Experimental Nuclear Physics

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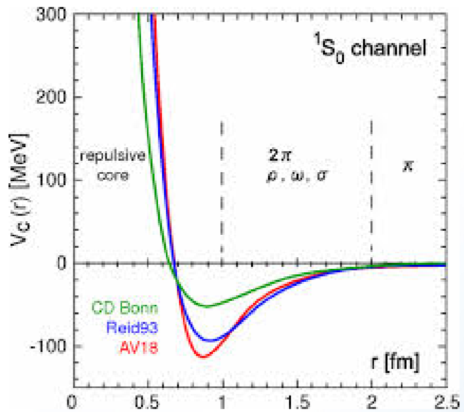
Brookhaven Nation Laboratory

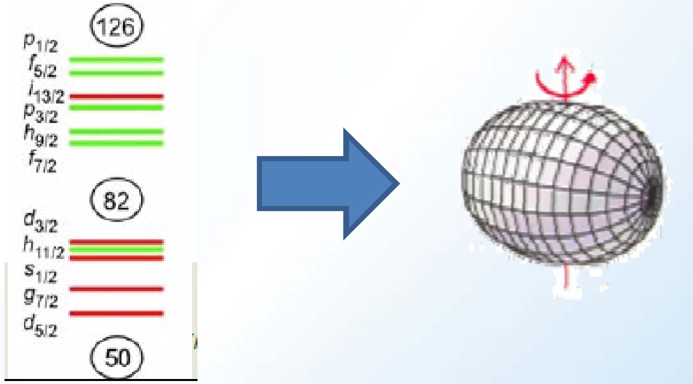
The Purpose of Nuclear Structure Physics

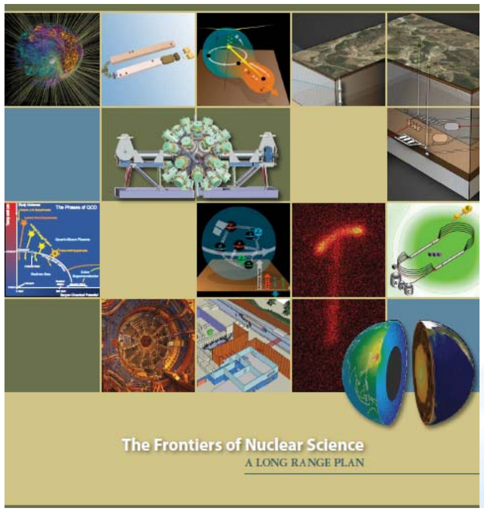
Overarching questions that drive research

- What is the nature of the nuclear force that binds protons and neutrons in stable nuclei and rare isotopes?

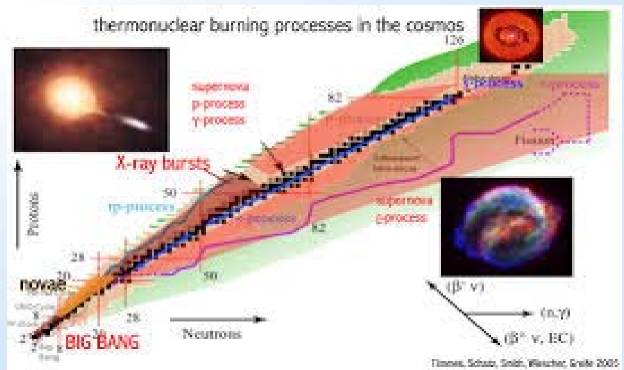


- What is the origin of simple patterns in complex nuclei?





