2358-10

Joint ICTP-IAEA Workshop on Nuclear Structure Decay Data: Theory and Evaluation

6 - 17 August 2012

Experimental Nuclear Physics

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Experimental Nuclear Physics: Part I

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Brookhaven Nation Laboratory

- How to make nuclei

- How to observe their decay

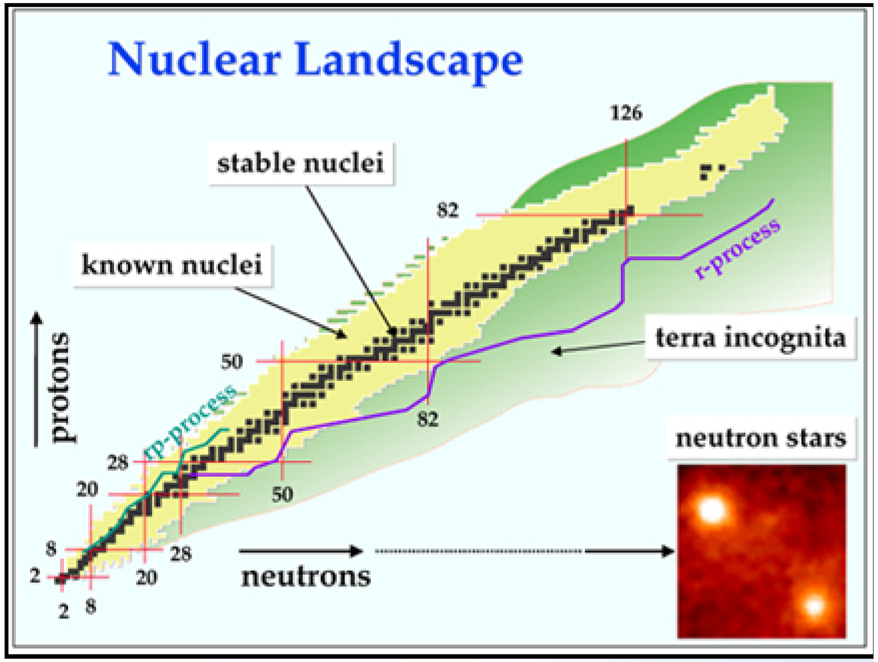
History : 100 years and counting

1896-1898	The beginning:-	Becquerel and Curie make first discovery of radioactivity
1910-1938	Discovery Era:-	Nuclear size, Neutron, Isotopes, Masses, Binding Energy
1939-1945	Fission Era:-	Fission….and activity leading to bombs & nuclear power
1946-1970	Light Ion Era:-	Near Stability, Shell and Collective Models.
1971-2001	Heavy Ion Era:-	Far from Stability, Shapes, Hot, High Spin, Very Heavy.
2002-20??	RIB Era:-	Neutron Rich “Terra Incognita”

The Scope of Nuclear Structure Physics

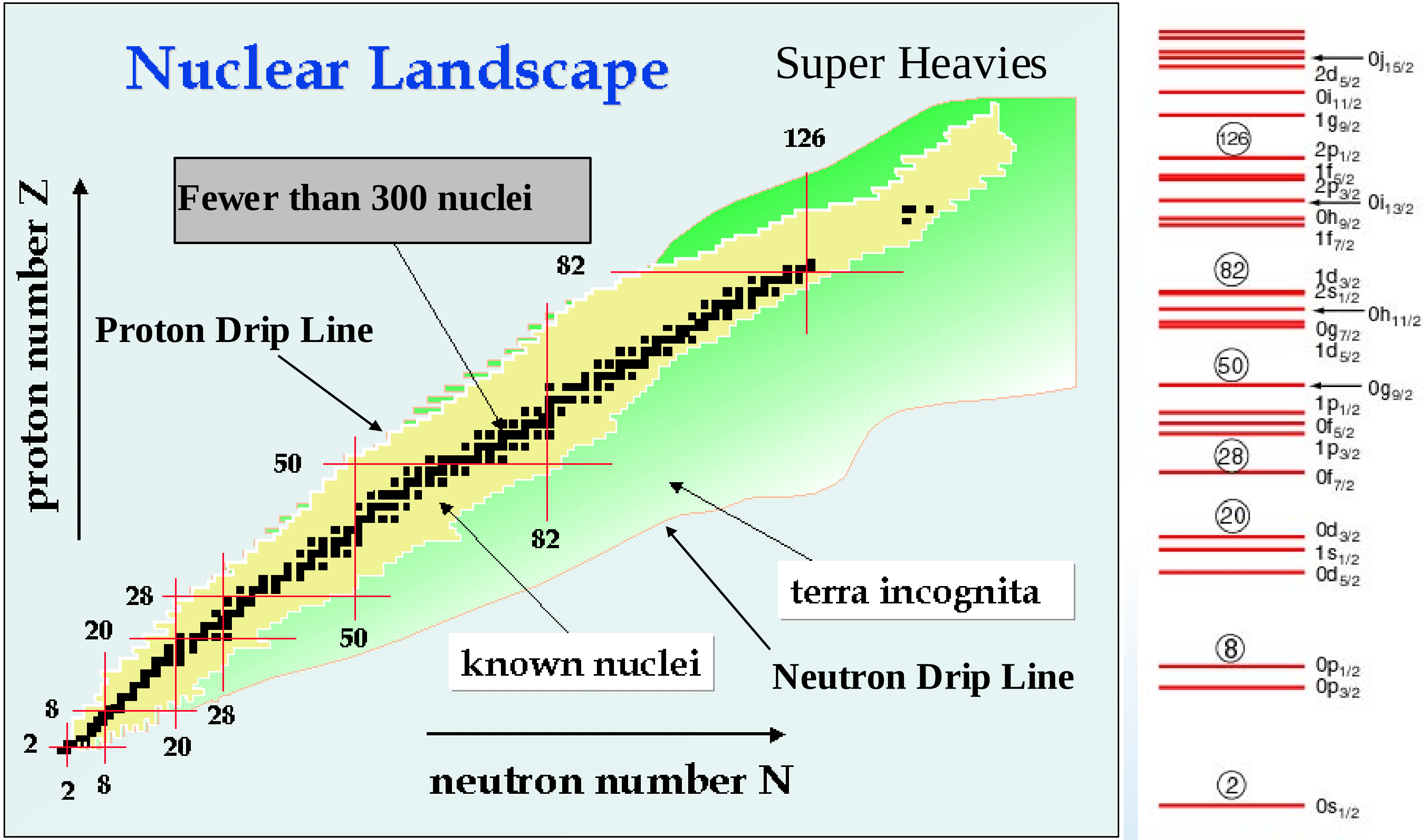
The Four Frontiers

1. **Proton Rich Nuclei**
2. **Neutron Rich Nuclei**
3. **Heaviest Nuclei**
4. **Evolution of structure within these boundaries**



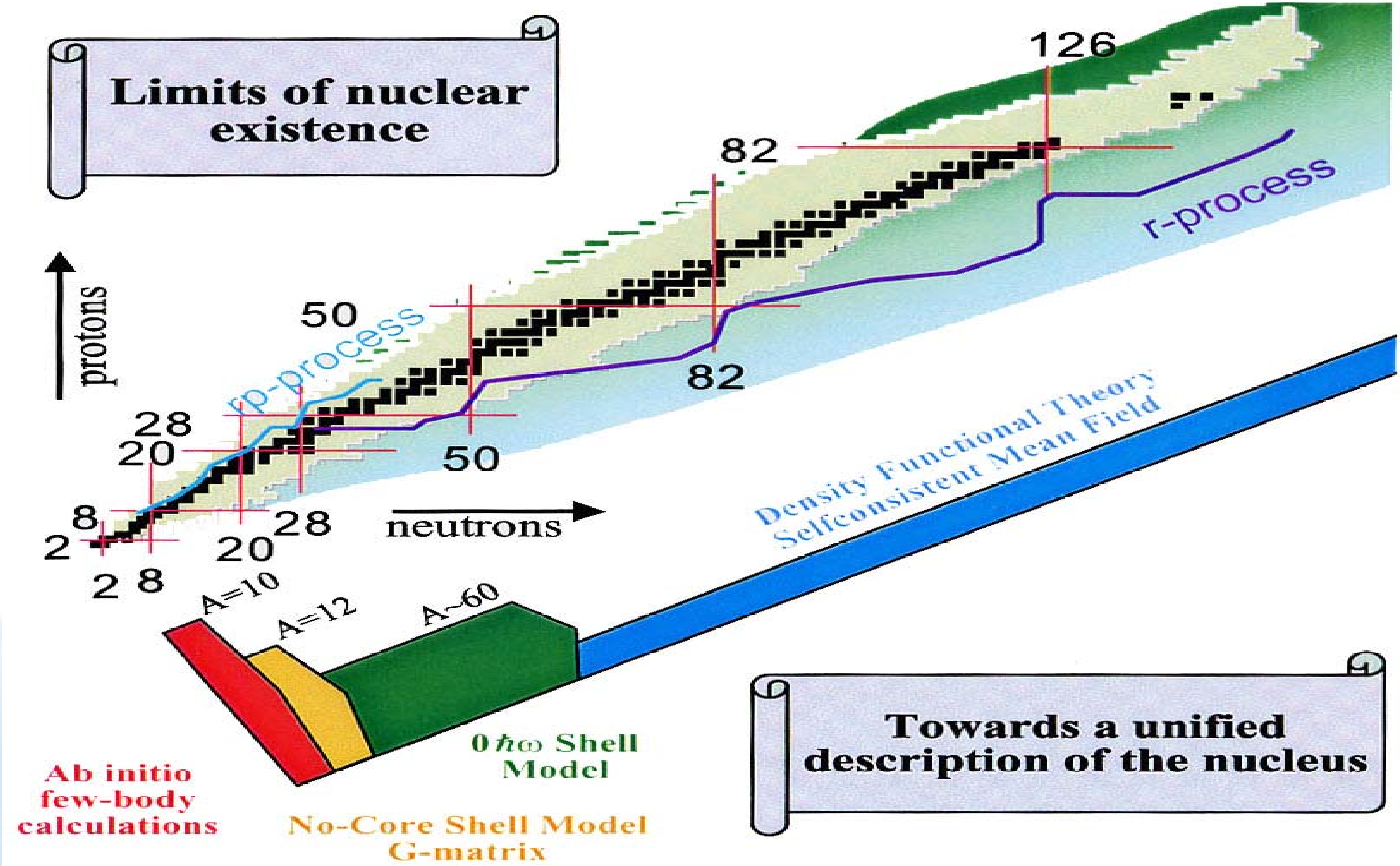
Terra incognita — huge gene pool of new nuclei

We can customize our system – fabricate "designer" nuclei to *isolate and amplify* specific physics or interactions


Nuclear Landscape
Super Heavies
Fewer than 300 nuclei
126
82
Proton Drip Line
proton number Z
50
82
28
20
50
8
2
28
20
2
8
known nuclei
terra incognita
Neutron Drip Line
neutron number N
126
82
50
28
20
8
2
0j15/2
2d5/2
0i11/2
1g9/2
2p1/2
1f5/2
2p3/2
0i13/2
0h9/2
1f7/2
1d3/2
2s1/2
0h11/2
0g7/2
1d5/2
0g9/2
1p1/2
0f5/2
1p3/2
0f7/2
0d3/2
1s1/2
0d5/2
0p1/2
0p3/2
0s1/2

The Theoretical Landscape

Experiment and Theory are NOT separate sciences!!!!!



Sizes and forces (very basic)

How big is a nucleus ??

Sizes and forces (very basic)

Uncertainty principle

$$\Delta E \Delta t > \frac{\hbar}{2}$$

Substitute …

$$E = mc^2 \qquad \mathrm{v} = x/t$$

…to give

$$\Delta m \frac{\Delta x}{c} > \frac{\hbar}{2}$$

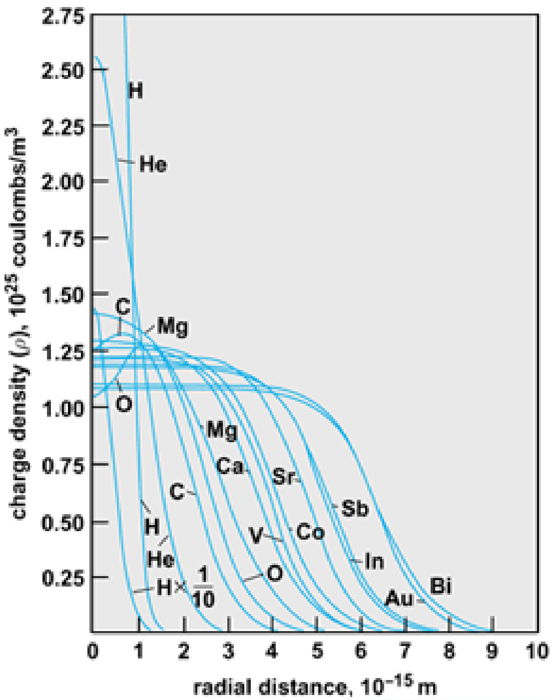
Nuclear force - pion exchange

$$\Delta m \sim 140\ MeV$$

$$\hbar c/_2 \sim 10^{-13}\ MeV \cdot m$$

$$\Rightarrow \quad \Delta x \sim 10^{-15} m$$

Nuclei are on the fermi scale



From electron scattering we know nuclear density is independent of A

$$\rho = A/_V = const$$

$$V \sim A \sim R^3$$

$$\Rightarrow \quad R = R_o A^{1/3}$$

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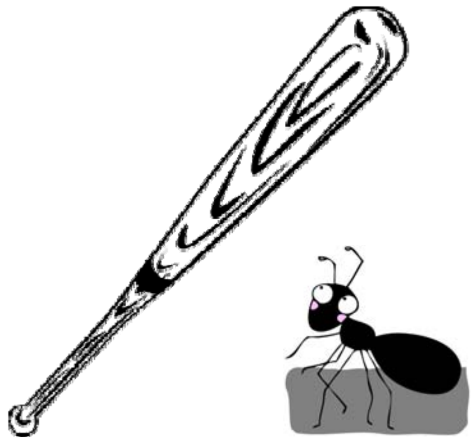
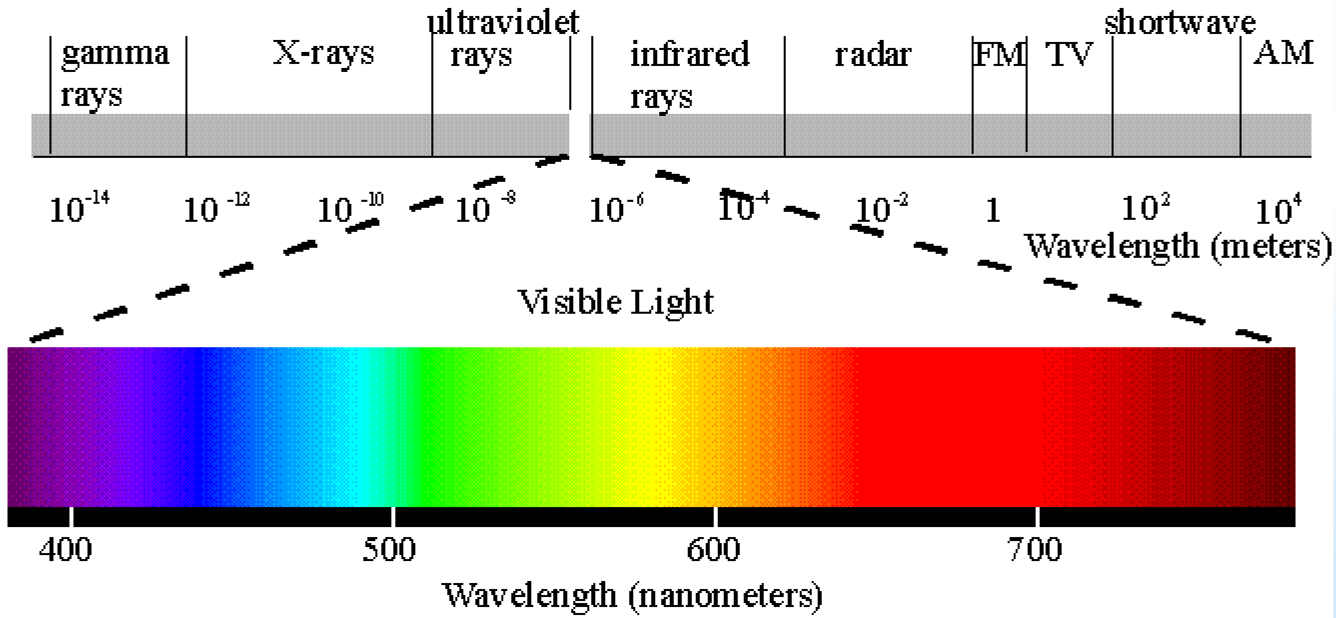
Choosing the right probe



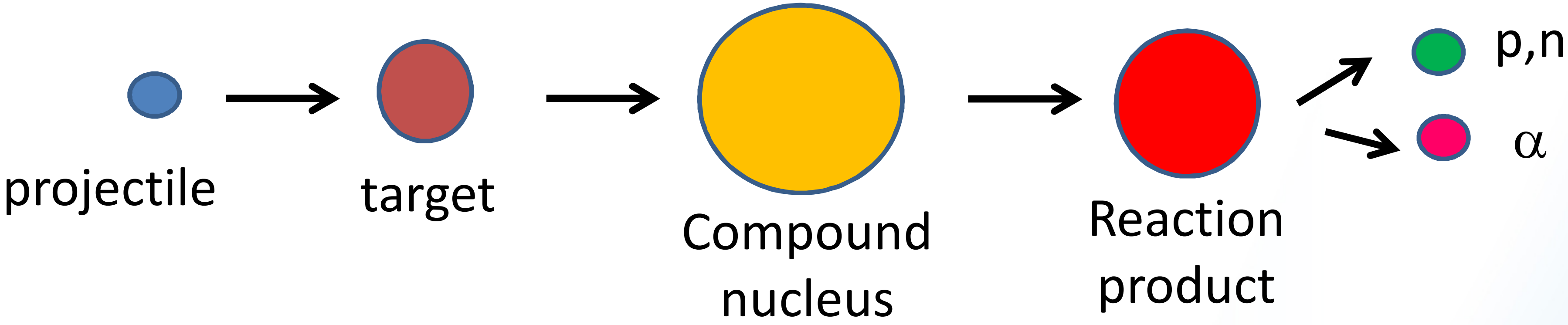
Energy of probe related to size of probee and production device

What's as big as a nucleus??

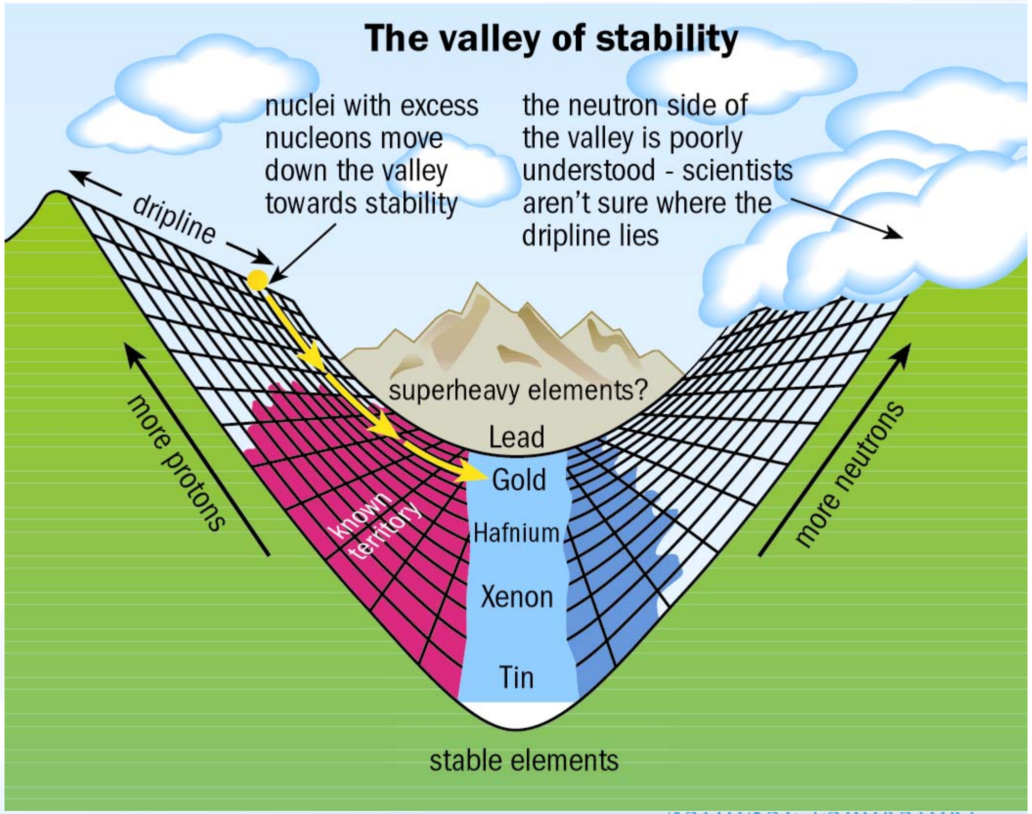
Another nucleus !!



