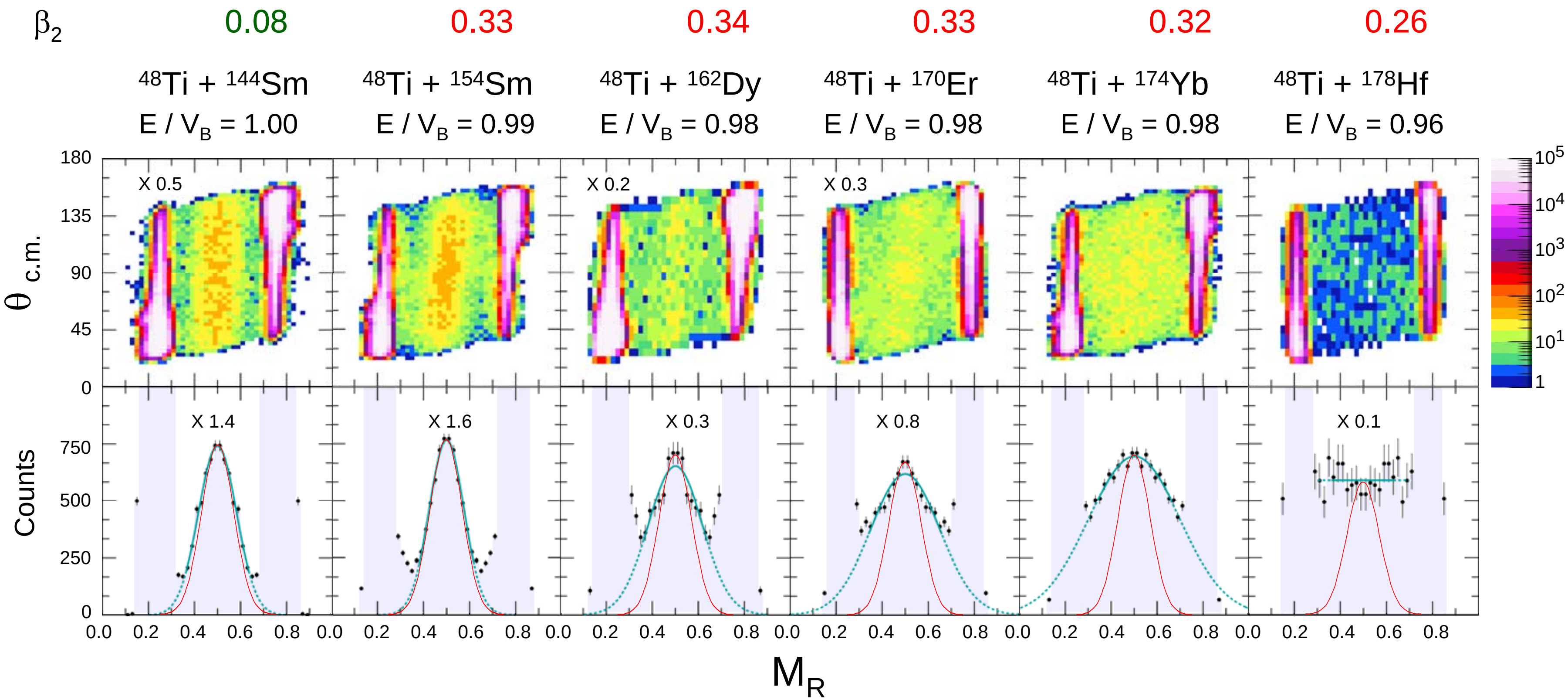




R. du Rietz et al. PRL 106(2011)052701