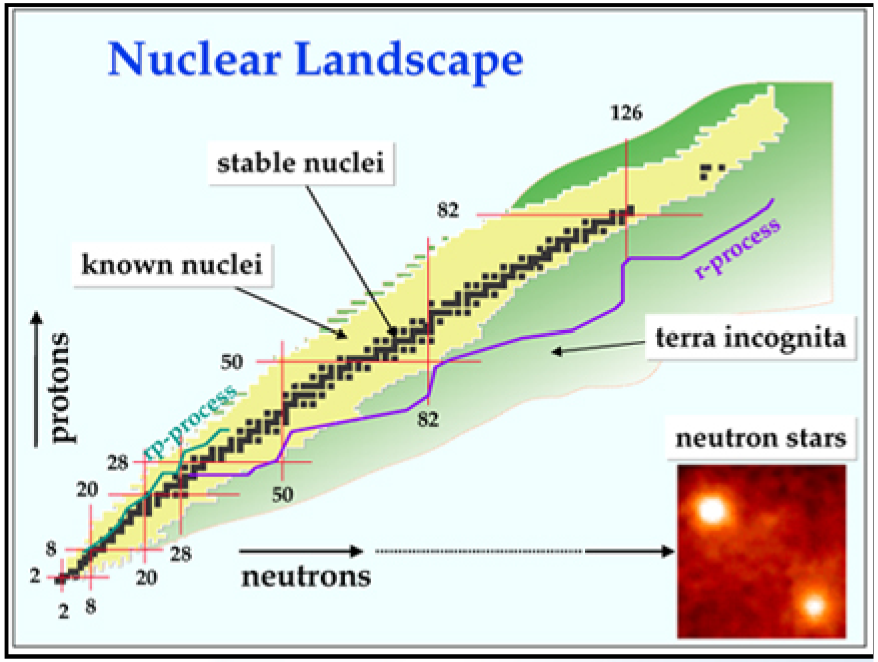
- What is the origin of the elements in the cosmos?



The Scope of Nuclear Structure Physics

The Four Frontiers

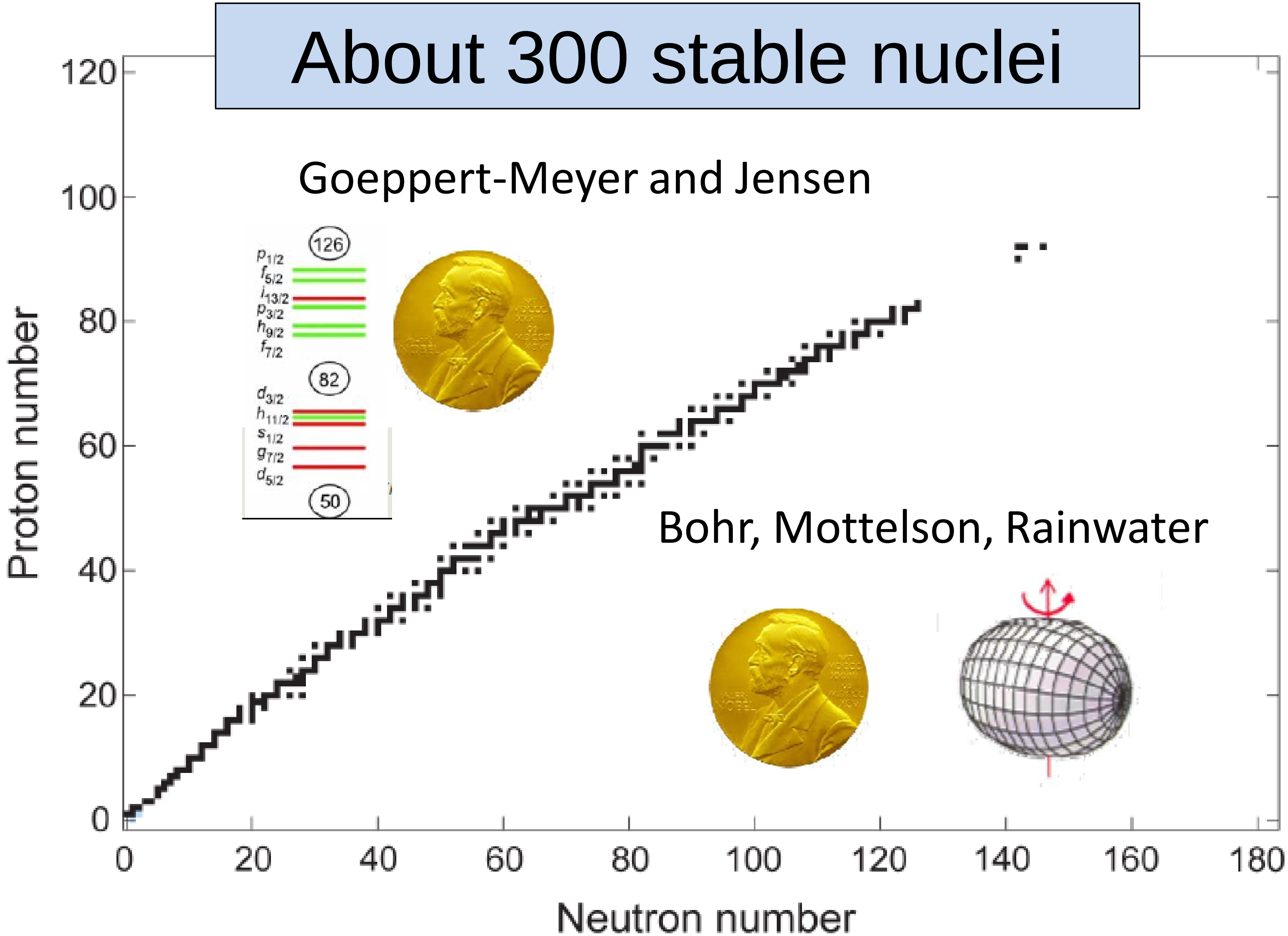
1. **Proton Rich Nuclei**
2. **Neutron Rich Nuclei**
3. **Heaviest Nuclei**
4. **Evolution of structure within these boundaries**