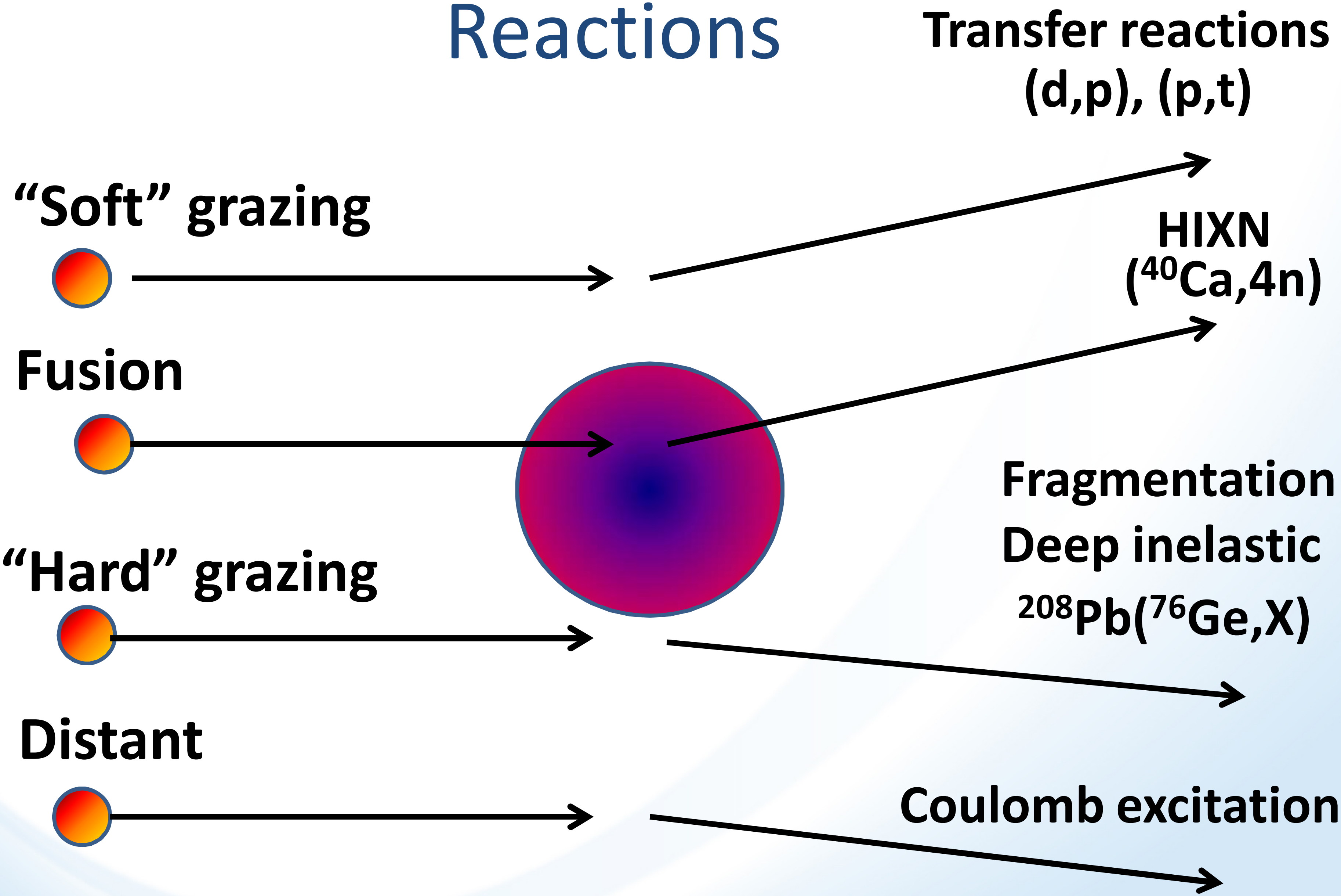
Schematic view of nuclear reactions



- ❑ Gamma ray
- ❑ Neutron
- ❑ Light charged particle
- ❑ Heavy ion
- ❑ Radioactive decay



Reactions

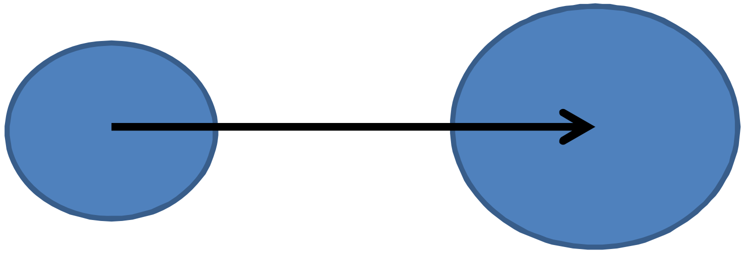

Transfer reactions
(d,p), (p,t)
"Soft" grazing
HIXN
(^{40}Ca,4n)
Fusion
Fragmentation
Deep inelastic
^{208}Pb(^{76}Ge,X)
"Hard" grazing
Distant
Coulomb excitation

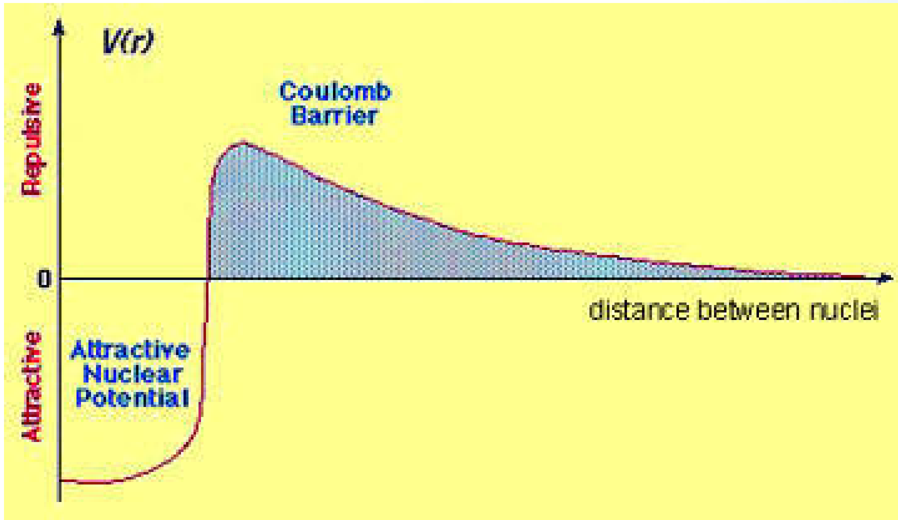
Heavy Ions at the Coulomb barrier:

VERY Classical

What does it take to get two nuclei to fuse??

Need to overcome the Coulomb barrier





$$R = R_o A^{1/3}$$

$$V \sim \frac{1.24 * Z_b Z_t}{(A_b^{1/3} + A_t^{1/3})}$$

Heavy-ion Fusion Evaporation Reactions

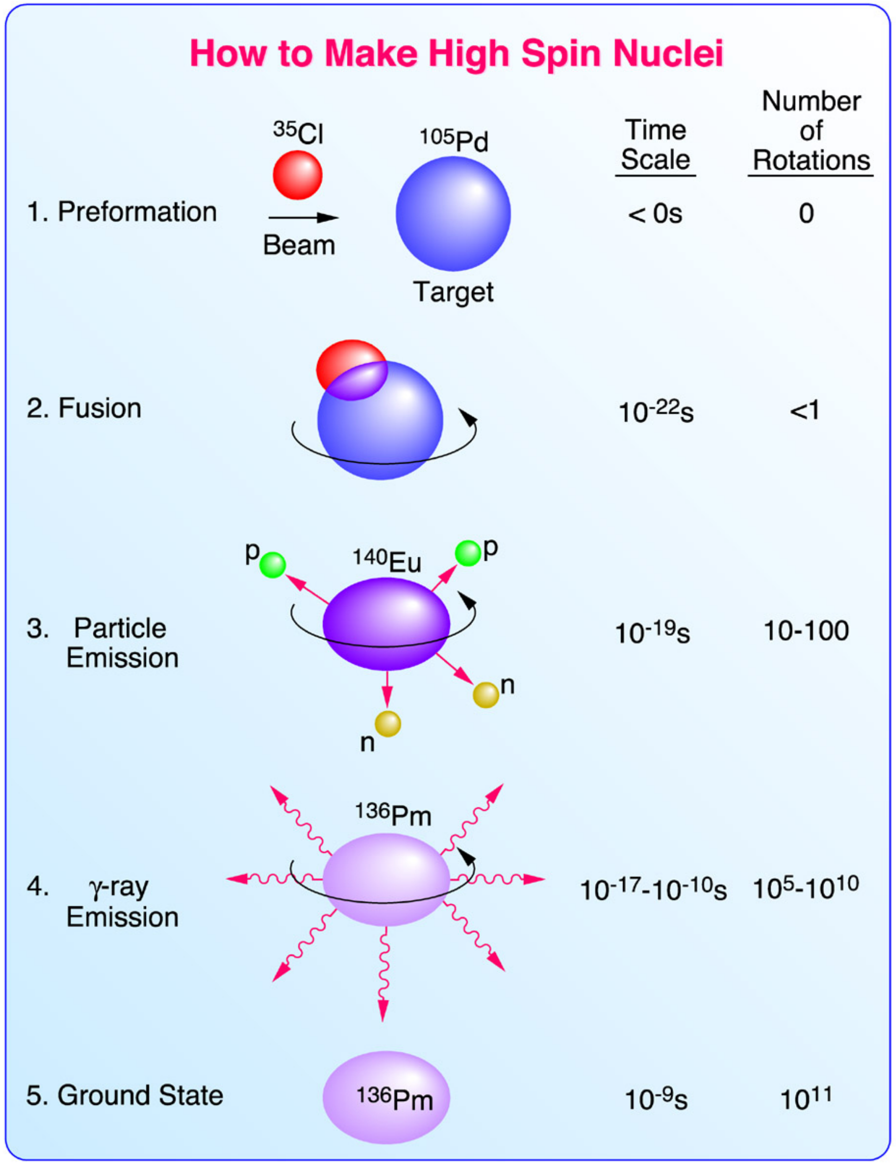
The appeal of near barrier heavy ions

The heavy ion era (1970 ~ ????) opened up the proton-rich nuclei landscape for exploration, from stability to beyond the proton drip line.

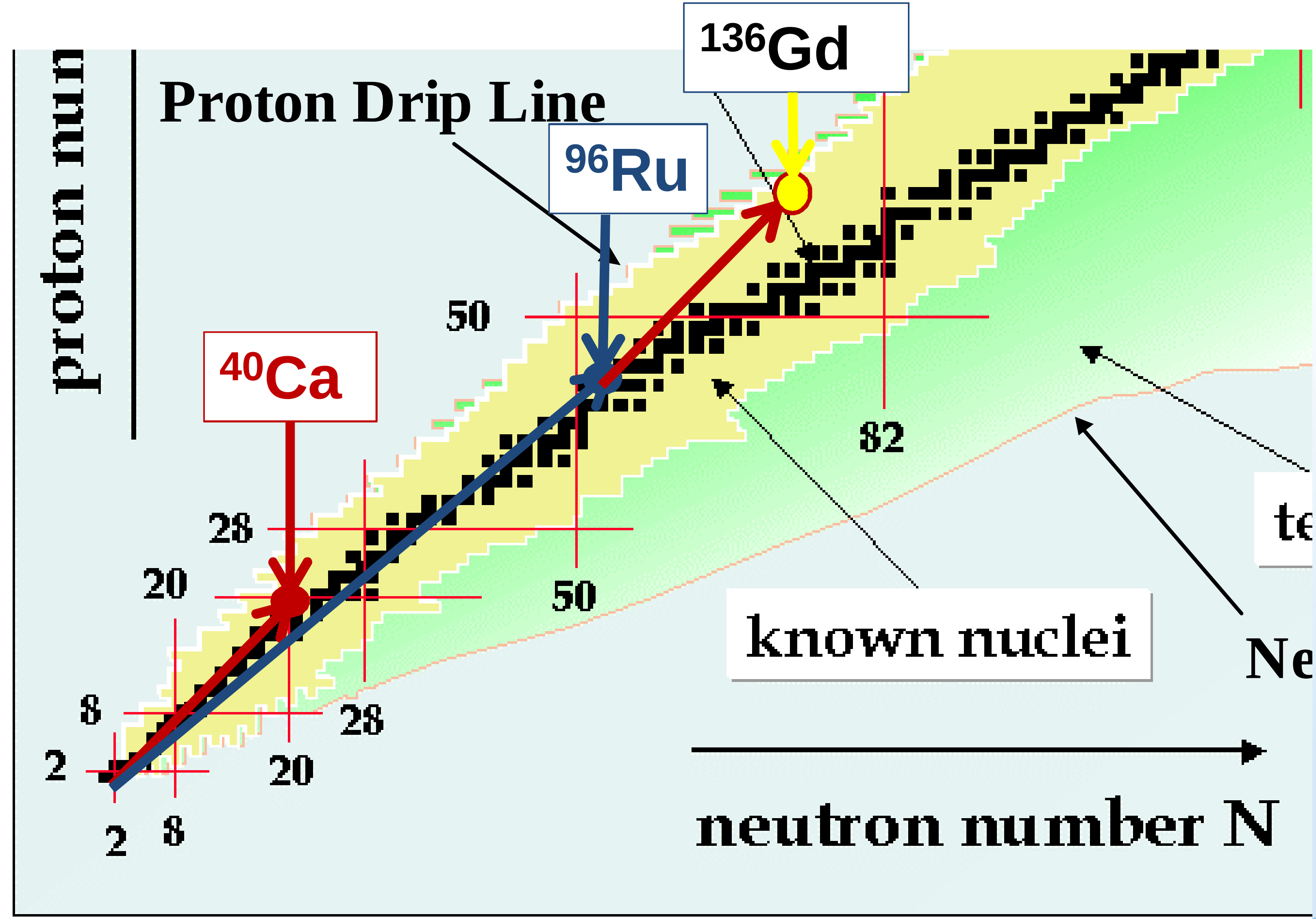
It also opened the cornucopia of High Spin Phenomena

And the path to very heavy nuclei.

Taming Heavy ion fusion and turning it into a spectroscopy tool took two decades.

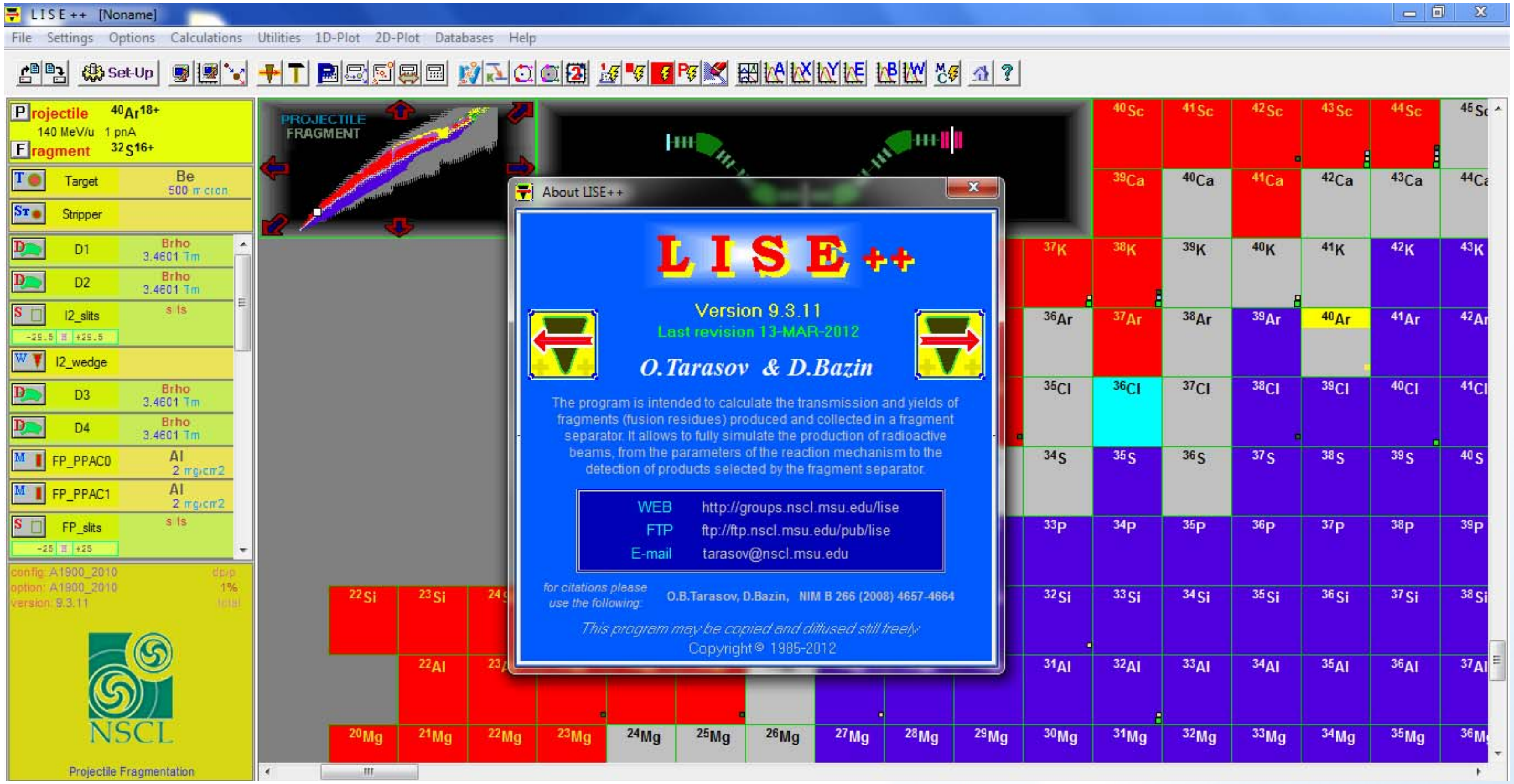


$^{40}Ca + ^{96}Ru \rightarrow ^{136}Gd^{*}$



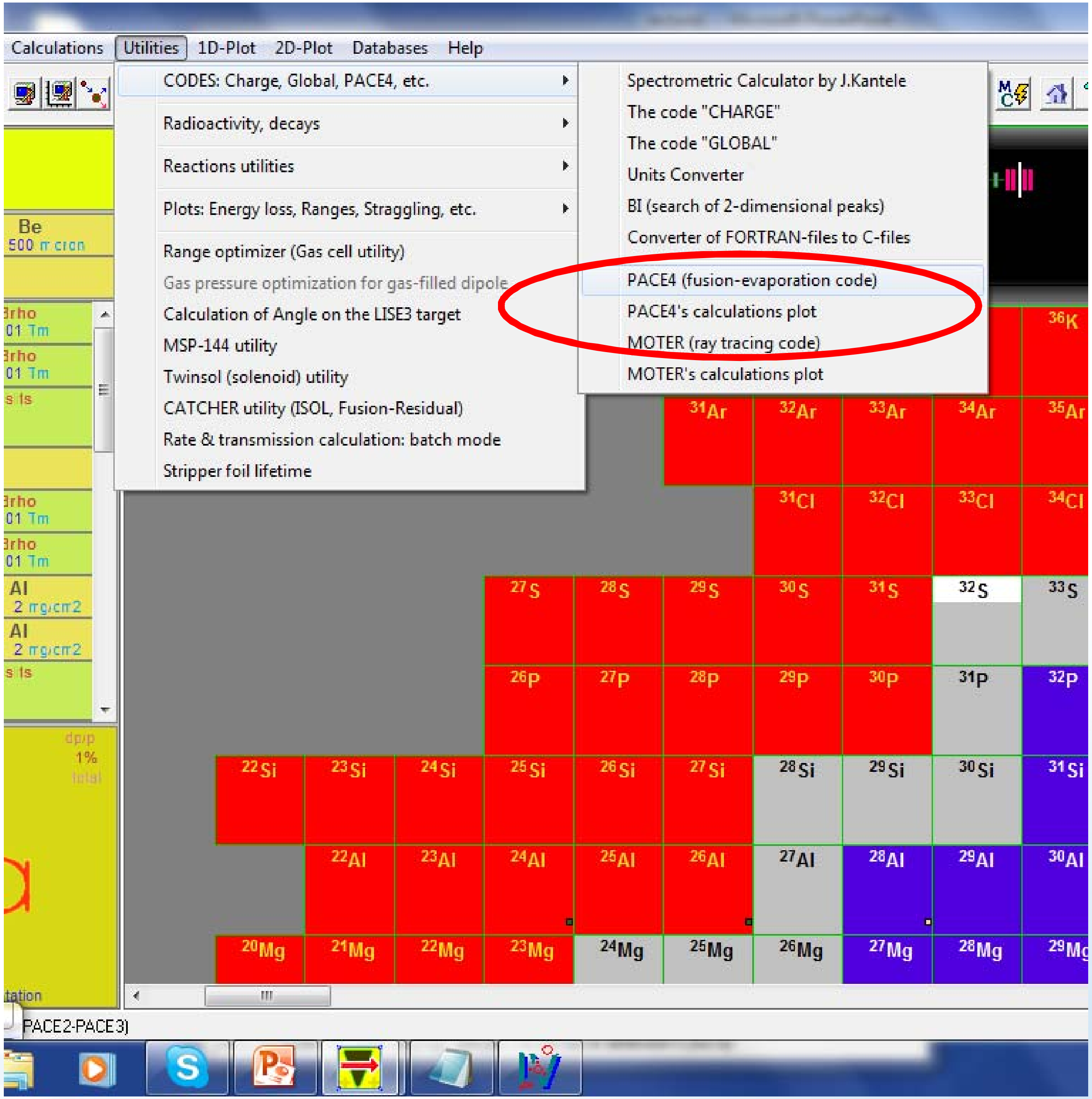
(Almost) Always leads to proton-rich nuclei