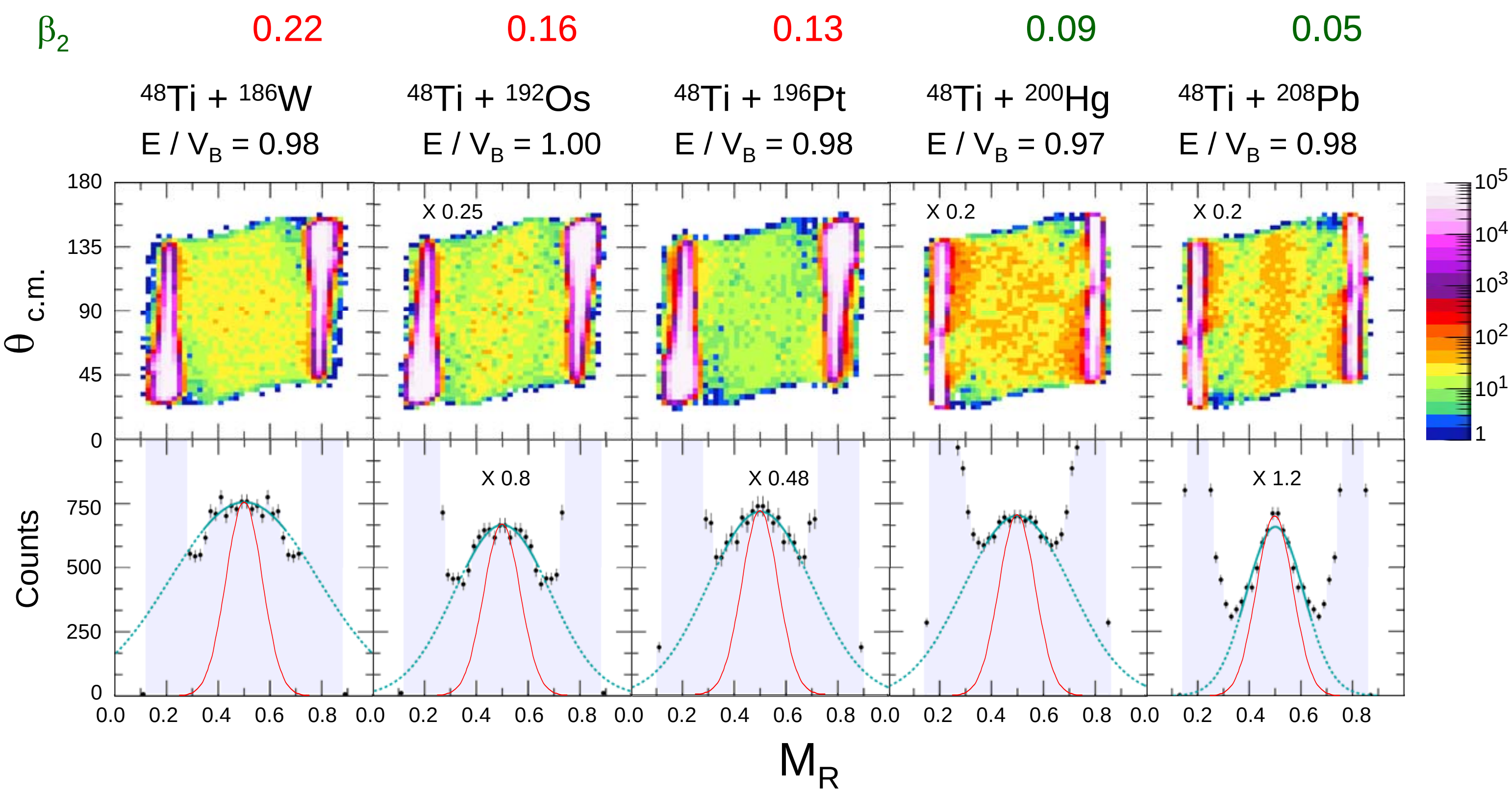
Difficulty of forming heavy elements at low E_X