Terra incognita — huge gene pool of new nuclei

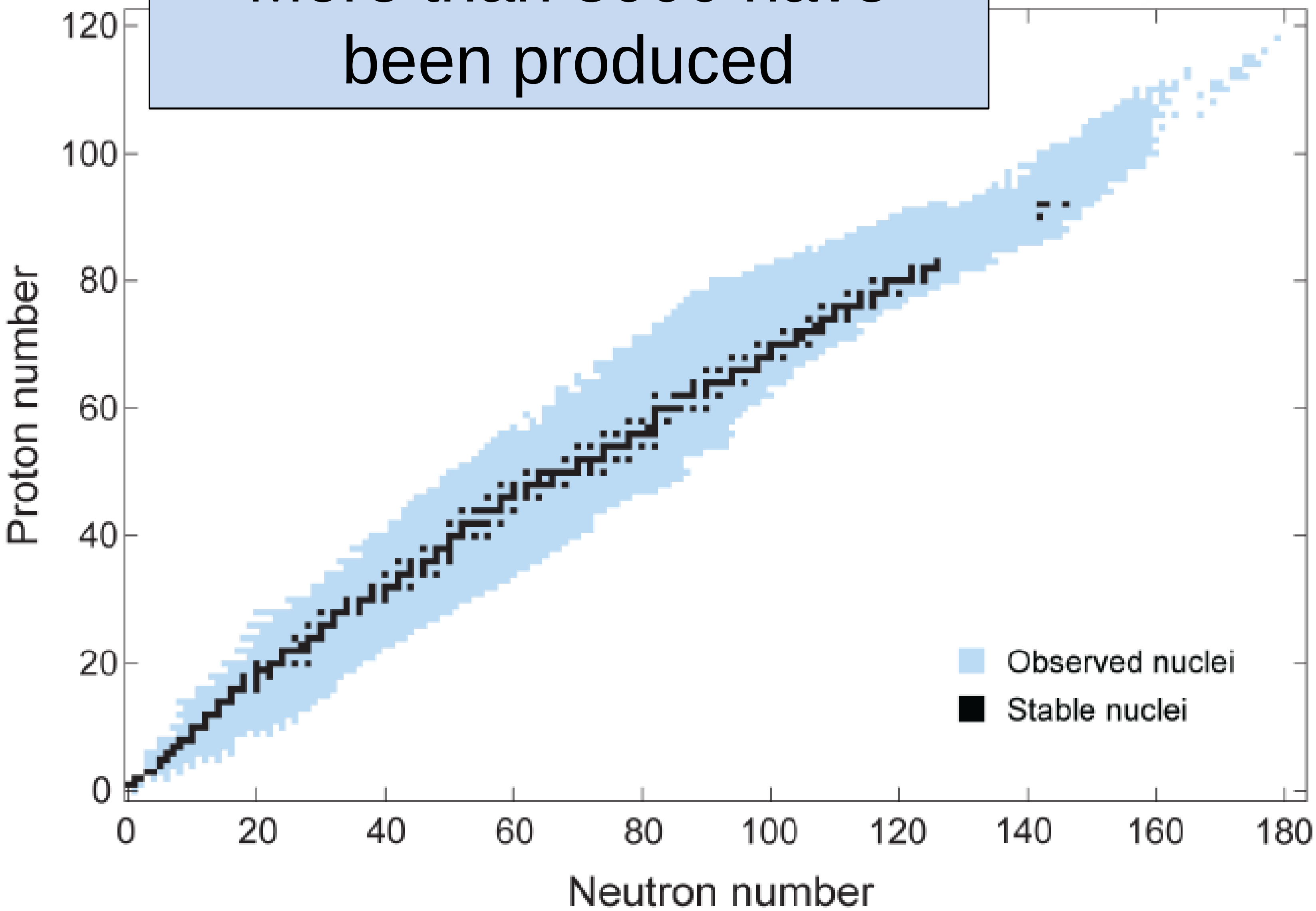
We can customize our system – fabricate "designer" nuclei to *isolate and amplify* specific physics or interactions