A nice tool for planning experiments …



- Designed for fragmentation reactions
- Lots of good basic calculators

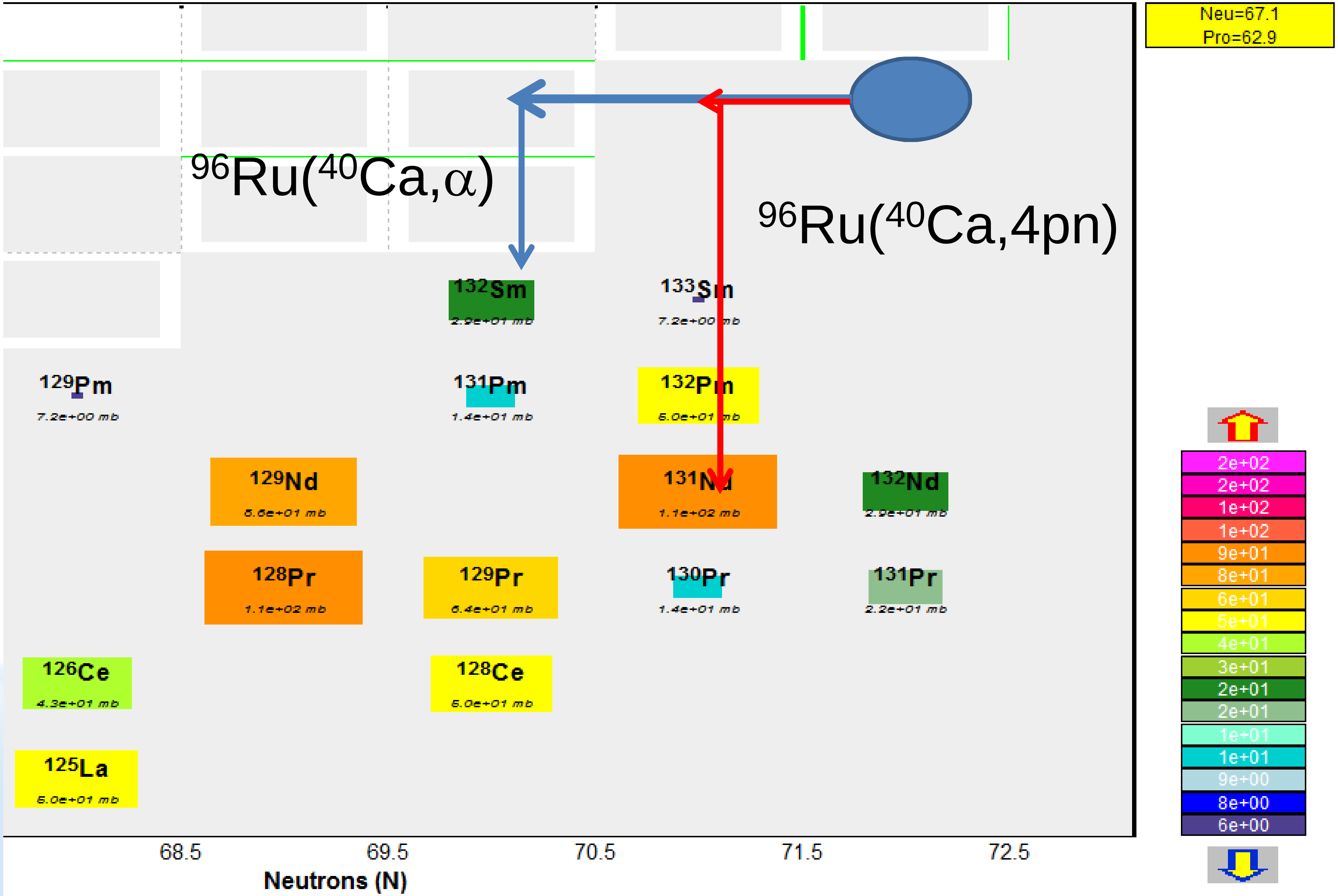
http://lise.nscl.msu.edu/lise.html

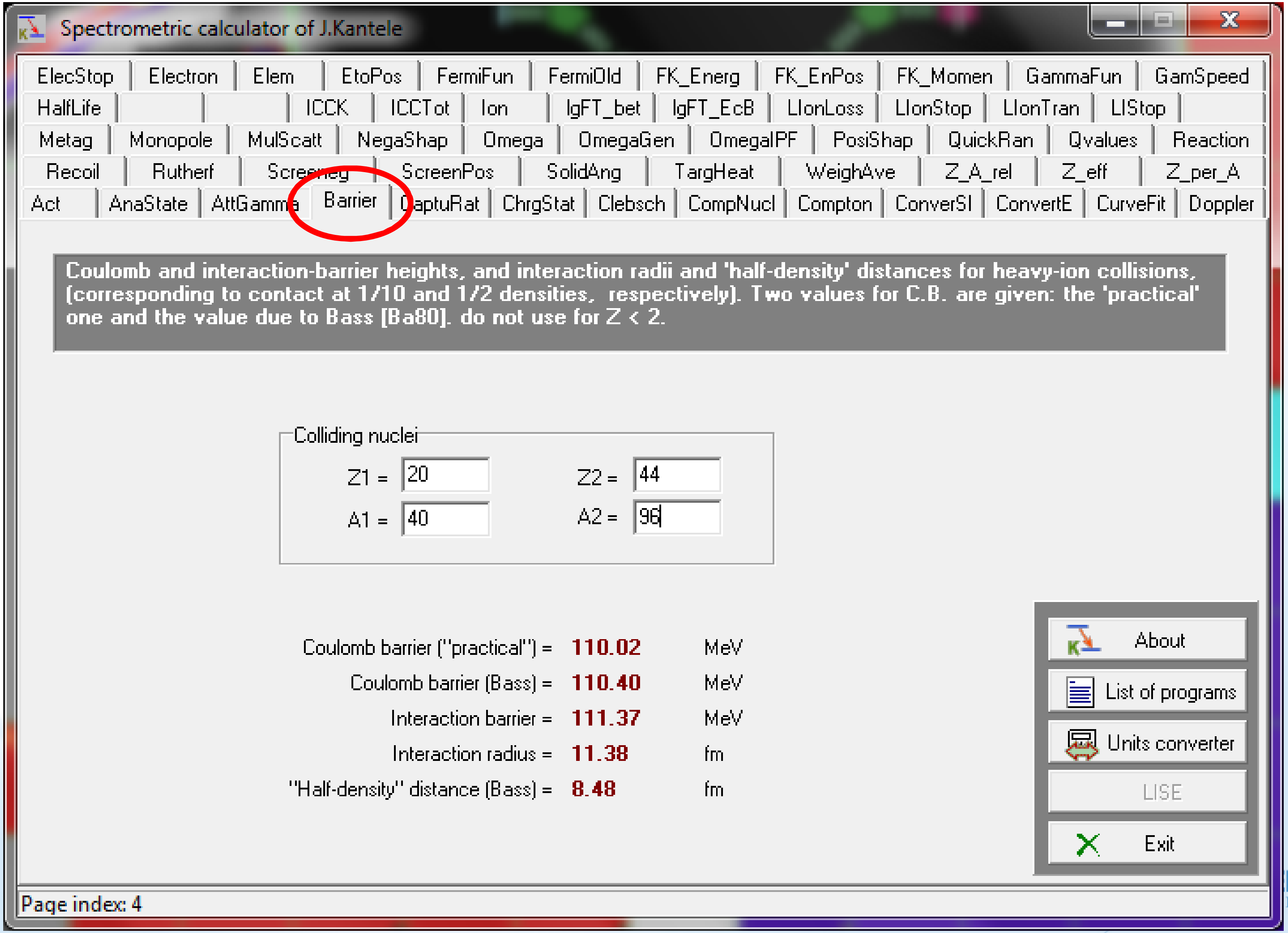


Calculations
Utilities
1D-Plot
2D-Plot
Databases
Help
CODES: Charge, Global, PACE4, etc.
Radioactivity, decays
Reactions utilities
Plots: Energy loss, Ranges, Straggling, etc.
Range optimizer (Gas cell utility)
Gas pressure optimization for gas-filled dipole
Calculation of Angle on the LISE3 target
MSP-144 utility
Twinsol (solenoid) utility
CATCHER utility (ISOL, Fusion-Residual)
Rate & transmission calculation: batch mode
Stripper foil lifetime
Spectrometric Calculator by J.Kantele
The code "CHARGE"
The code "GLOBAL"
Units Converter
BI (search of 2-dimensional peaks)
Converter of FORTRAN-files to C-files
PACE4 (fusion-evaporation code)
PACE4's calculations plot
MOTER (ray tracing code)
MOTER's calculations plot
PACE2-PACE3)

Cross-sections (PACE4)

EVAPORATION - Compound nucleus ^{136}Gd; Mode 1
Excitation energy 65.8 MeV
Compound nucleus formation cross section: 7.15e+02 mb




Spectrometric calculator of J.Kantele
ElecStop
Electron
Elem
EtoPos
FermiFun
FermiOld
FK_Energ
FK_EnPos
FK_Momen
GammaFun
GamSpeed
HalfLife
ICCK
ICCTot
Ion
IgFT_bet
IgFT_EcB
LIonLoss
LIonStop
LIonTran
LIStop
Metag
Monopole
MulScatt
NegaShap
Omega
OmegaGen
OmegaIPF
PosiShap
QuickRan
Qvalues
Reaction
Recoil
Rutherf
ScreenPos
SolidAng
TargHeat
WeighAve
Z_A_rel
Z_eff
Z_per_A
Act
AnaState
Barrier
ChrgStat
Clebsch
CompNucl
Compton
ConverSI
ConvertE
CurveFit
Doppler
Coulomb and interaction-barrier heights, and interaction radii and 'half-density' distances for heavy-ion collisions, (corresponding to contact at 1/10 and 1/2 densities, respectively). Two values for C.B. are given: the 'practical' one and the value due to Bass [Ba80]. do not use for Z < 2.
Colliding nuclei
Z1 = 20
Z2 = 44
A1 = 40
A2 = 96
Coulomb barrier ("practical") = 110.02 MeV
Coulomb barrier (Bass) = 110.40 MeV
Interaction barrier = 111.37 MeV
Interaction radius = 11.38 fm
"Half-density" distance (Bass) = 8.48 fm
About
List of programs
Units converter
LISE
Exit
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Calculating the reaction yield

of reactions/sec = $N_{beam} N_{target} \sigma$

Typical beam current ~ 1-100 enA

$N_{beam} = 10x10^{-9} / 1.6x10^{-19}$ → 10^{10} particles/sec

$N_{target} = [\, N_A/A]$*thickness

Typical target thickness ~ 0.1 – 10 mg/cm^2

$N_{target} = [\, 6x10^{23}/100]*1x10^{-3}$ → $6x10^{18}$ particles/cm^2

Looks like we are winning …

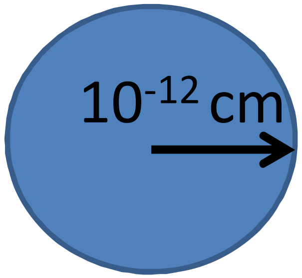
Calculating the reaction yield

$$\# \text{ of reactions/sec} = N_{beam} N_{target} \sigma$$

$N_{beam} = 10\text{x}10^{-9} / 1.6\text{x}10^{-19}$ → 10^{10} particles/sec

$N_{target} = [\ 6\text{x}10^{23}/100]*1\text{x}10^{-3}$ → $6\text{x}10^{18}$ particles/cm^2

Cross section: remember the size of a nucleus



Probability of "hitting" the nucleus ~ πR^2

$$1 \text{ barn (b)} = 10^{-24} \text{ cm}^2$$

Typical fusion cross sections are in the mb's

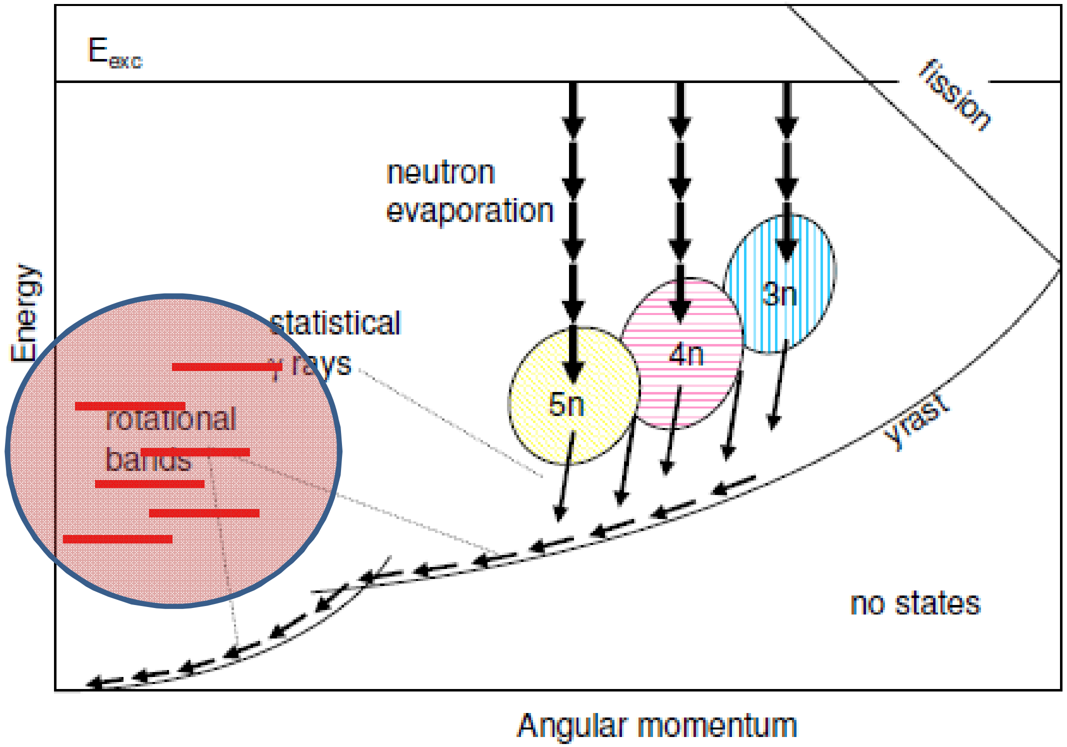
$$\# \text{ of reactions/sec} = 10^{10} \text{ x } 6\text{x}10^{18} \text{ x } 100\text{x}10^{-27}$$

$$\# \text{ of reactions/sec} = 6000$$

Decay of the Compound Nucleus

Heavy beam:

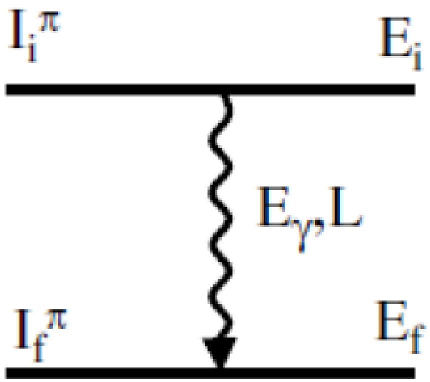
- Need high energy
- Brings in high angular momentum



Light beam:

- Can use lower E
- Brings in less angular momentum

Gamma-Ray Emission



$$E_\gamma = E_i - E_f$$

$$\left|I_i - I_f\right| \leq L \leq I_i + I_f$$

$$\Delta\pi(EL) = (-1)^L$$

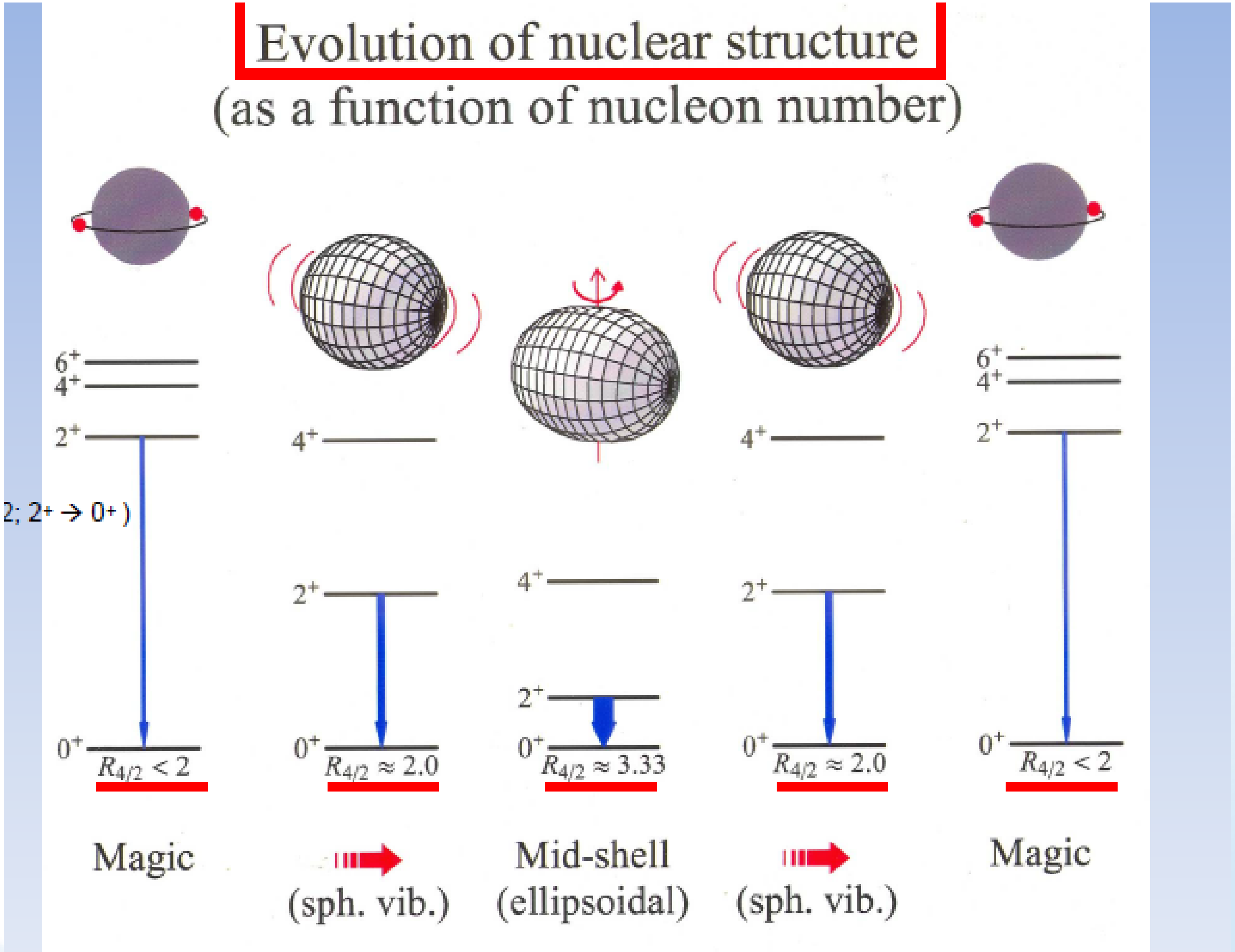
$$\Delta\pi(ML) = (-1)^{L+1}$$

Possible decay modes:

- β decay
- p,n emission
- α emission
- Internal conversion
- Fission
- γ-ray emission

Gamma-ray emission is usually the dominant decay mode

- Energy
- Spin, Parity
- Magnetic, quadrupole moment
- Lifetime
- …

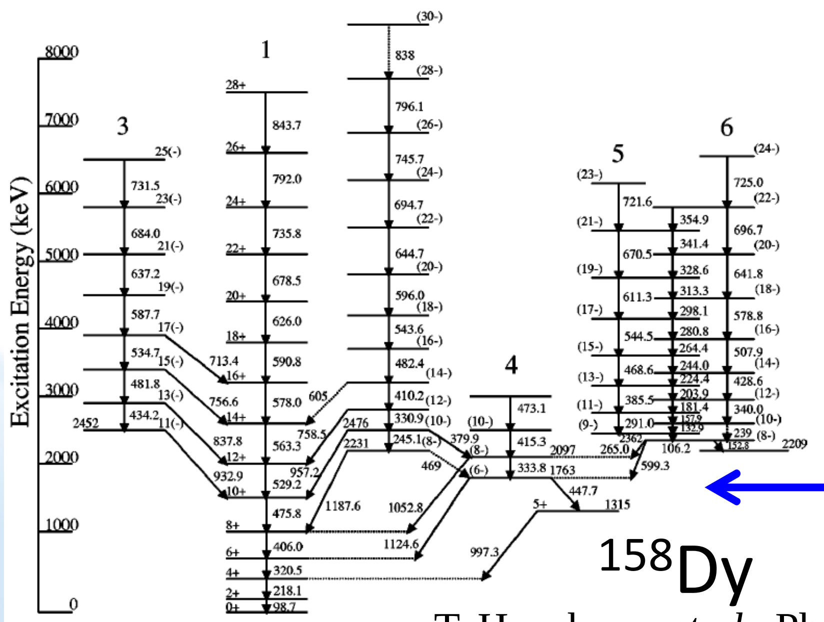

Evolution of nuclear structure
(as a function of nucleon number)
6+
4+
2+
2; 2+ → 0+)
0+
R4/2 < 2
4+
2+
0+
R4/2 ≈ 2.0
4+
2+
0+
R4/2 ≈ 3.33
4+
2+
0+
R4/2 ≈ 2.0
6+
4+
2+
0+
R4/2 < 2
Magic
(sph. vib.)
Mid-shell
(ellipsoidal)
(sph. vib.)
Magic

Gamma rays tell you something about shape

Y.X. Luo *et al.*, Nucl. Phys. A **32**, 874 (2012).