Increased mass width with increasing fissility for ~constant β_2



^{208}Pb target appears favourable – cold fusion

~constant mass width for decreasing β_2

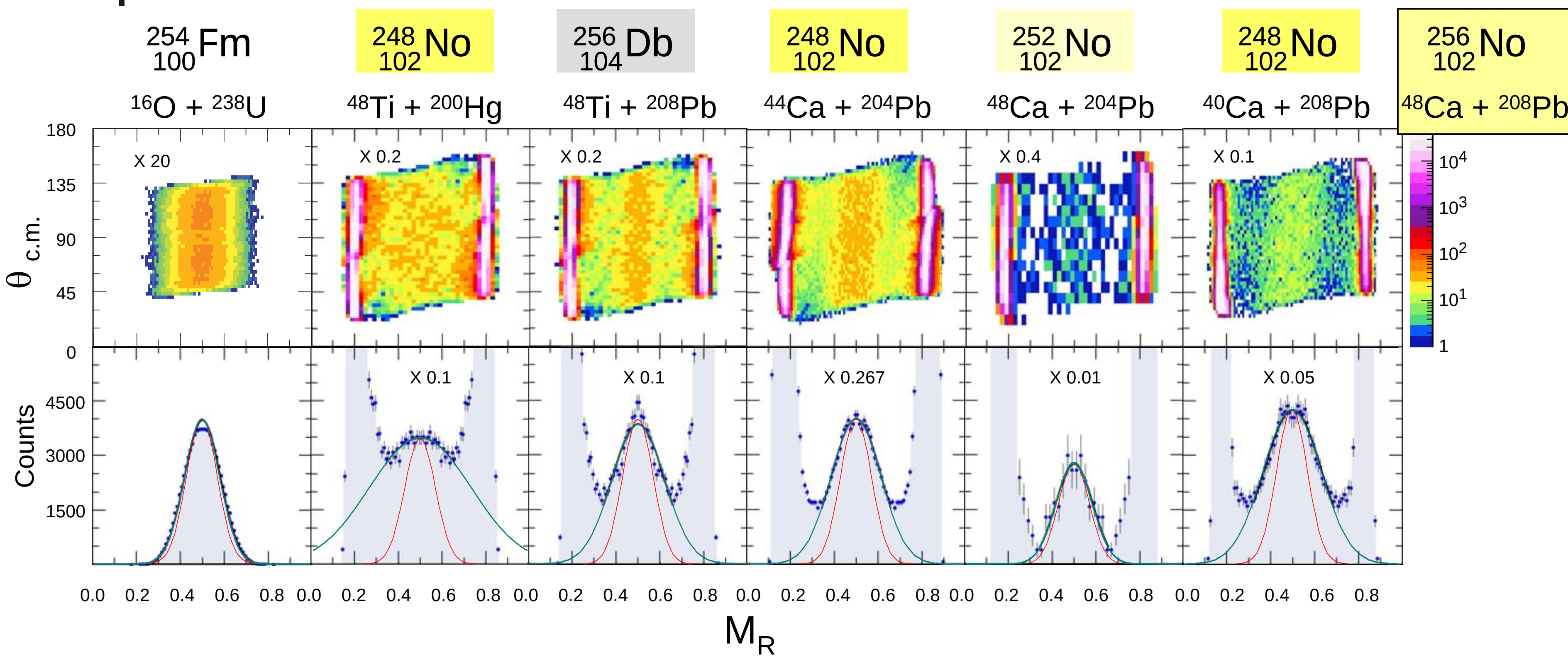


narrow mass width for ^{208}Pb

E. Prokhorova et al., NPA802(2008)45

C. Simenel et al., PLB710 (2012) 607

Nuclear structure effects in superheavy element formation

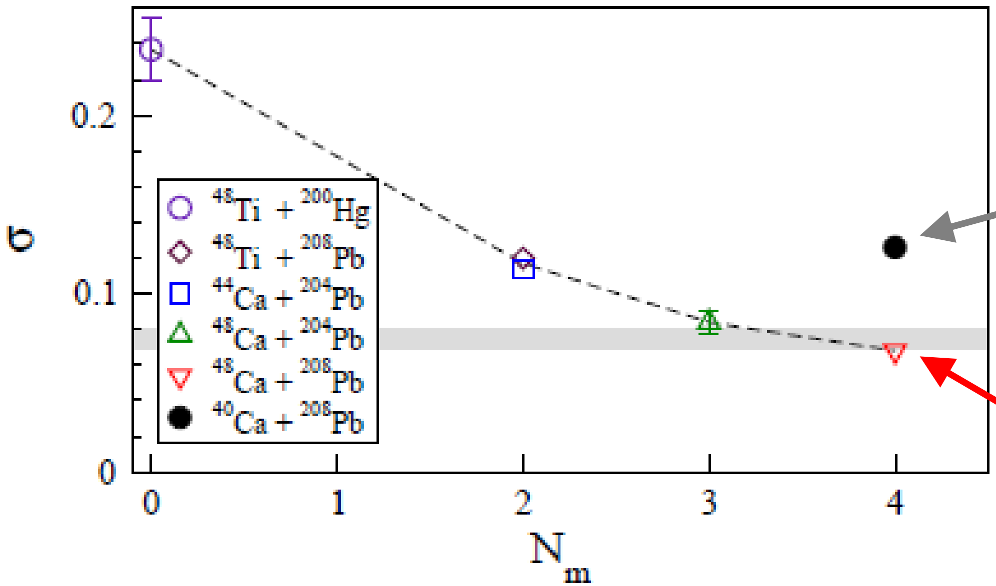


σ_{MR}	0.081	0.237	0.120	0.114	0.084	0.126	0.068
err	0.001	0.018	0.003	0.002	0.006	0.004	0.002
N_{magic}	2	0	2	2	3	4	4

Entrance channel closed shells and N/Z mismatch

Isospin equilibration will increase energy damping as nuclei overlap:

- colliding nuclei will stop moving closer → quasi-fission



Fast N/Z equilibration.
TDHF calculated outcomes:

$^{40}Ca + ^{208}Pb$
P(no transfer) ~ 10^{-4}

Average transfer outcome:
$^{42}Ar + ^{206}Po$ $N_m = 0$

$^{48}Ca + ^{208}Pb$
P(no transfer) ~ 0.5

C. Simenel et al., PLB 710 (2012) 607

The Future

Exciting quantum physics in near-barrier nuclear collisions

Direct funding of facility operations

Australian Government recognizes need for dedicated operational funding for national infrastructure

- Support for external accelerator users (national, international)
- Take pressure off research grants supporting facility operations

Good beam definition, unique instrumentation, reliable beams

- Recent users from ORNL (USA), GSI (Germany)
- New collaboration CIAE (H.Q. Zhang, C.J. Lin – China)
- Interest in using facility, instrumentation from GANIL (France)