What do we know ??



What do we know ??

More than 3000 have been produced



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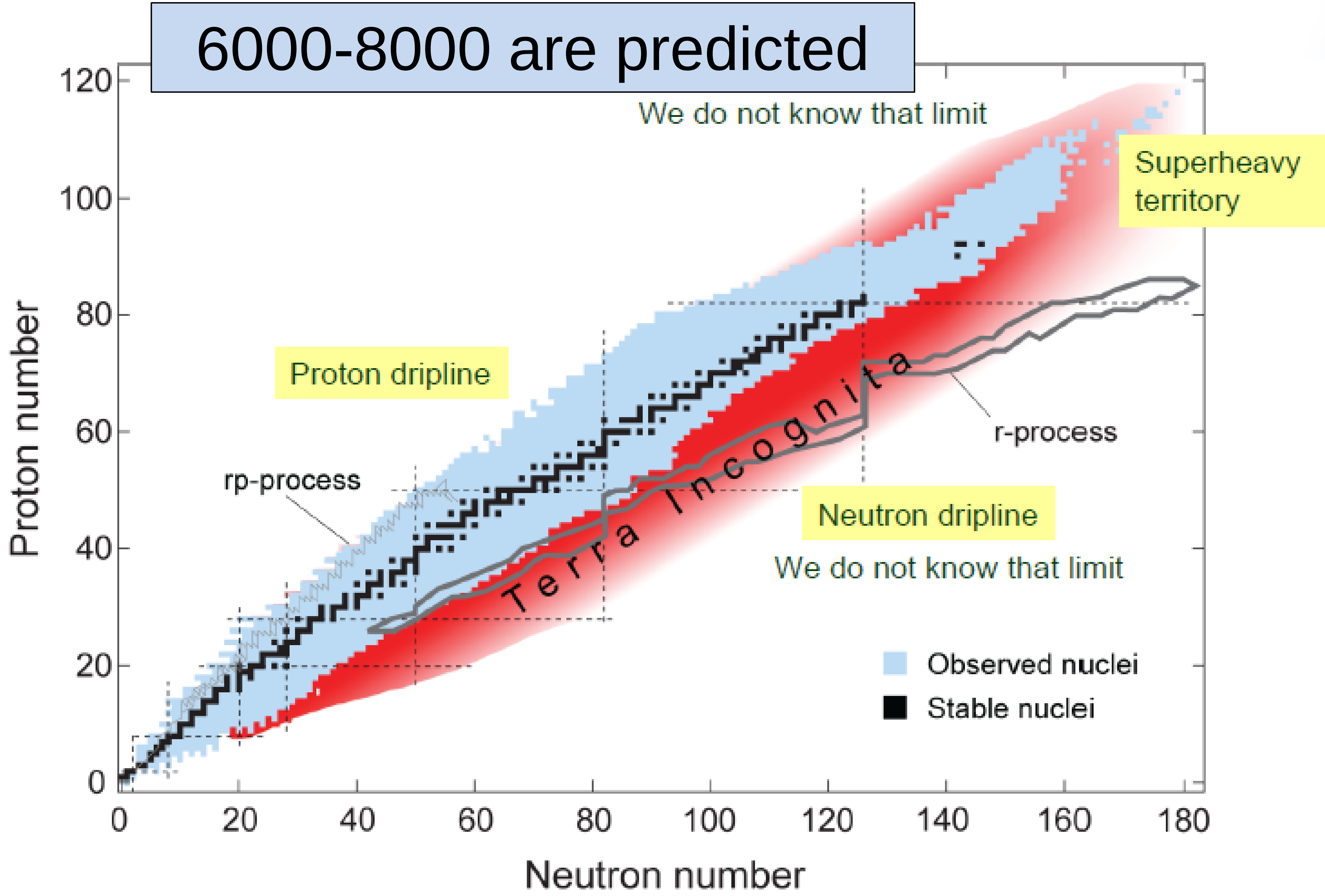
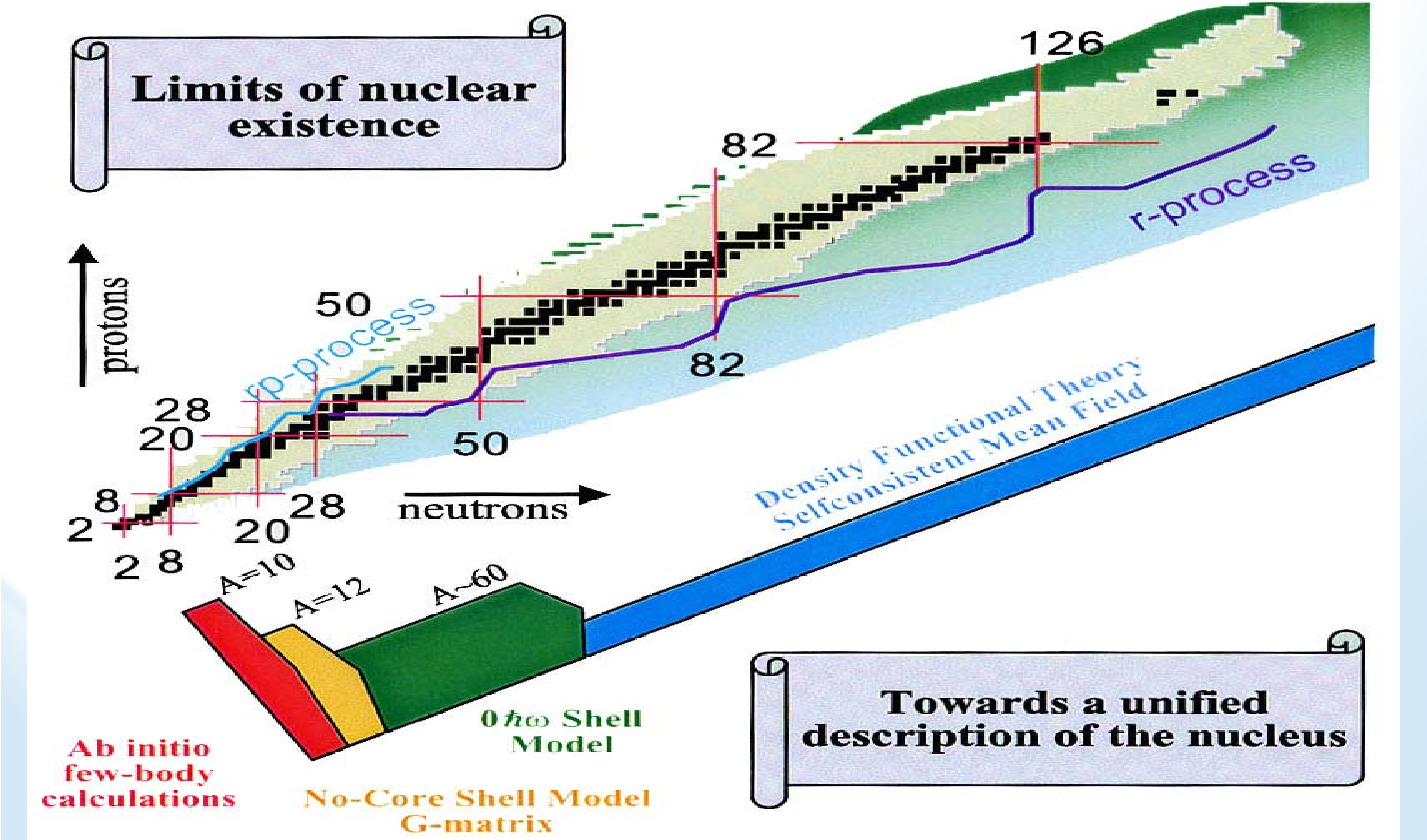
What do we know ??