$^{118}_{48}Cd_{70}$

Non-regular pattern: Non-collective, single particle



Regular, band-like pattern: Collective; has a "shape"

^{158}Dy

T. Hayakawa *et al.*, Phys. Rev. C **68**, 067303 (2003).

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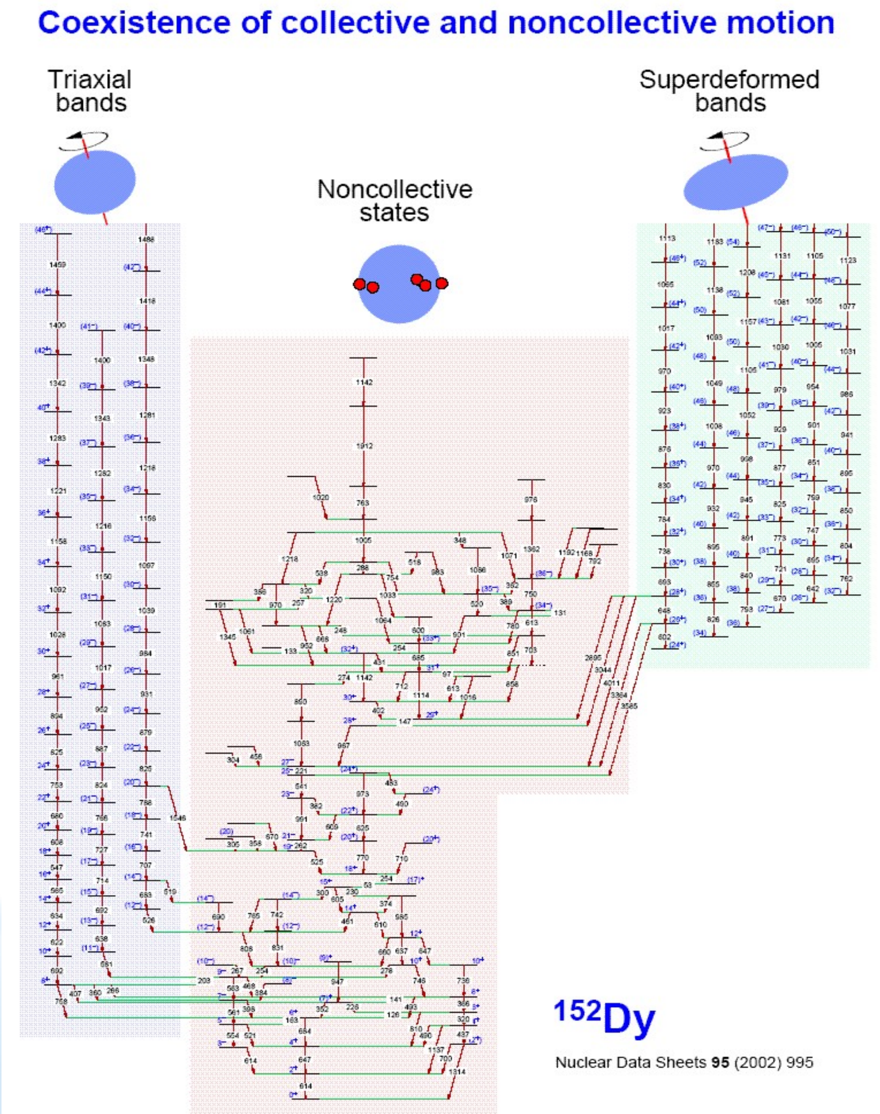
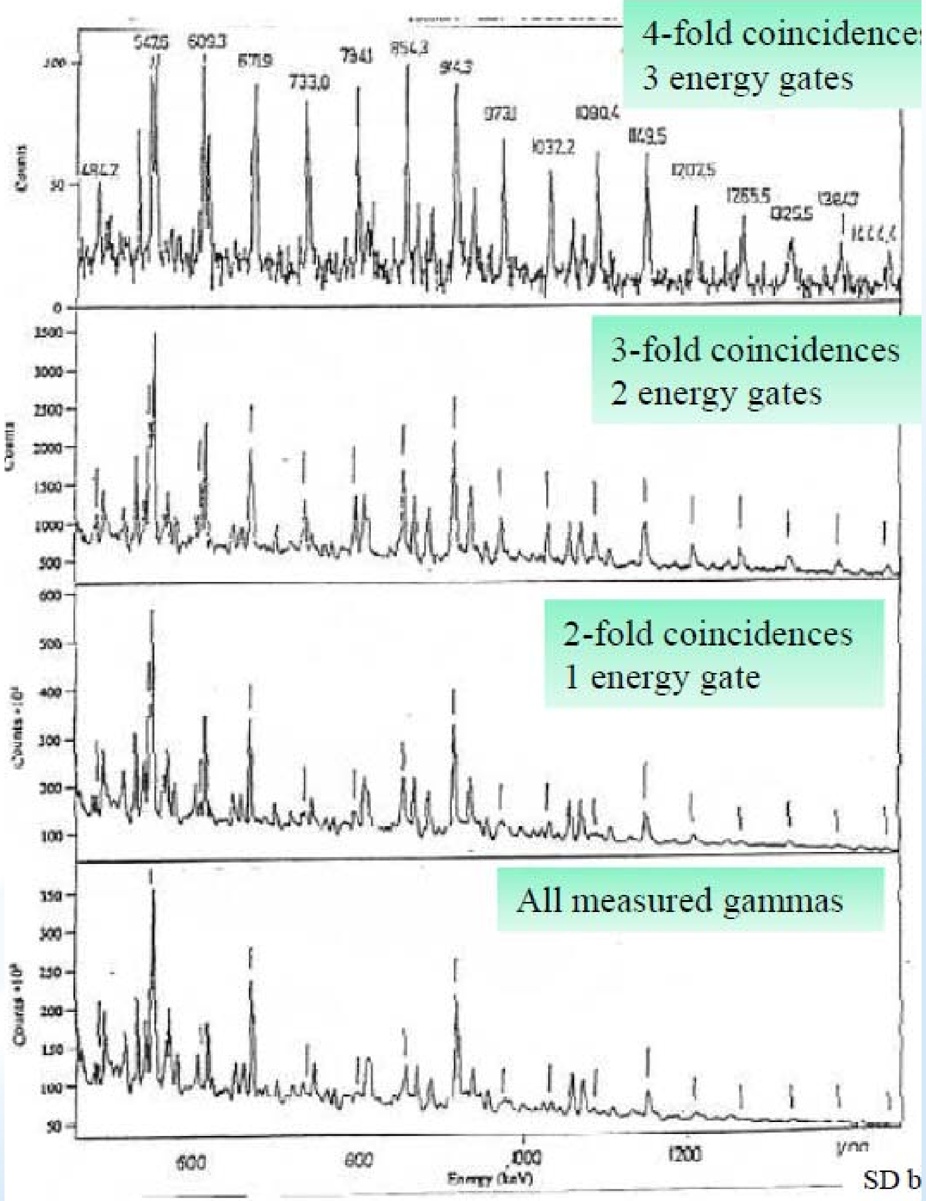
Partial Level Scheme of ^{152}Dy

… as an example of the richness of γ-ray spectroscopic information



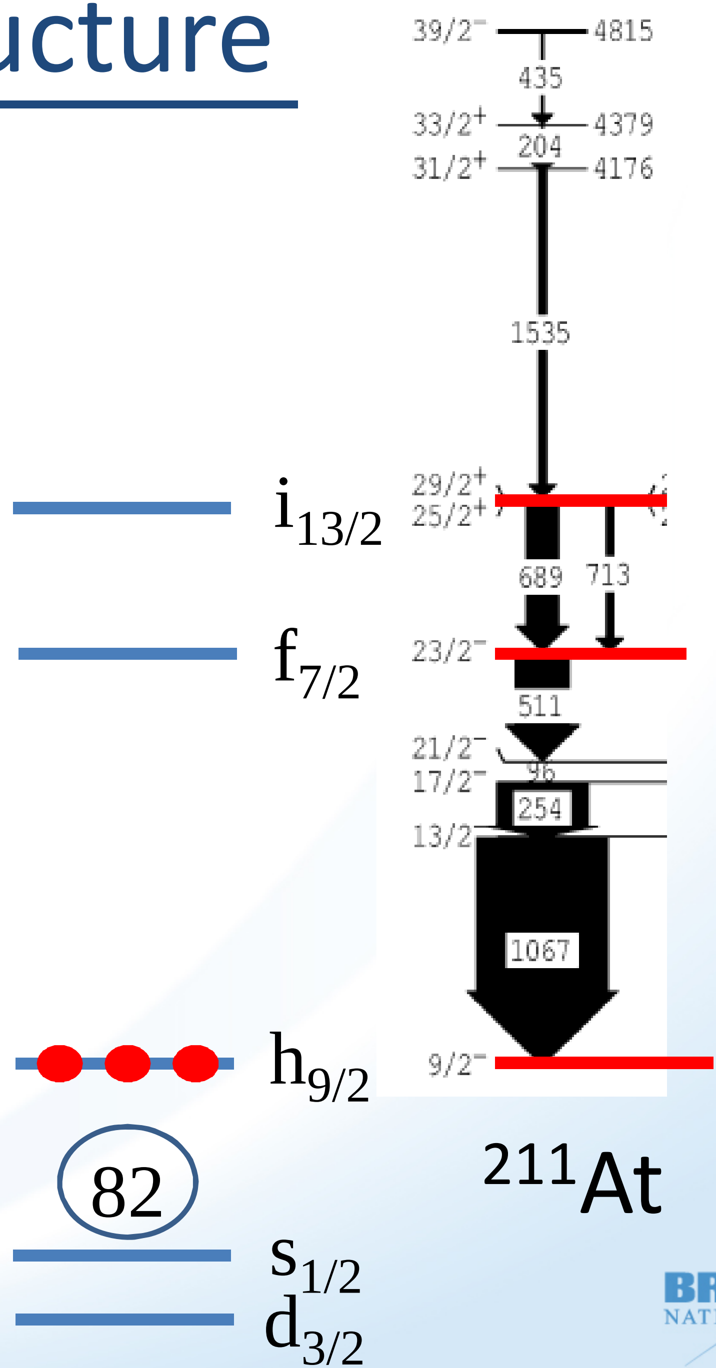


Single particle structure

^{211}At

Z=85 N=126

Low-lying structure dominated by 3 valence protons



Radiation Detectors

- **Almost all work on the same general idea**
- **When an energetic charged particle passes through matter it will rapidly slow down and lose its energy by interacting with the atoms of the material (detector or body)**
  - **Mainly with the atomic electrons**
- **It will 'kick' these electrons off of the atoms leaving a trail of ionized atoms behind it (like a vapor trail of a jet plane)**
- **Radiation detectors use a high voltage and some electronics to measure these vapor trails. They measure a (small) electric current).**
- **The larger the energy the deposited, the larger the signal measured**

Gamma-ray interactions with matter

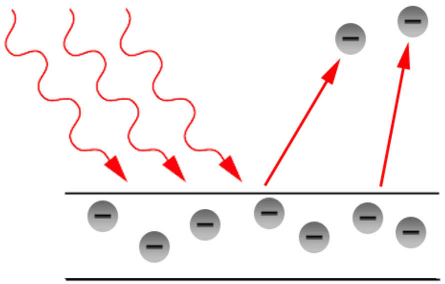
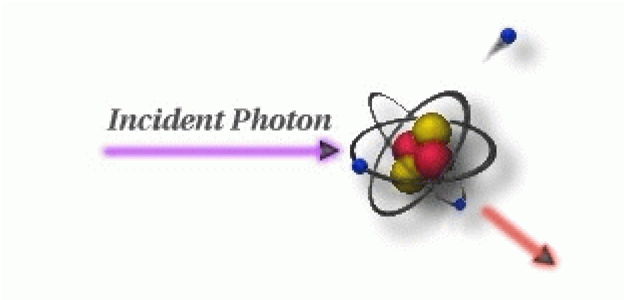
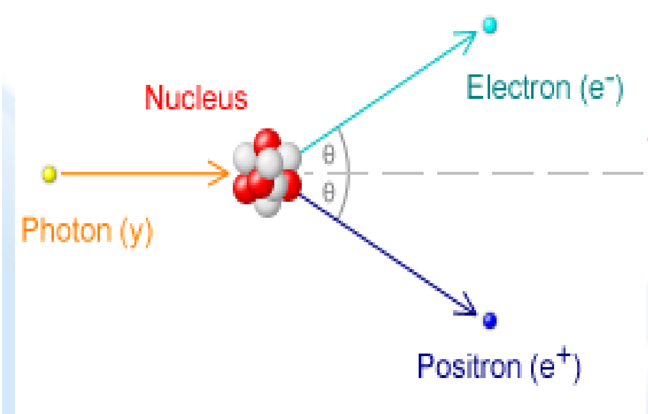


Photo effect – photoelectron is ejected carrying the total γ-ray energy



Compton Scattering – Elastic scattering of γ ray off an electron. A fraction of the γ ray energy is transferred to the electron



Pair production – In the Coulomb field of the nucleus, a positron-electron pair can be formed. The pair has γ-ray energy minus $2m_ec^2$

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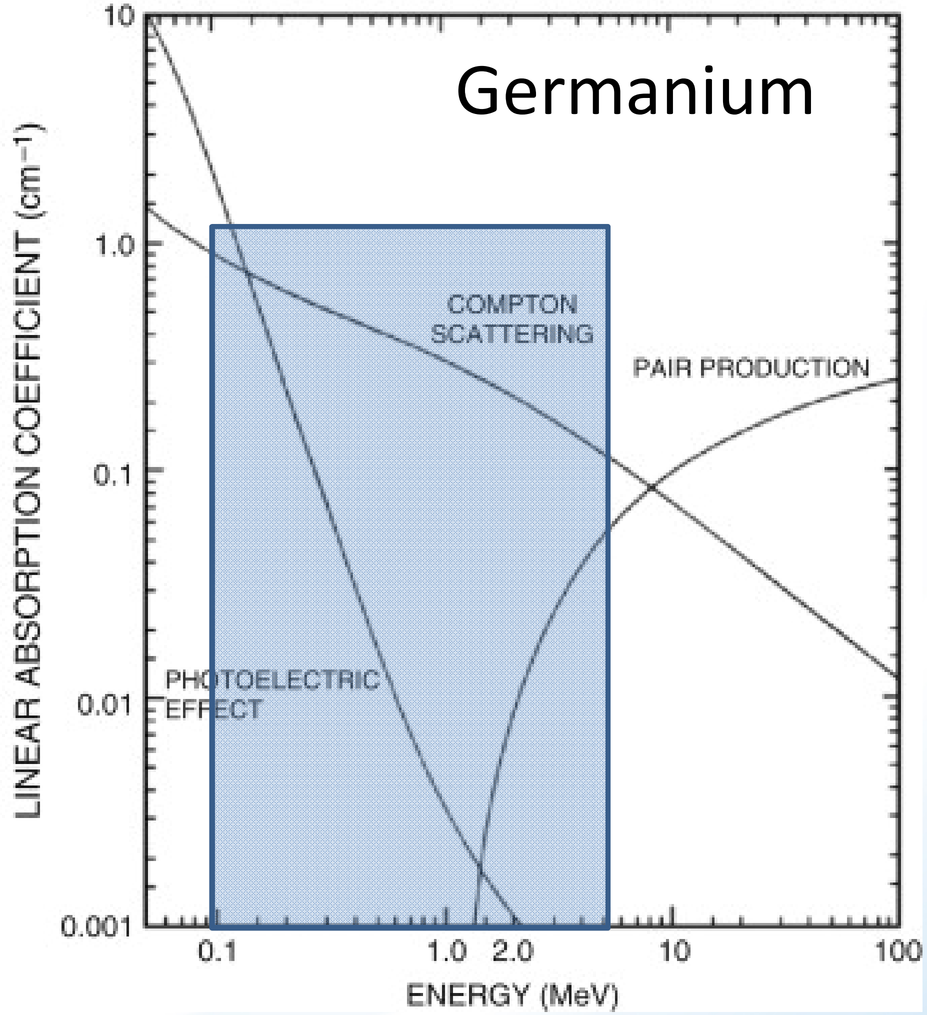
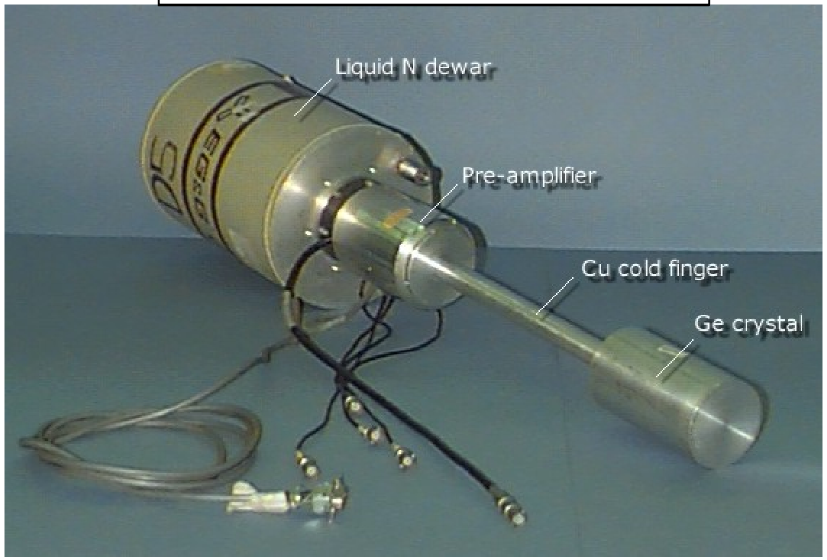
Gamma-ray interactions with matter