The Theoretical Landscape

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



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

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

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

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

or

$$\Delta x \sim 10^{-13} cm$$

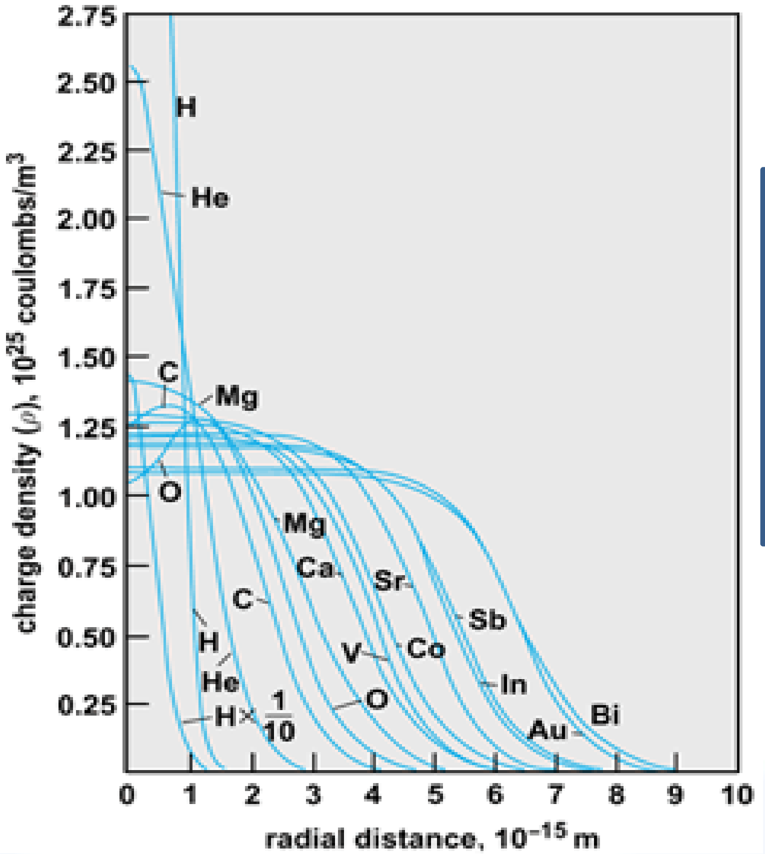
Sizes and forces (very basic)

REVIEWS OF MODERN PHYSICS VOLUME 28, NUMBER 3

Electron Scattering and Nuclear Struct

ROBERT HOFSTADTER

University, Stanford, California



to the Weiszacker semiempirical formula, and, in the case of the heaviest elements, on the energies and half-lives of alpha activities. All approaches led to the same general range of values of the nuclear radii for a uniformly charged sphere, which was taken universally as the appropriate model of the nucleus. The results can be summarized in a well-known formula for the radius of a uniform sphere

$$R = r_0 A^{\frac{1}{3}} \times 10^{-13} \text{ cm}. \qquad (1)$$

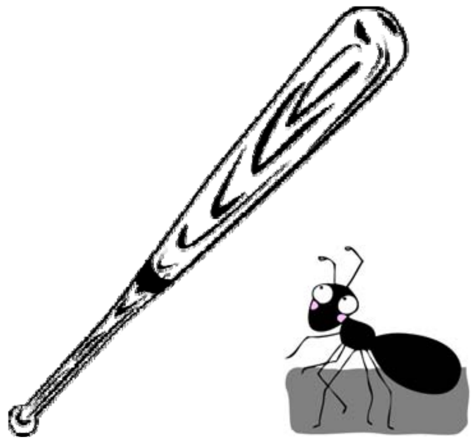
Henceforth, we shall measure all distances in terms of 10^{-13} cm as a unit and shall call this unit the fermi. For example, this formula puts the edge of the nuclear sphere of gold at a distance of 8.45 fermis from the center of the nucleus, if the constant r_0 is given a good

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

$$\rho = {}^{A}/_{V} = const$$

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

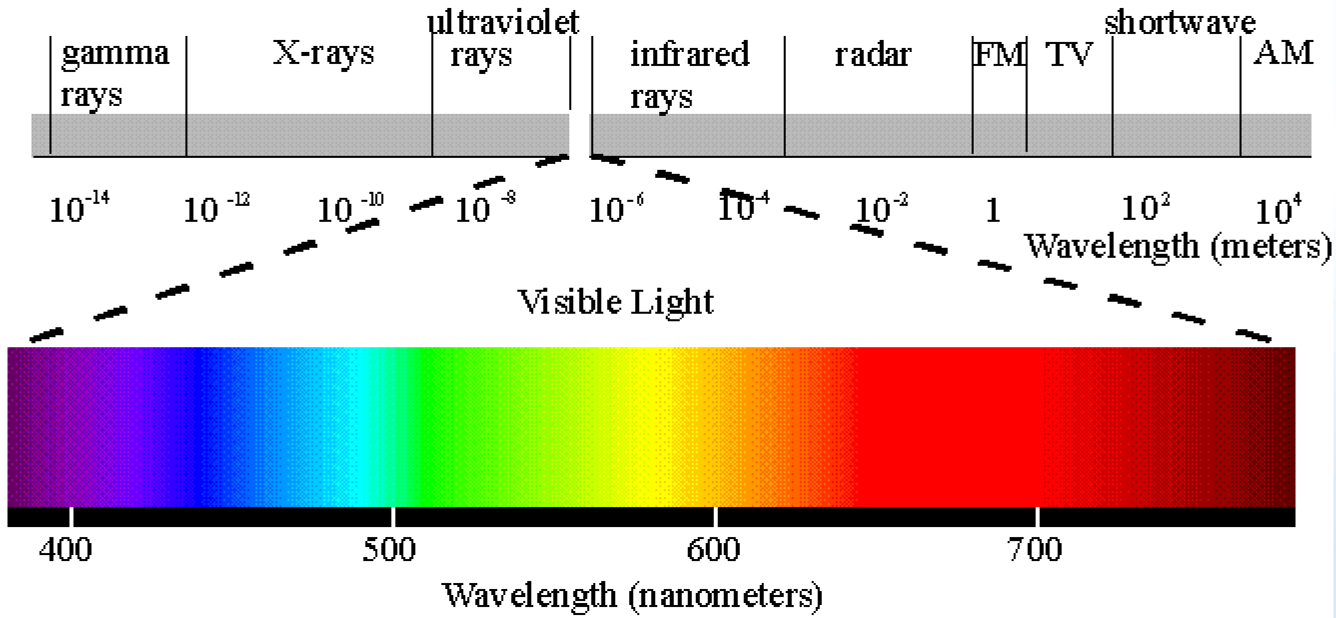
Choosing the right probe



Energy of probe related to size of probee and production device

What's as big as a nucleus??

Another nucleus !!