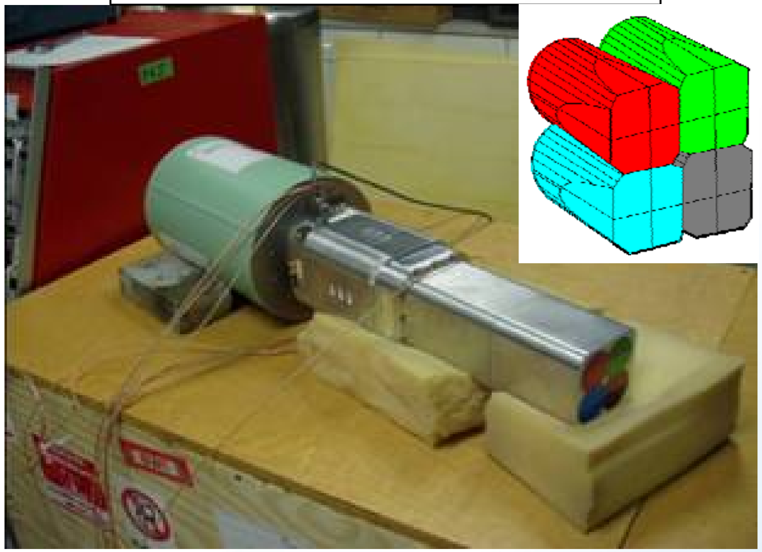


The “best” gamma-ray detector

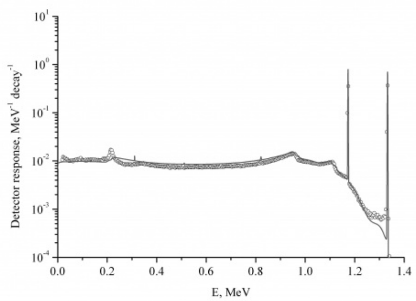
HPGe detector

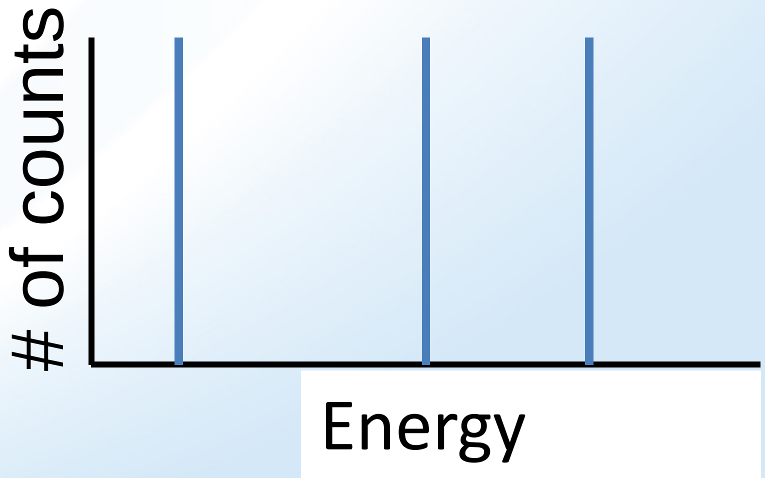


Clover detector

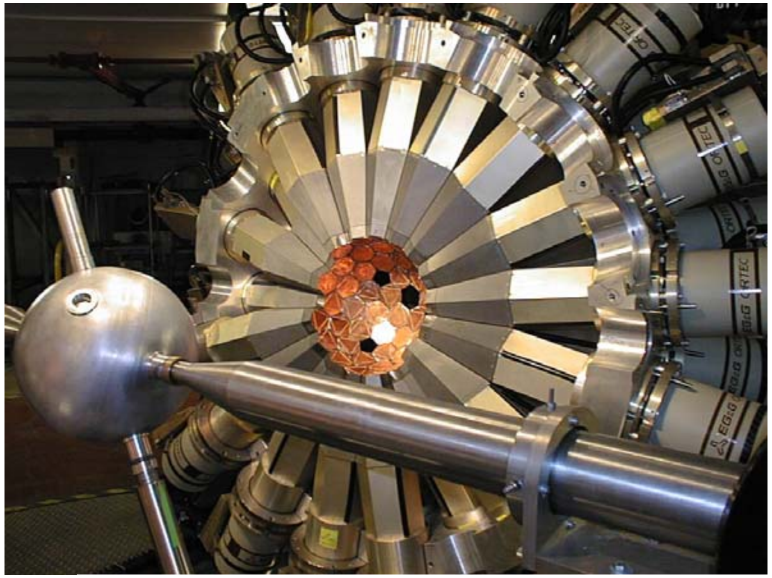


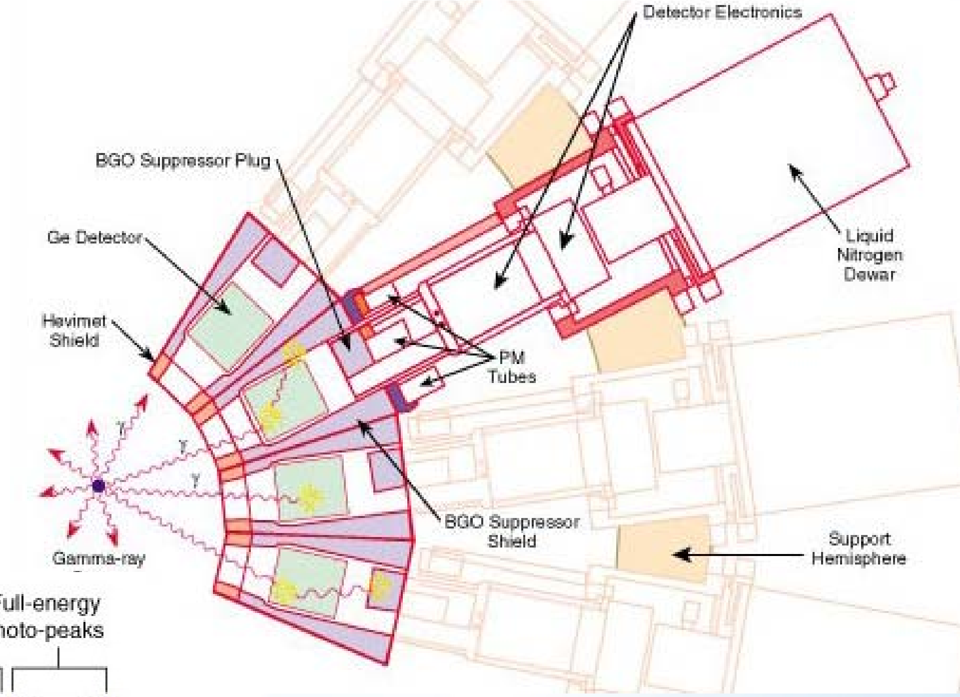
This happens about 70% of the time !!

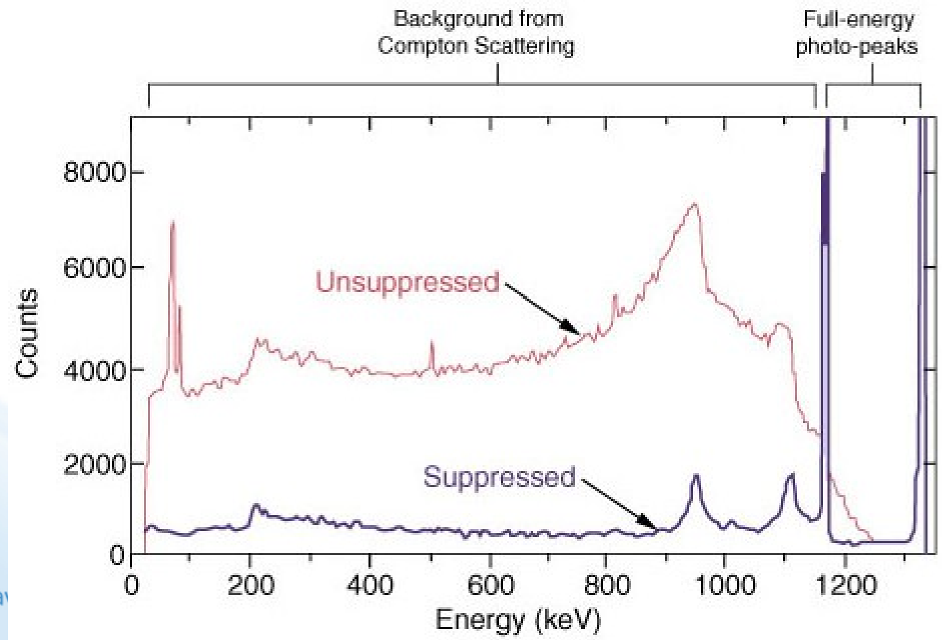


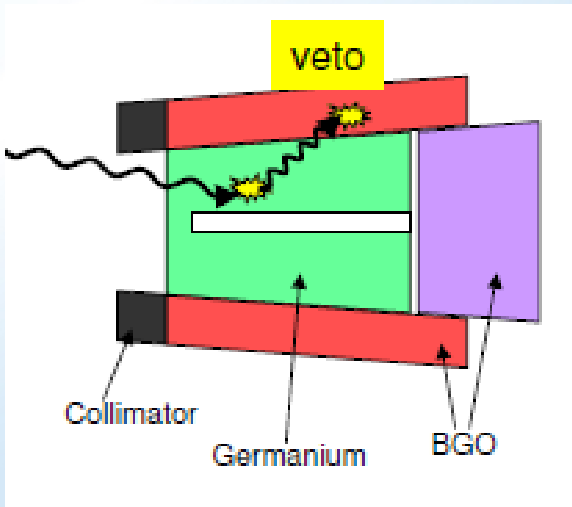


Compton Suppression



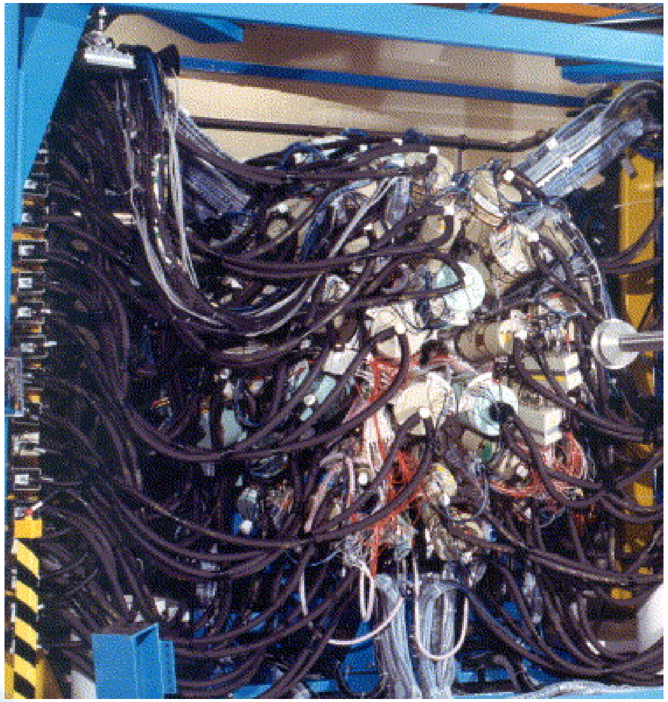




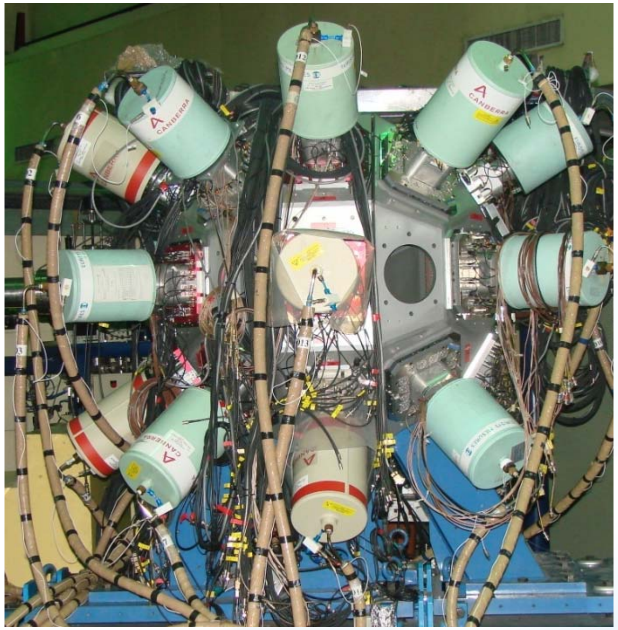


Compton Suppressed Arrays

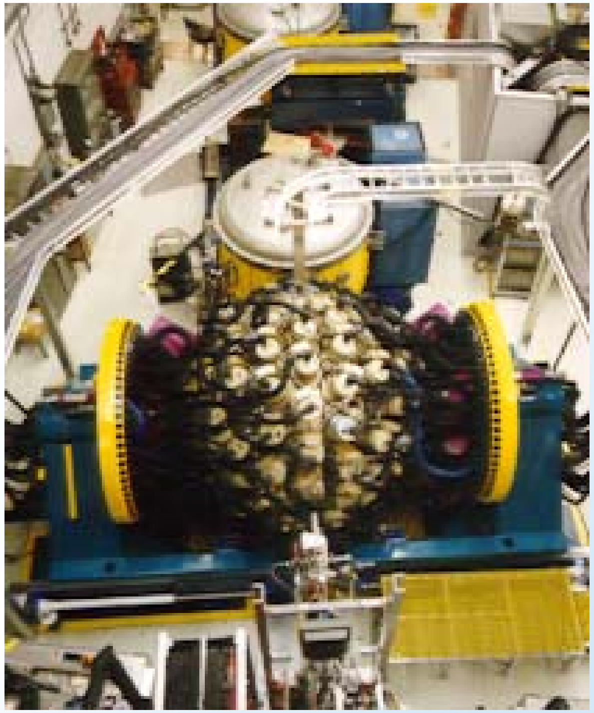
For the last ~ 15 - 20 years, large arrays of Compton-suppressed Ge detectors such as EuroBall, JUROBALL , GASP, EXOGAM, TIGRESS, INGA, Gammasphere and others have been the tools of choice for nuclear spectroscopy.



EUROBALL

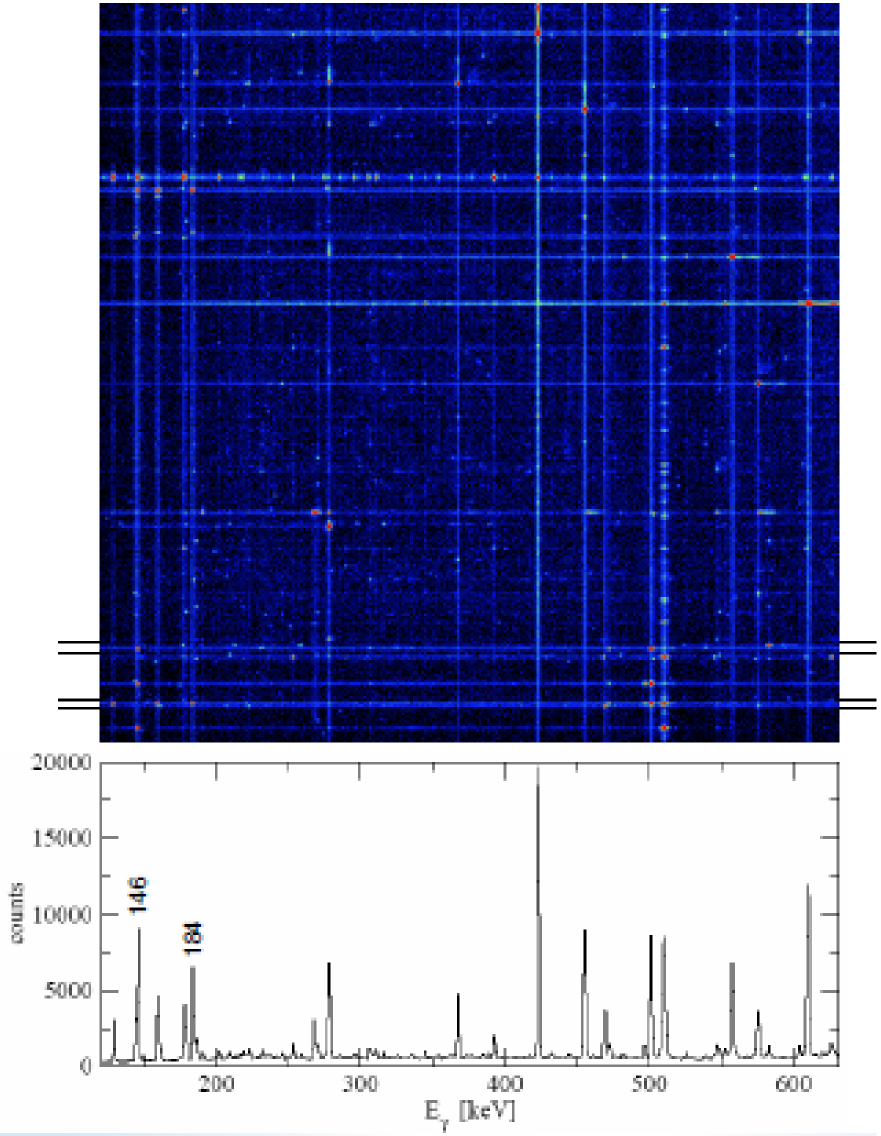


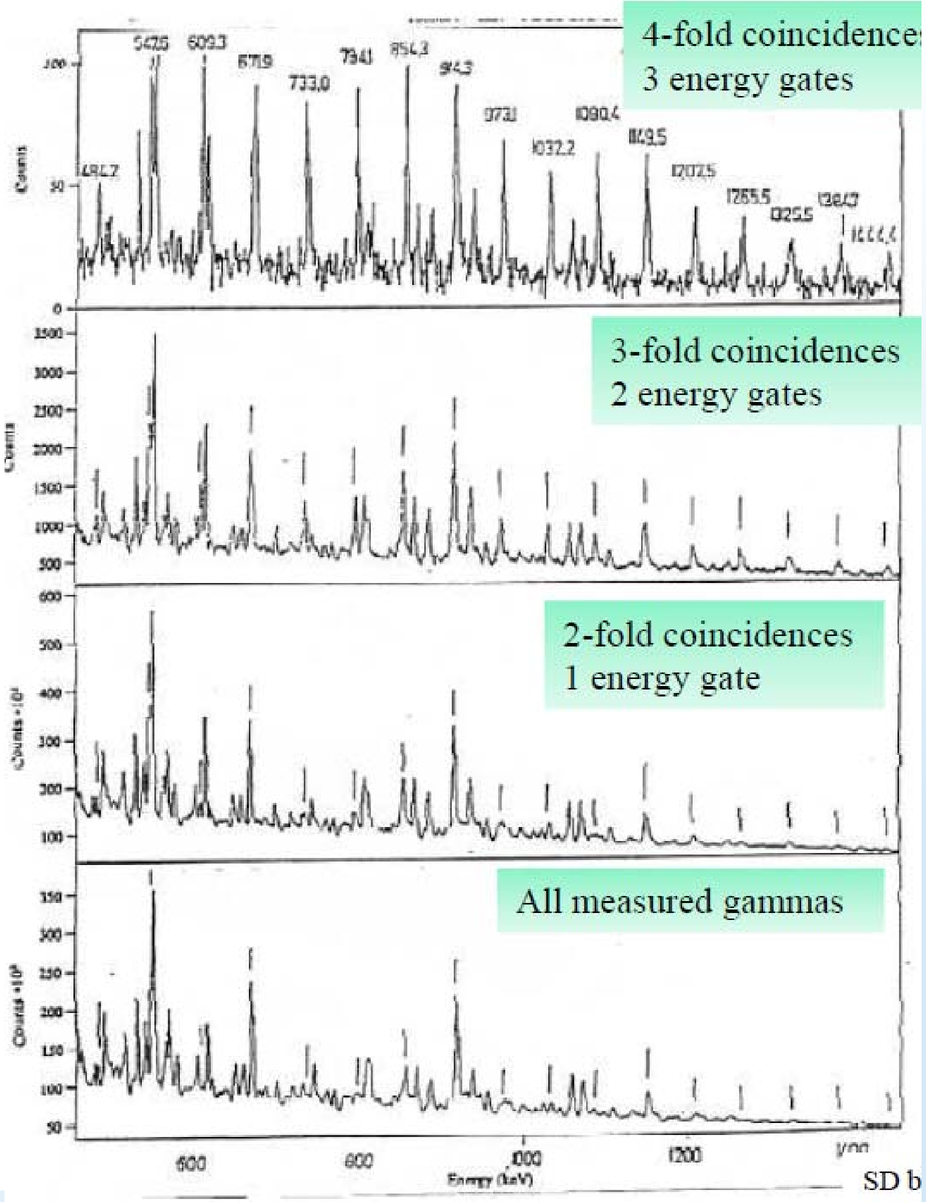
INGA

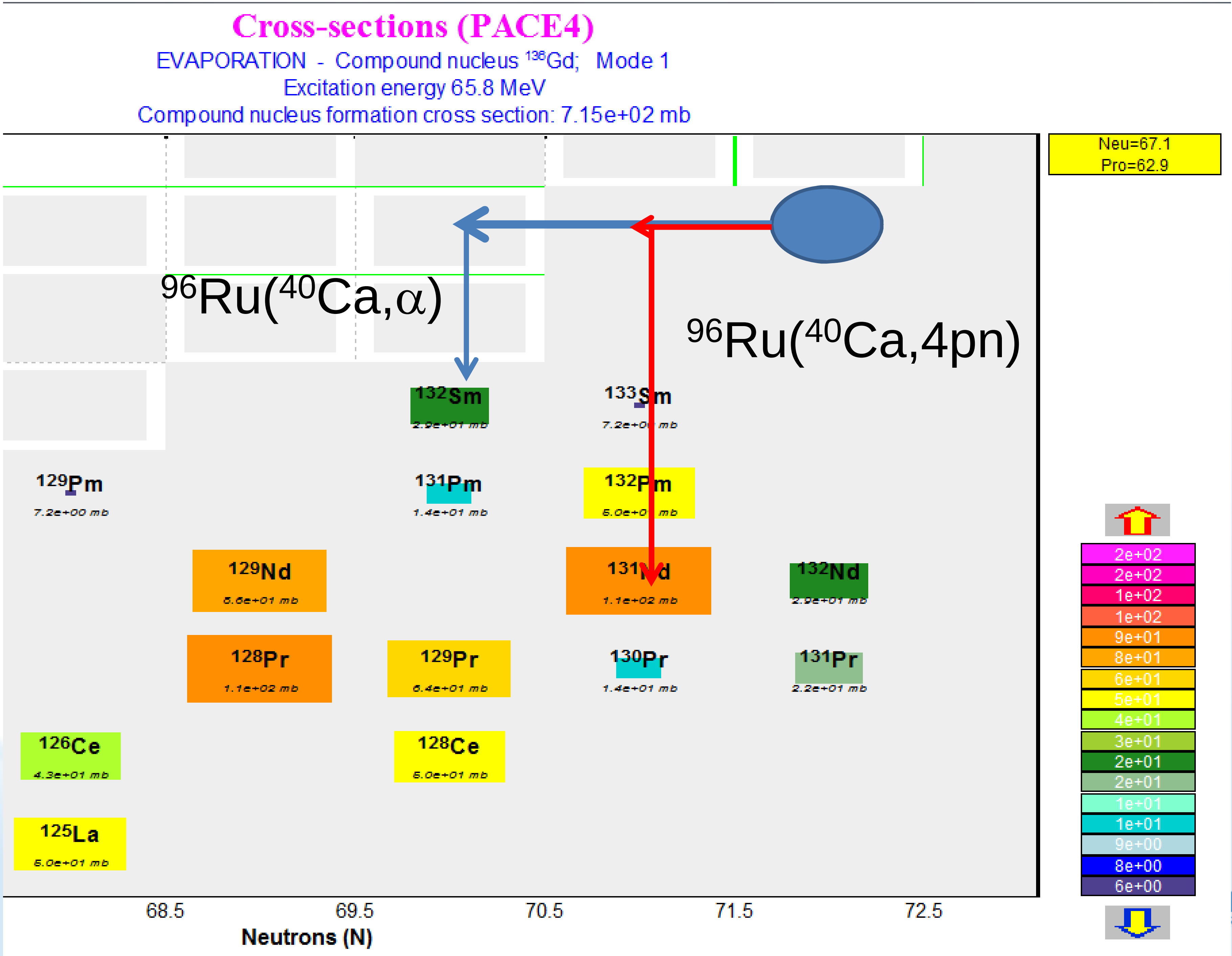


Gammasphere

γ-γ coincidence: a must in constructing a level scheme







Cross-sections (PACE4)
EVAPORATION - Compound nucleus 136Gd; Mode 1
Excitation energy 65.8 MeV
Compound nucleus formation cross section: 7.15e+02 mb
Neu=67.1
Pro=62.9
96Ru(40Ca,α)
96Ru(40Ca,4pn)
132Sm
133Sm
7.2e+00 mb
129Pm
7.2e+00 mb
131Pm
1.4e+01 mb
132Pm
129Nd
131Nd
1.1e+02 mb
132Nd
128Pr
1.1e+02 mb
129Pr
6.4e+01 mb
130Pr
1.4e+01 mb
131Pr
2.2e+01 mb
126Ce
4.3e+01 mb
128Ce
125La
2e+02
2e+02
1e+02
1e+02
9e+01
8e+01
6e+01
5e+01
4e+01
3e+01
2e+01
2e+01
1e+01
1e+01
9e+00
8e+00
6e+00
68.5
69.5
70.5
71.5
72.5
Neutrons (N)

Channel Selection for gamma-ray spectroscopy: Finding a needle in a haystack

Detection of Light Charged Particles (a,p,n)

PLUS Efficient, flexible, powerful.....inexpensive.

MINUS Countrate limited, Contaminant (Carbon etc, isotopic impurities) makes absolute identification of new nuclei difficult.

CROSS SECTION LOWER LIMIT ~100μb   that is, $\sim 10^{-4}$

Detection of Residues in Vacuum Mass Separator

PLUS True M/q, even true M measurement. With suitable focal plane detector can be ULTRA sensitive. Suppresses contaminants.

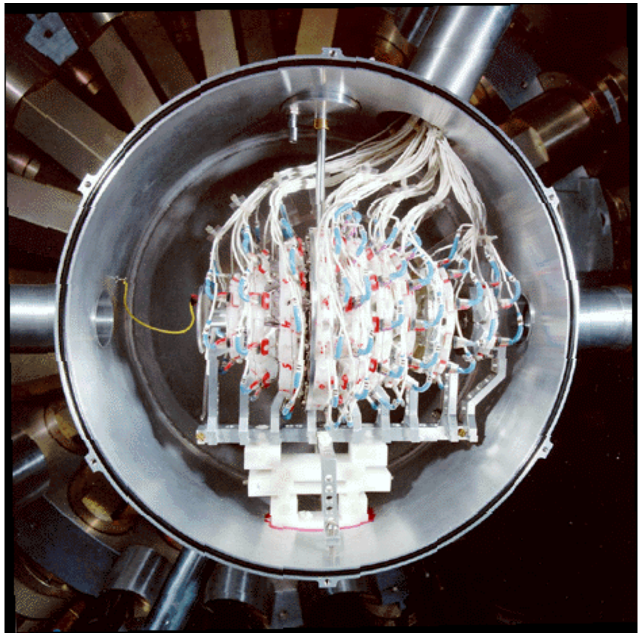
MINUS Low Efficiency

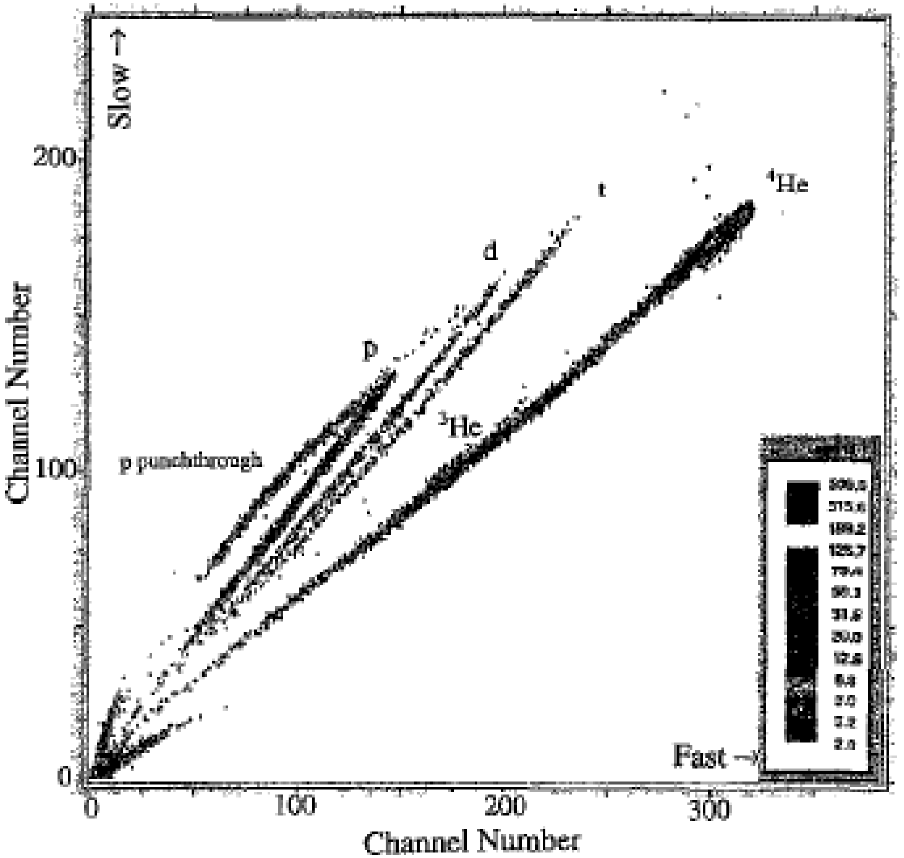
CROSS SECTION LOWER LIMIT ~100nb   that is $\sim 10^{-7}$

Detection of Residues in Gas Filled Separator

Improves efficiency of vacuum separators, at cost of mass information and cleanliness. In some cases (heavy nuclei) focal plane counters clean up the data for good sensitivity.

Microball charged particle detector

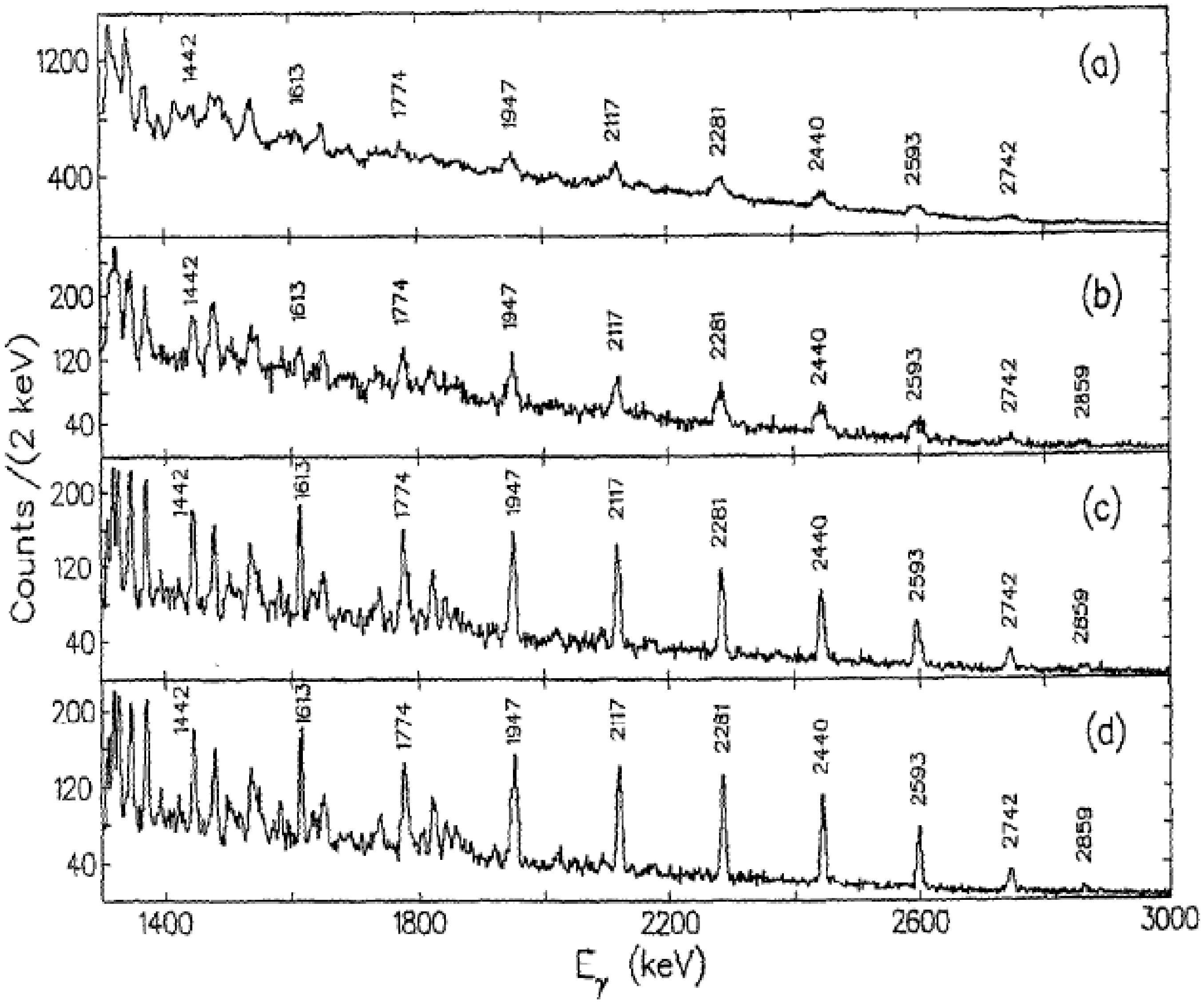




95 CsI(Tl) detectors

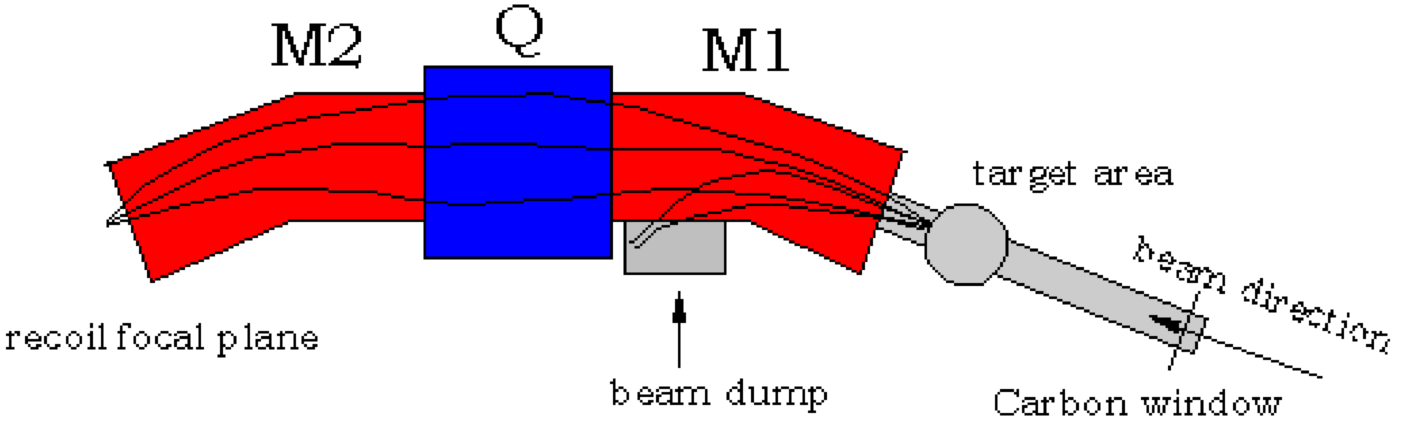
Nearly 4π coverage

Microball charged particle detector



Recoil Separators

Works on basic principle of charged particle moving in magnetic or electric field



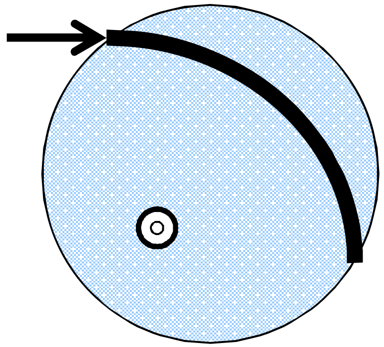
$$B\rho = mv/Q$$

Very useful in heavy mass region (and superheavies) where fission dominates the cross section

Types of Separators

Gas-Filled Separators

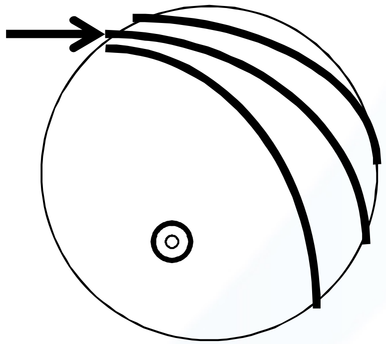
- RITU - Jyvaaskylaa
- BGS – Berkeley
- GFRS - Dubna
- GARIS – RIKEN
- TASCA - GSI



$B\rho = p/Q_{ave}$

$Q_{ave} \sim (v/v_0)\ Z^{1/3}$

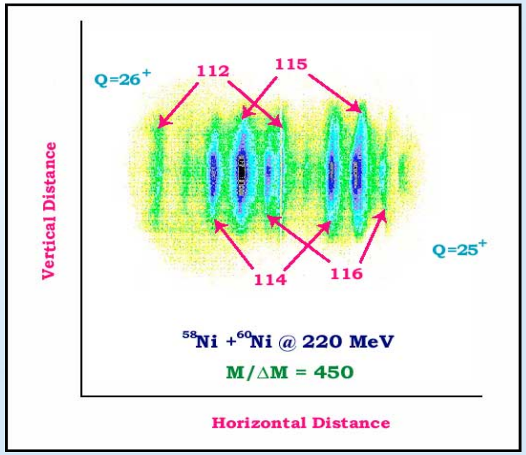
$B\rho \sim 0.0227\ A/Z^{1/3}$ [Tm]



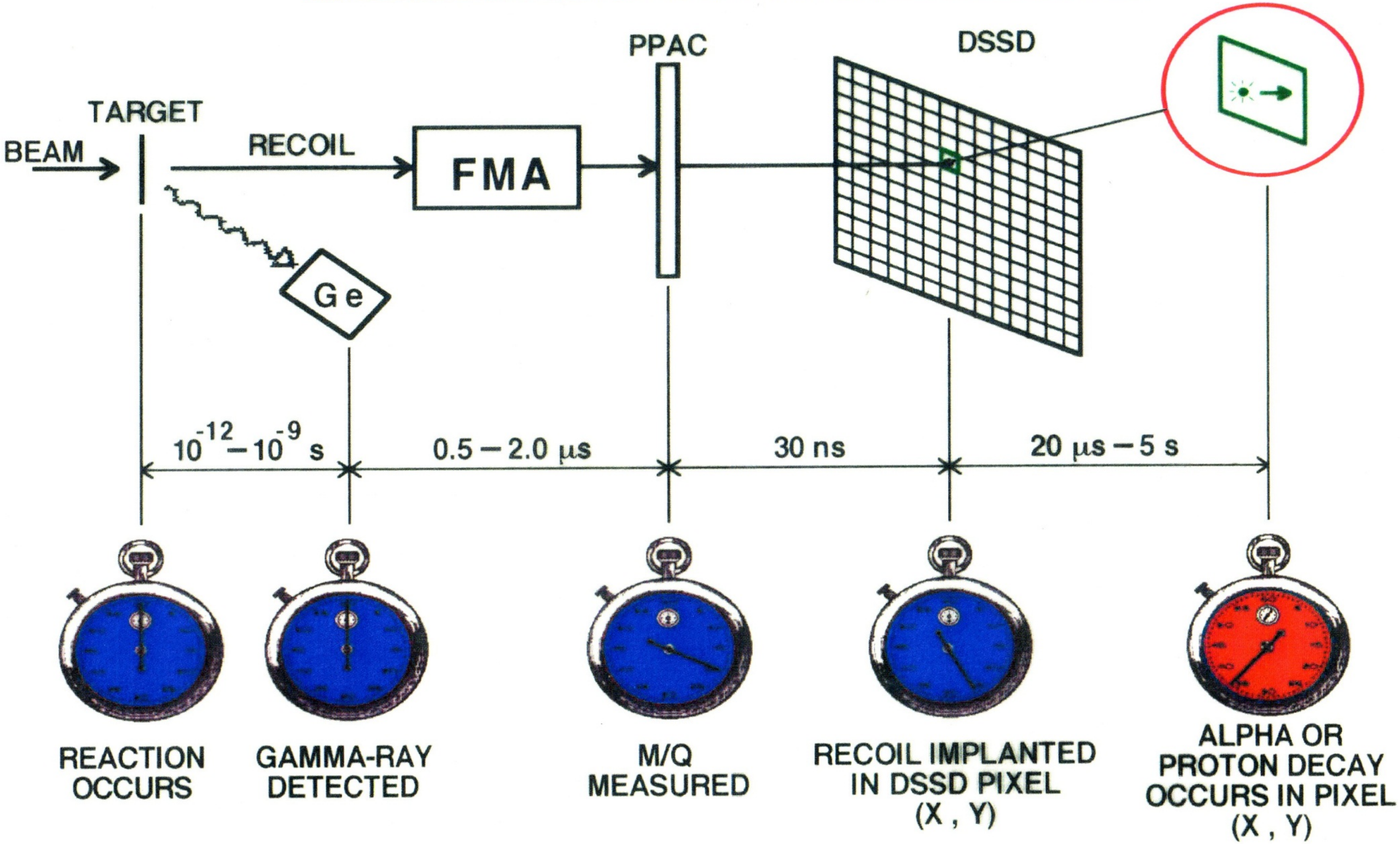
$B\rho_i = p/Q_i$

Vacuum Separators

- FMA – Argonne
- RMS – Oak Ridge



RECOIL DECAY TAGGING METHOD

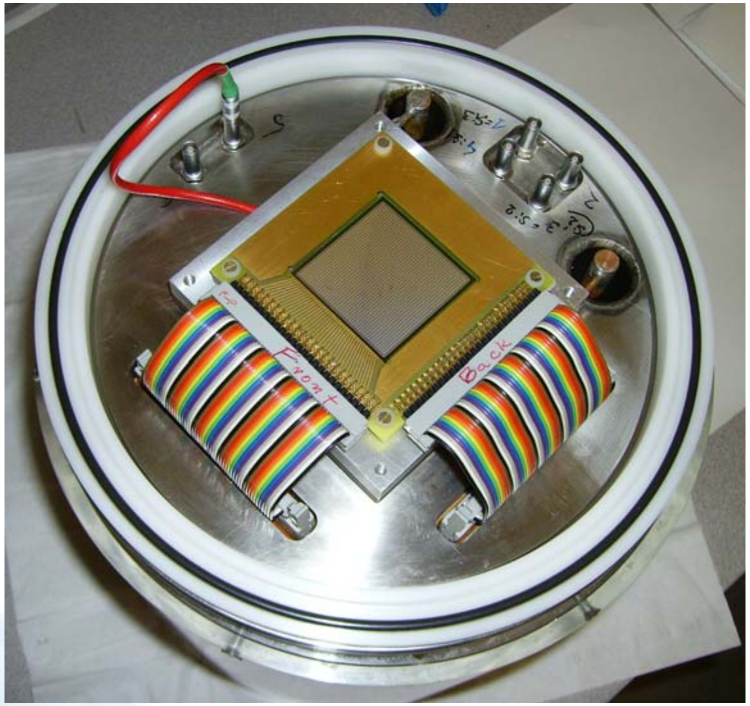


1 Prompt γ-rays correlated with M/Q and (X , Y) position of recoil in DSSD

2 Decay proton or alpha identifies nucleus that emitted the γ-rays

The heart of the technique

Double sided Si strip detector (DSSD)



Strips : 40x40 = 1600 pixels

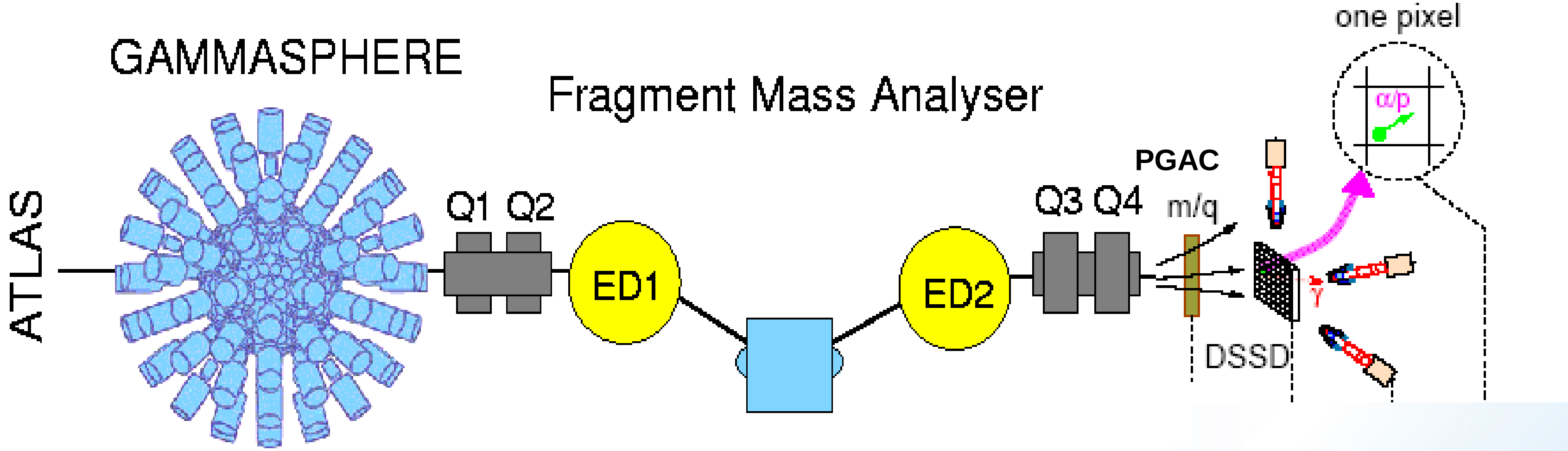
Records

- Implant, E and t
- Decay, E and t

PHYSICAL REVIEW C 85, 034329 (2012)

γ-ray spectroscopy of the odd-odd $N = Z + 2$ deformed proton emitter ^{112}Cs

P. T. Wady,[1,2] J. F. Smith,[1,2,*] E. S. Paul,[3] B. Hadinia,[1,2,†] C. J. Chiara,[4,‡] M. P. Carpenter,[5] C. N. Davids,[5] A. N. Deacon,[6] S. J. Freeman,[6] A. N. Grint,[3] R. V. F. Janssens,[5] B. P. Kay,[6,§] T. Lauritsen,[5] C. J. Lister,[5] B. M. McGuirk,[3] M. Petri,[3,‖] A. P. Robinson,[5,¶] D. Seweryniak,[5] D. Steppenbeck,[6,**] and S. Zhu[5]



112Ba	113Ba	114Ba 0.43 S ε: 99.10% εp: 20.00%
	112Cs 0.5 MS P: 100.00%	113Cs 16.7 µS P: 100.00% α
110Xe 93 MS α: 64.00% εp	111Xe 0.81 S ε: 90.00% α: 10.00%	112Xe 2.7 S ε: 99.16% α: 0.84%

Measure recoil in DSSD

Recoil proton energy in same pixel

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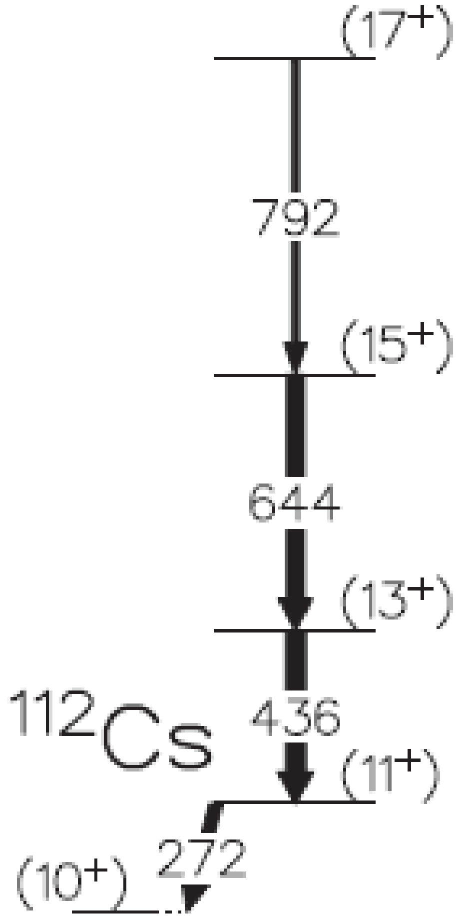
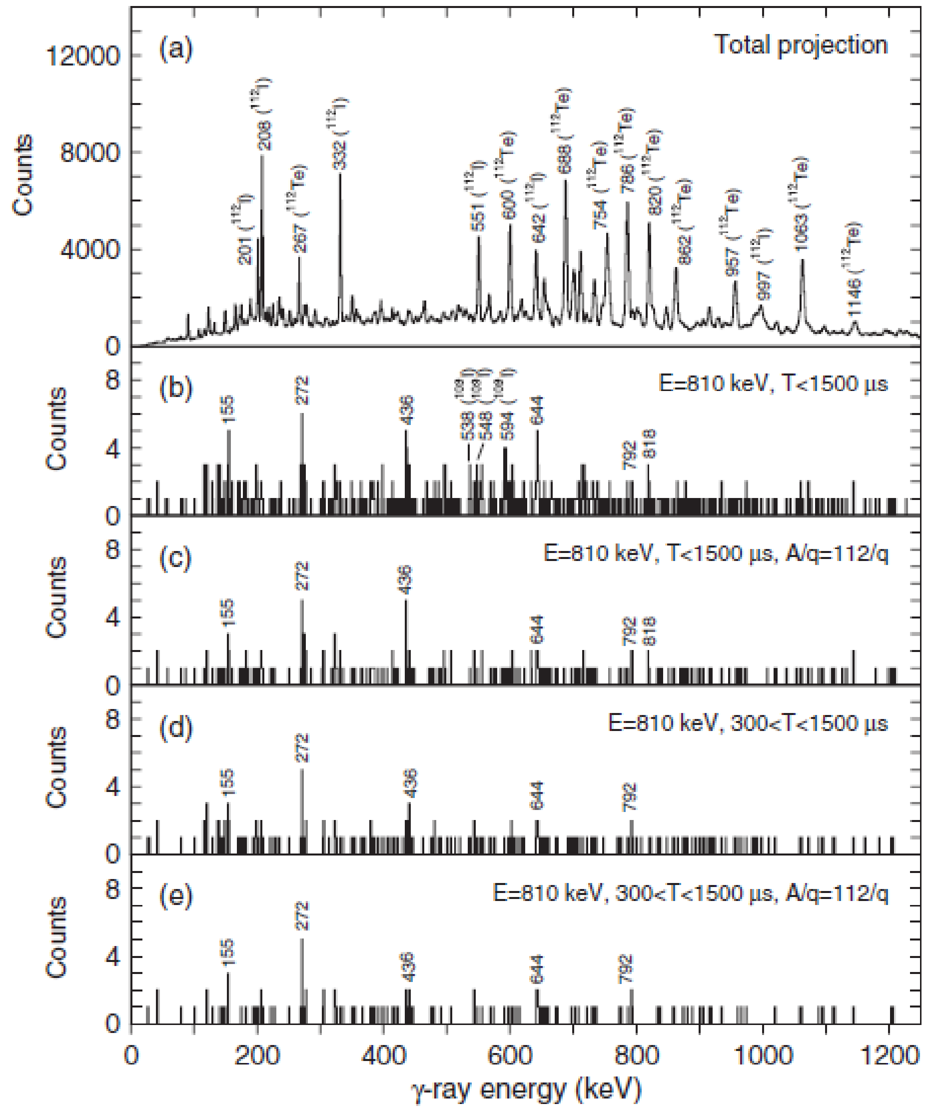
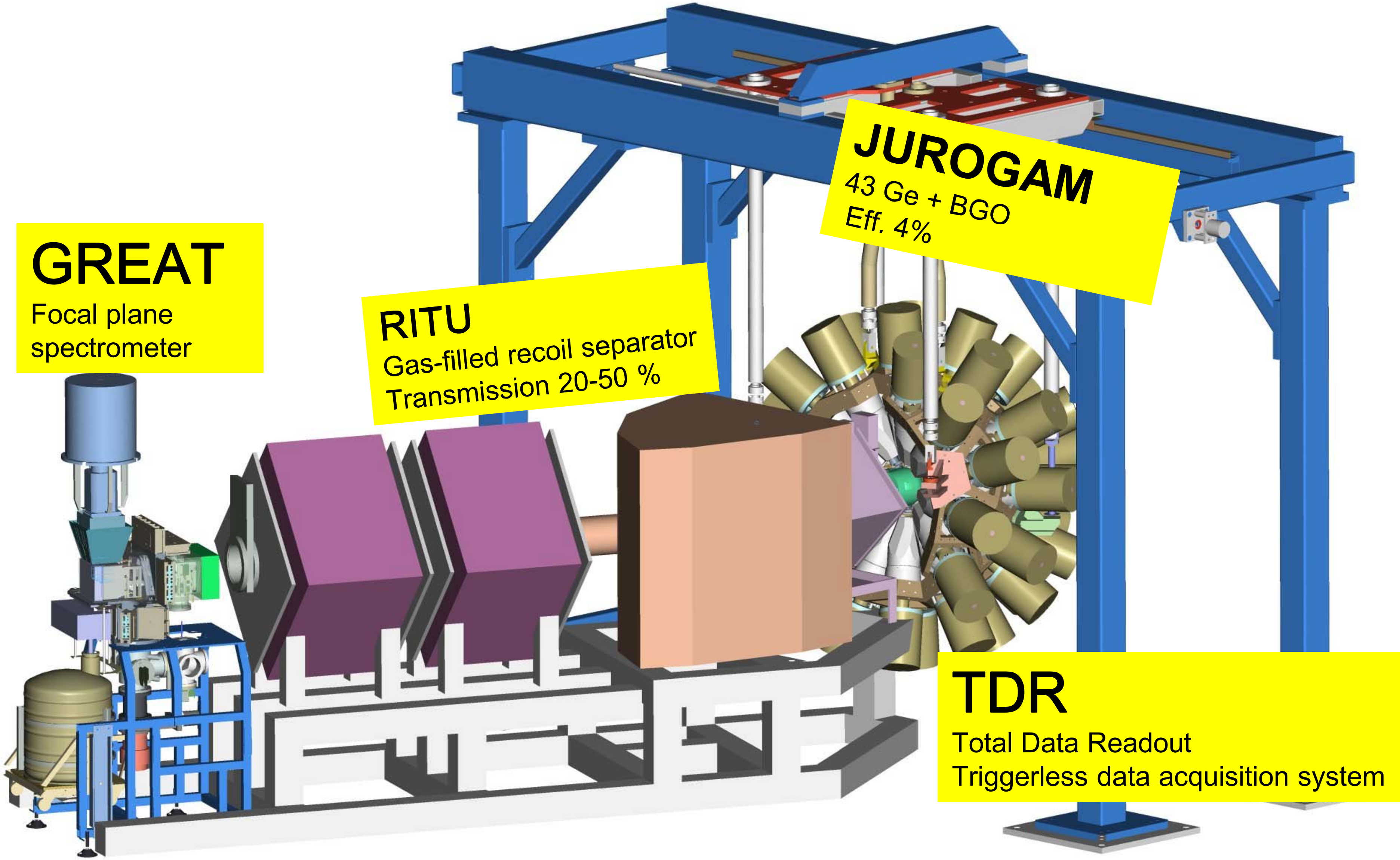




Brookhaven Science Associates

RDT Instrumentation at JYFL

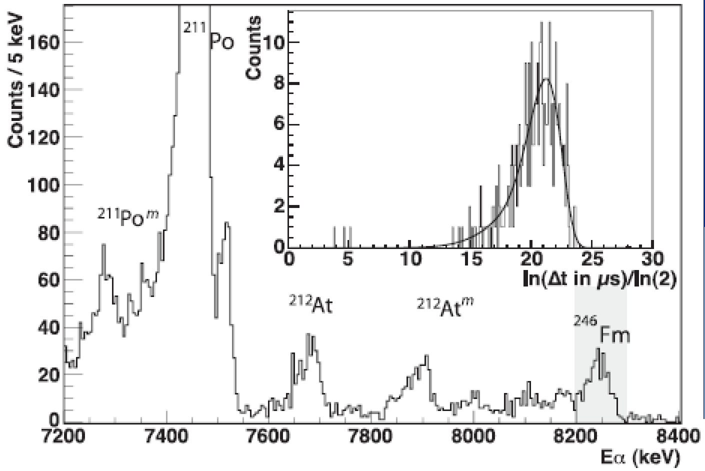


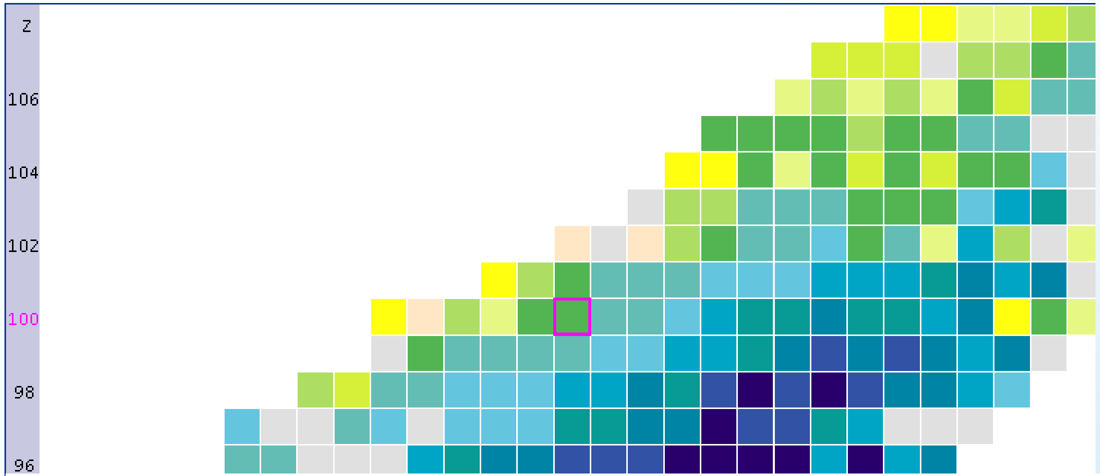
PHYSICAL REVIEW C **85**, 041301(R) (2012)

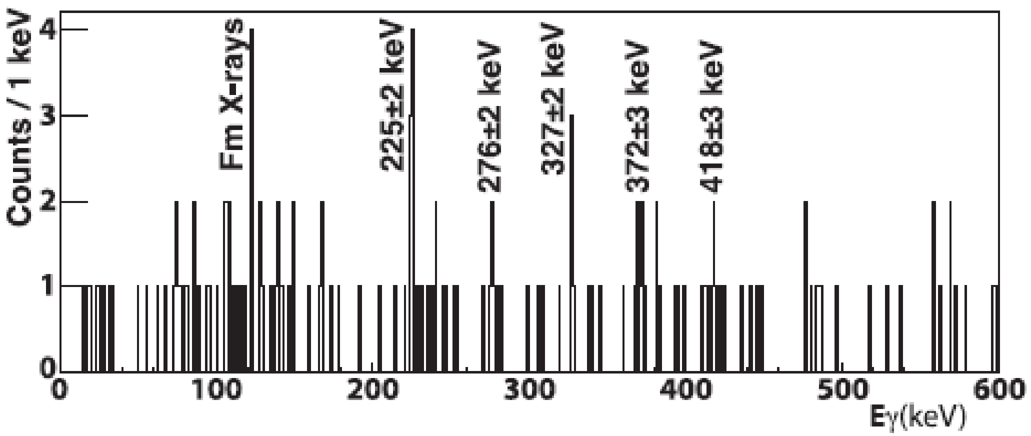
In-beam spectroscopy with intense ion beams: Evidence for a rotational structure in ^{246}Fm

J. Piot,[1,*] B. J.-P. Gall,[1] O. Dorvaux,[1] P. T. Greenlees,[2] N. Rowley,[3] L. L. Andersson,[4] D. M. Cox,[4] F. Dechery,[5] T. Grahn,[2] K. Hauschild,[2,6] G. Henning,[6,7] A. Herzan,[2] R.-D. Herzberg,[4] F. P. Heßberger,[8] U. Jakobsson,[2] P. Jones,[2,†] R. Julin,[2] S. Juutinen,[2] S. Ketelhut,[2] T.-L. Khoo,[7] M. Leino,[2] J. Ljungvall,[6] A. Lopez-Martens,[2,6] P. Nieminen,[2] J. Pakarinen,[9,‡] P. Papadakis,[4] E. Parr,[4] P. Peura,[2] P. Rahkila,[2] S. Rinta-Antila,[2] J. Rubert,[1] P. Ruotsalainen,[2] M. Sandzelius,[2] J. Sarén,[2] C. Scholey,[2] D. Seweryniak,[7] J. Sorri,[2] B. Sulignano,[5] and J. Uusitalo[2]

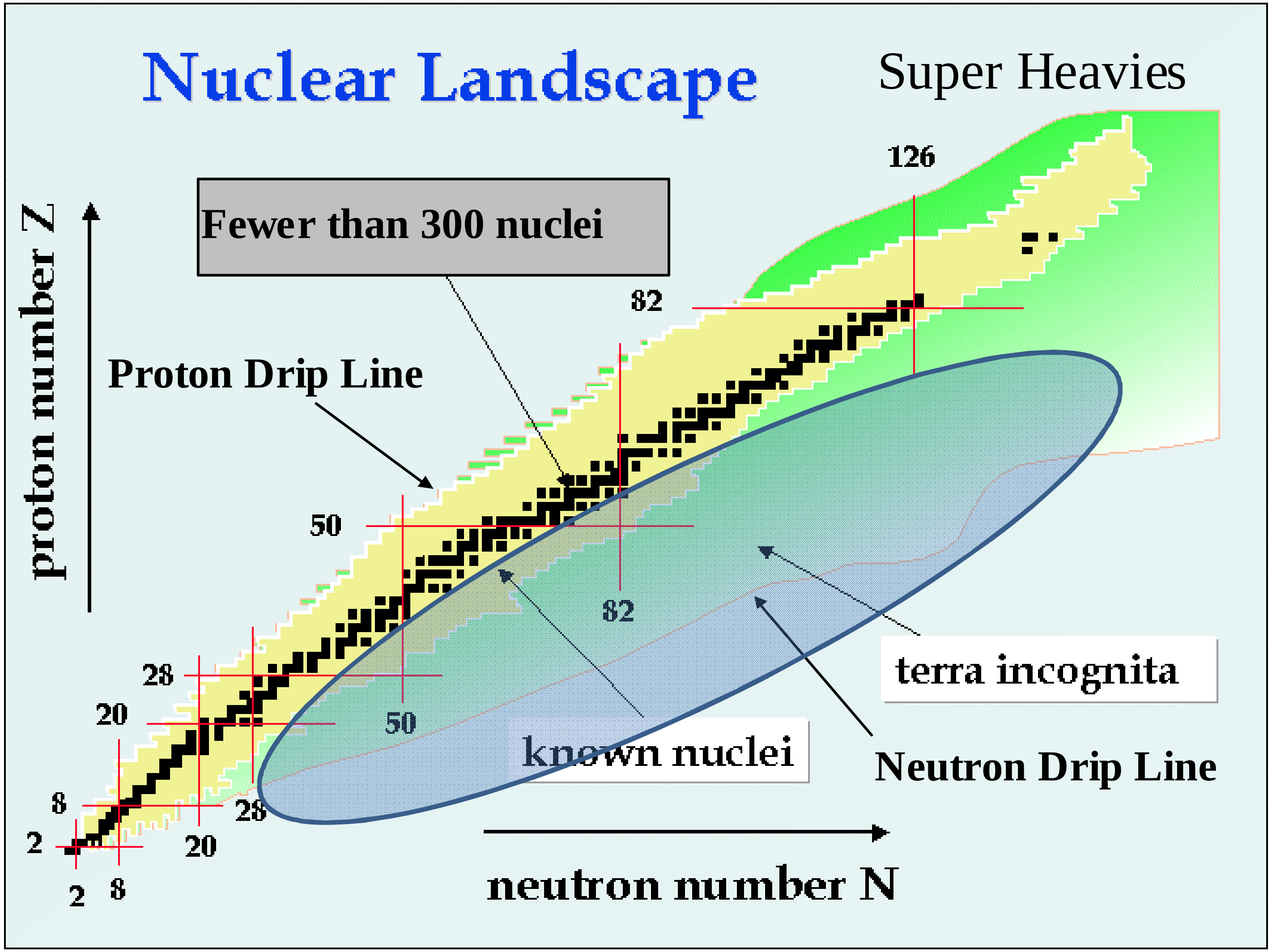
σ = 11 nb







The future

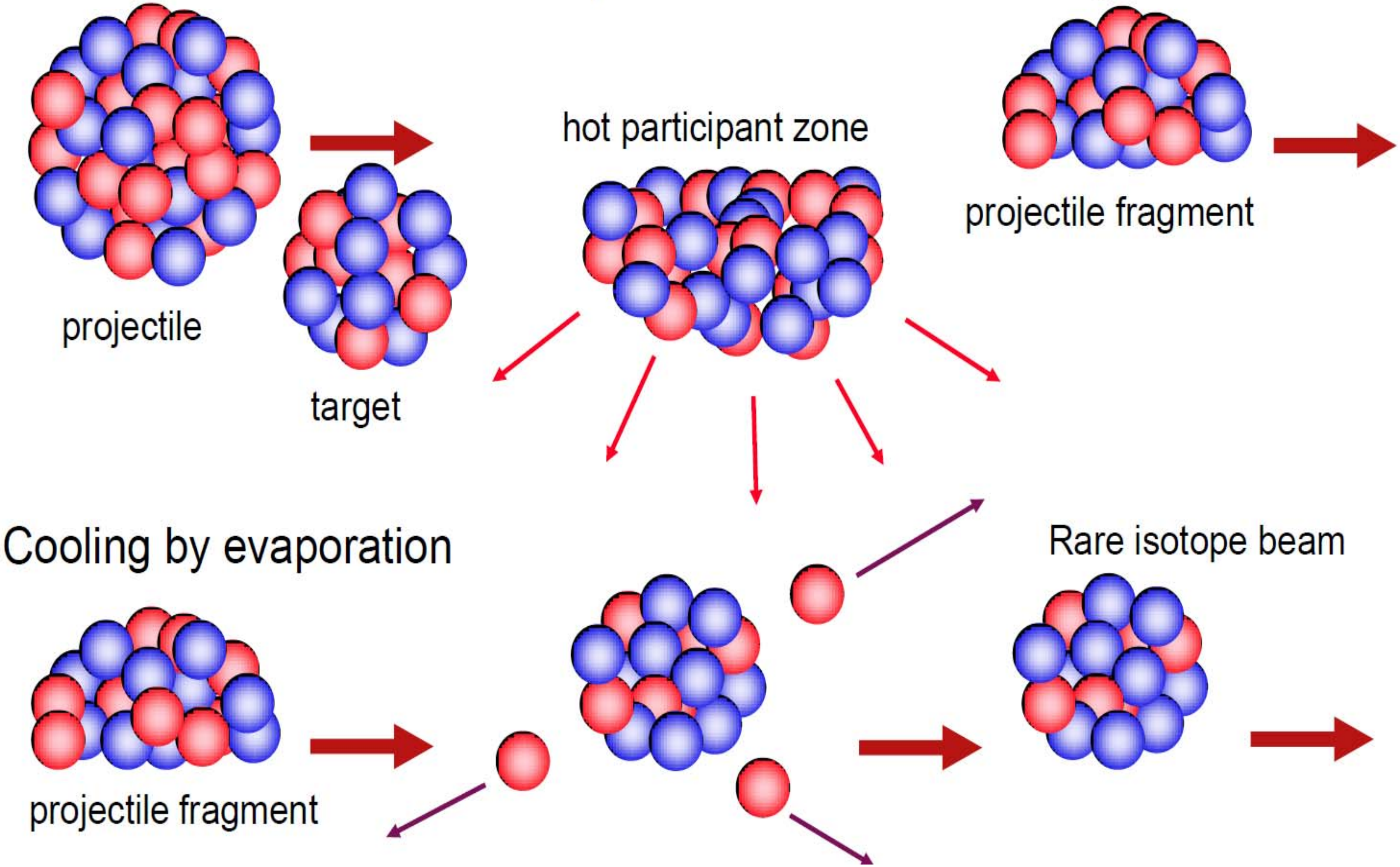

Nuclear Landscape
Super Heavies
126
Fewer than 300 nuclei
82
proton number Z
Proton Drip Line
50
82
28
20
50
8
28
2
20
2
8
terra incognita
known nuclei
Neutron Drip Line
neutron number N

Production of Rare Isotopes in Flight

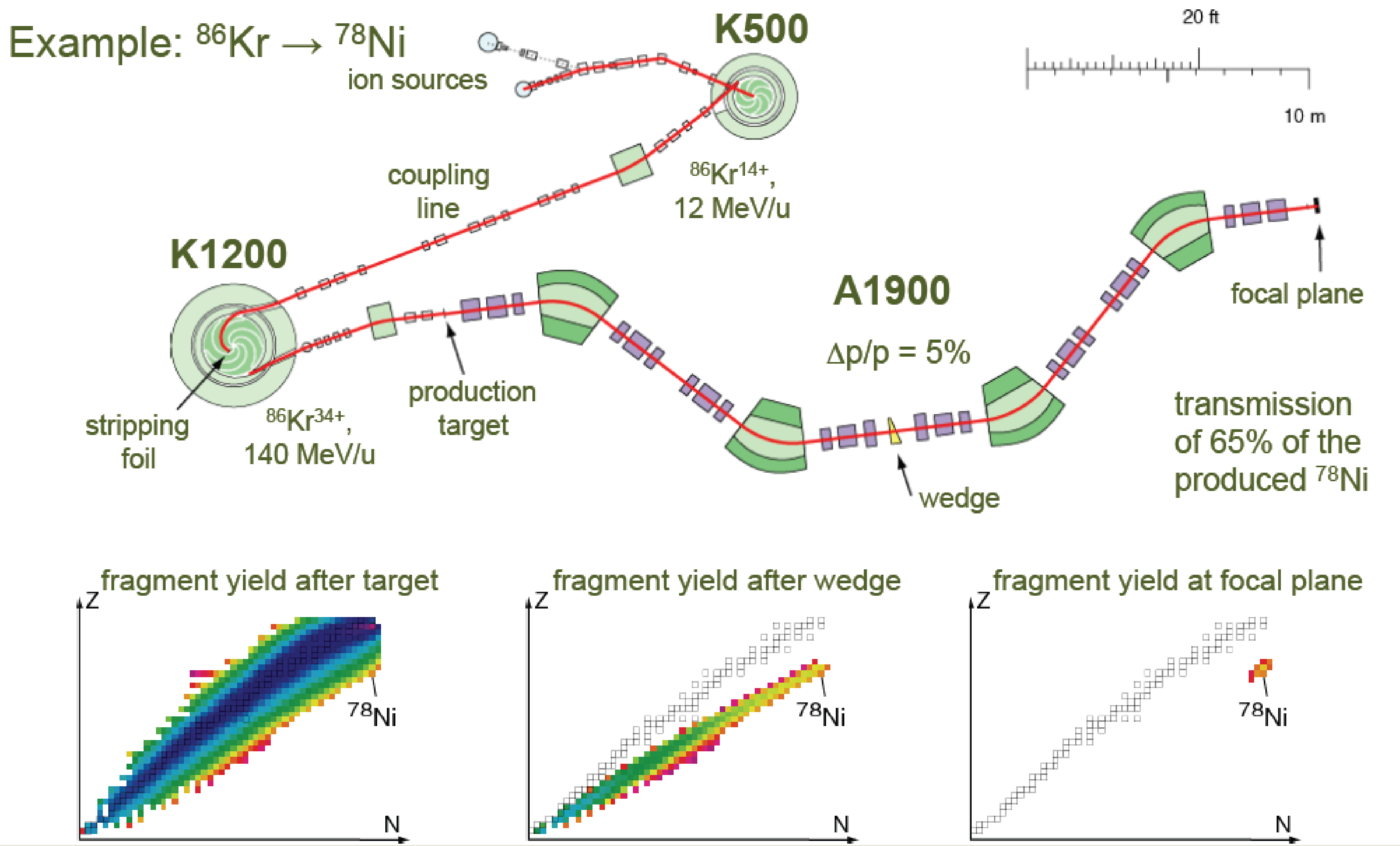
E > 50 MeV/nucleon

1. Accelerate heavy ion beam to high energy and pass through a thin target to achieve random removal of protons and neutrons in flight

2. Cooling by evaporation



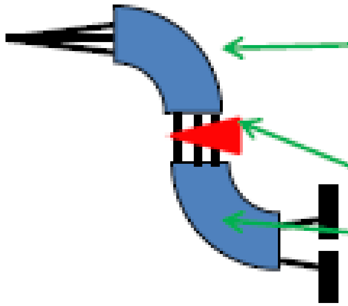
Example : In-Flight Production at NSCL



D.J. Morrissey, B.M. Sherrill, Philos. Trans. R. Soc. Lond. Ser. A Math Phys. Eng. Sci 356, 1985 (1998).

Particle identification

Separation with the fragment separator



Fragment separator

1st separation (A/Z selection)

$$\frac{mv^2}{r} = qvB \ , \qquad B\rho = \frac{mv}{q} \propto \frac{A}{Z}$$

2nd separation

(energy degrader + dipole magnet → $\frac{A^{2.5}}{Z^{1.5}}$ selection)

$$\text{energy loss } (\Delta E) \propto \frac{Z^2}{V^2}$$

Particle identification (Z,A) is based on the TOF, Bρ, ΔE measurement

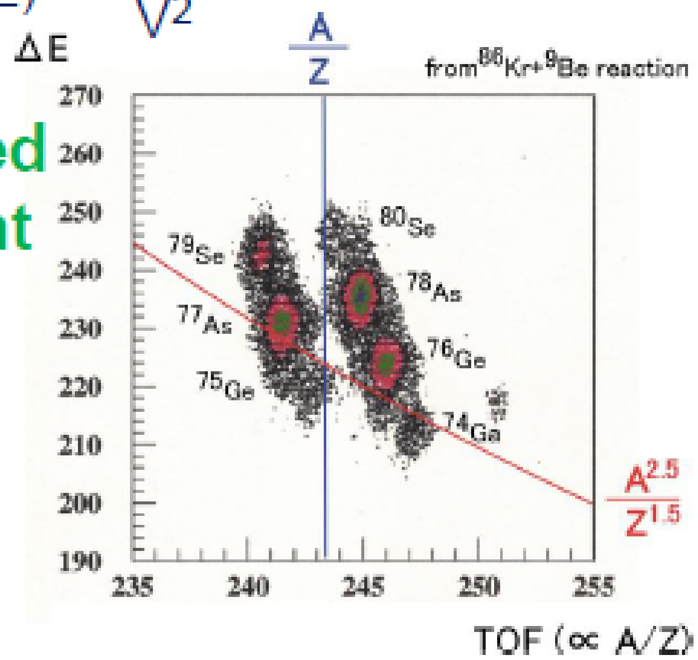
$$\mathrm{TOF} \propto 1/v$$

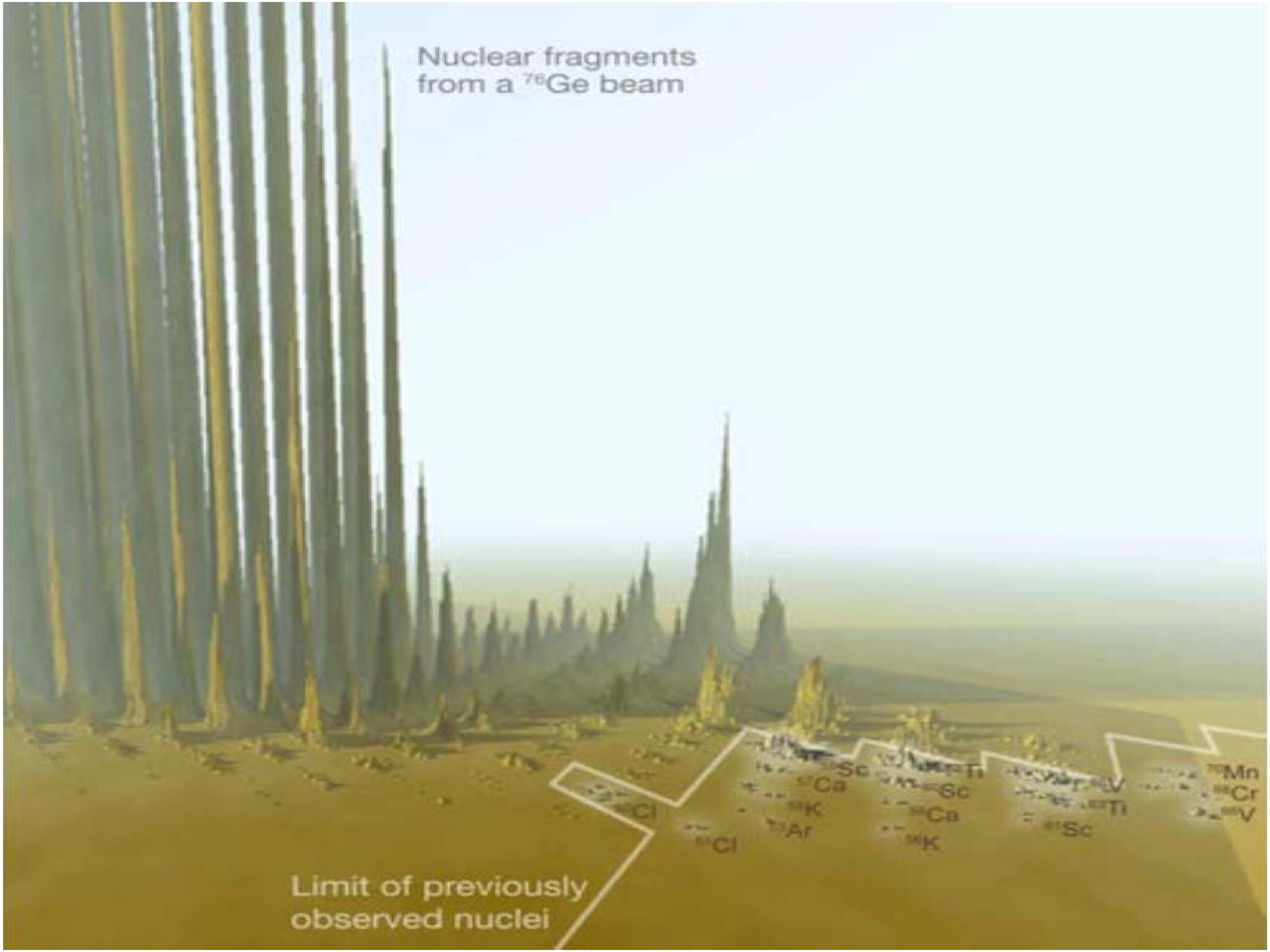
$$B\rho \propto \frac{A}{Z} v$$

$$\Delta E \propto \frac{Z^2}{v^2}$$

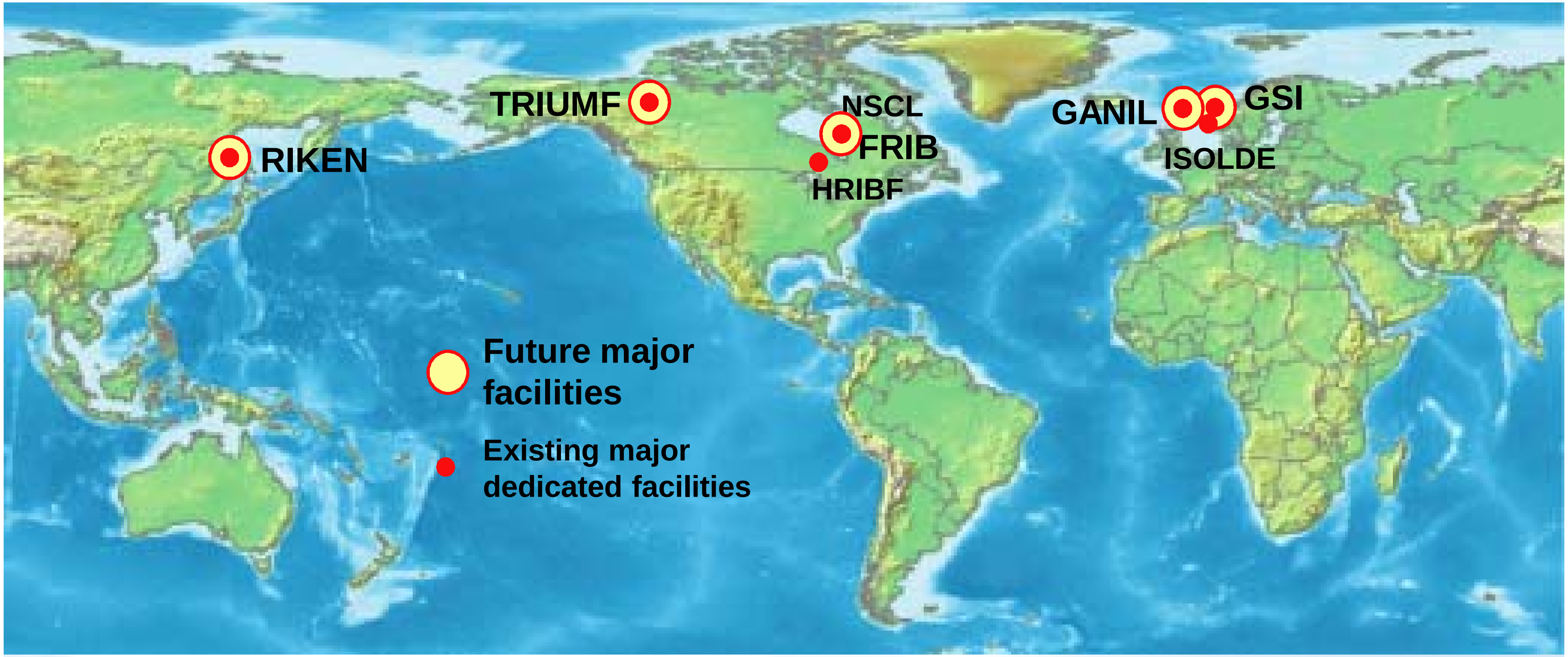
Z

Z/A




Nuclear fragments
from a ^{76}Ge beam
Sc
Ca
K
Ar
Cl
Cl
Ti
Sc
Ca
K
V
Ti
Sc
Mn
Cr
V
Limit of previously
observed nuclei

Radioactive Ion Beam Facilities Worldwide



Lots of new, exciting data on the horizon !!