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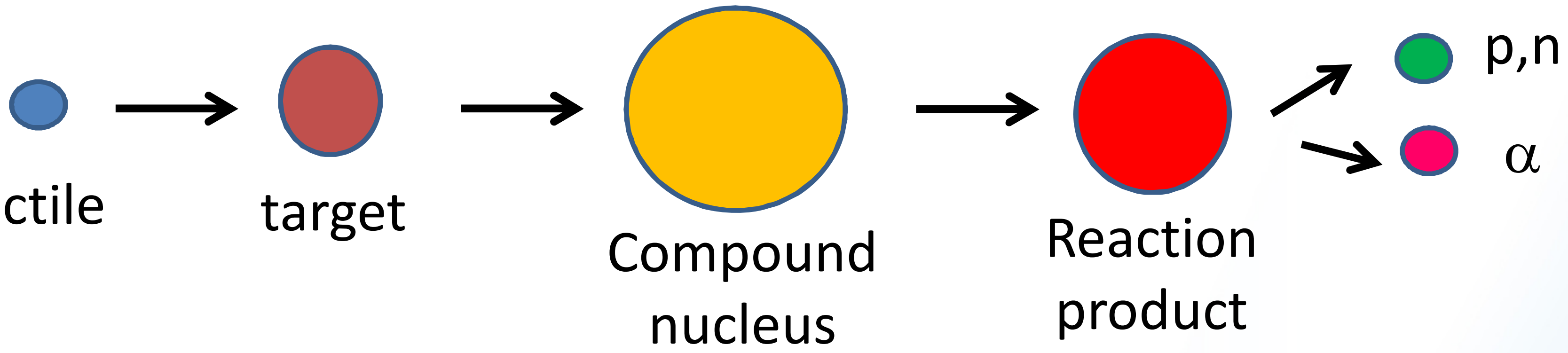
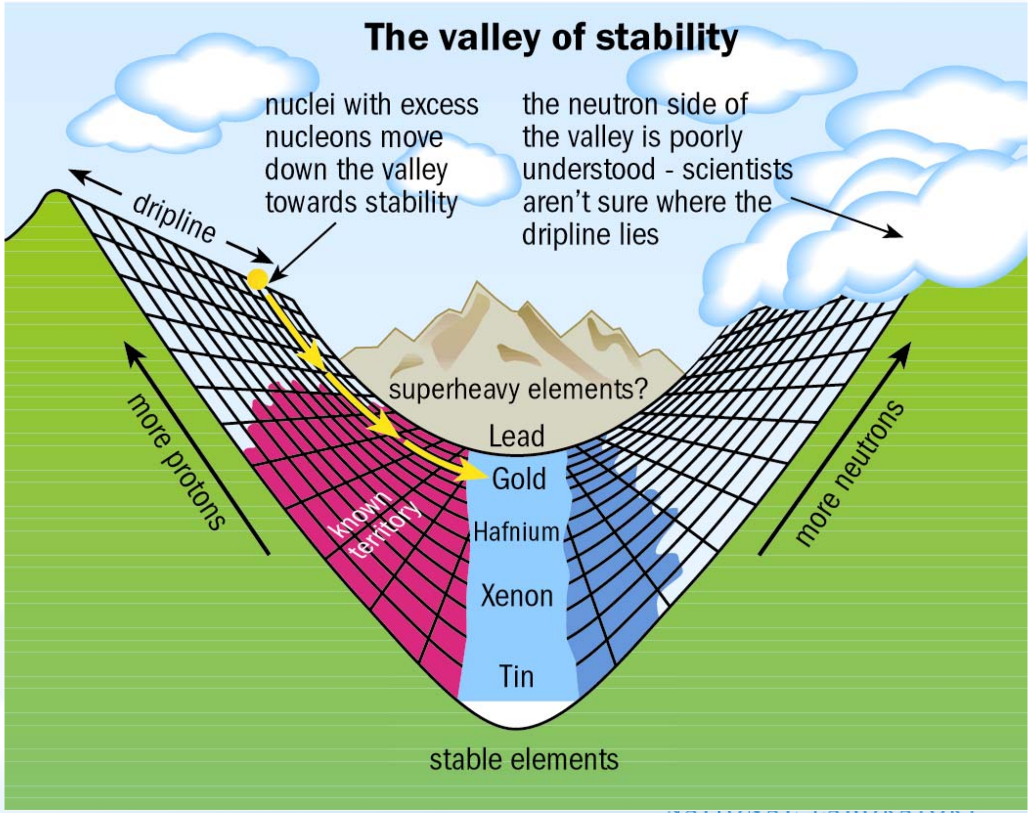
- **Beam/Reaction**
- **Channel Selection**
- **Detectors**
- **Data Analysis**
- **Theory**

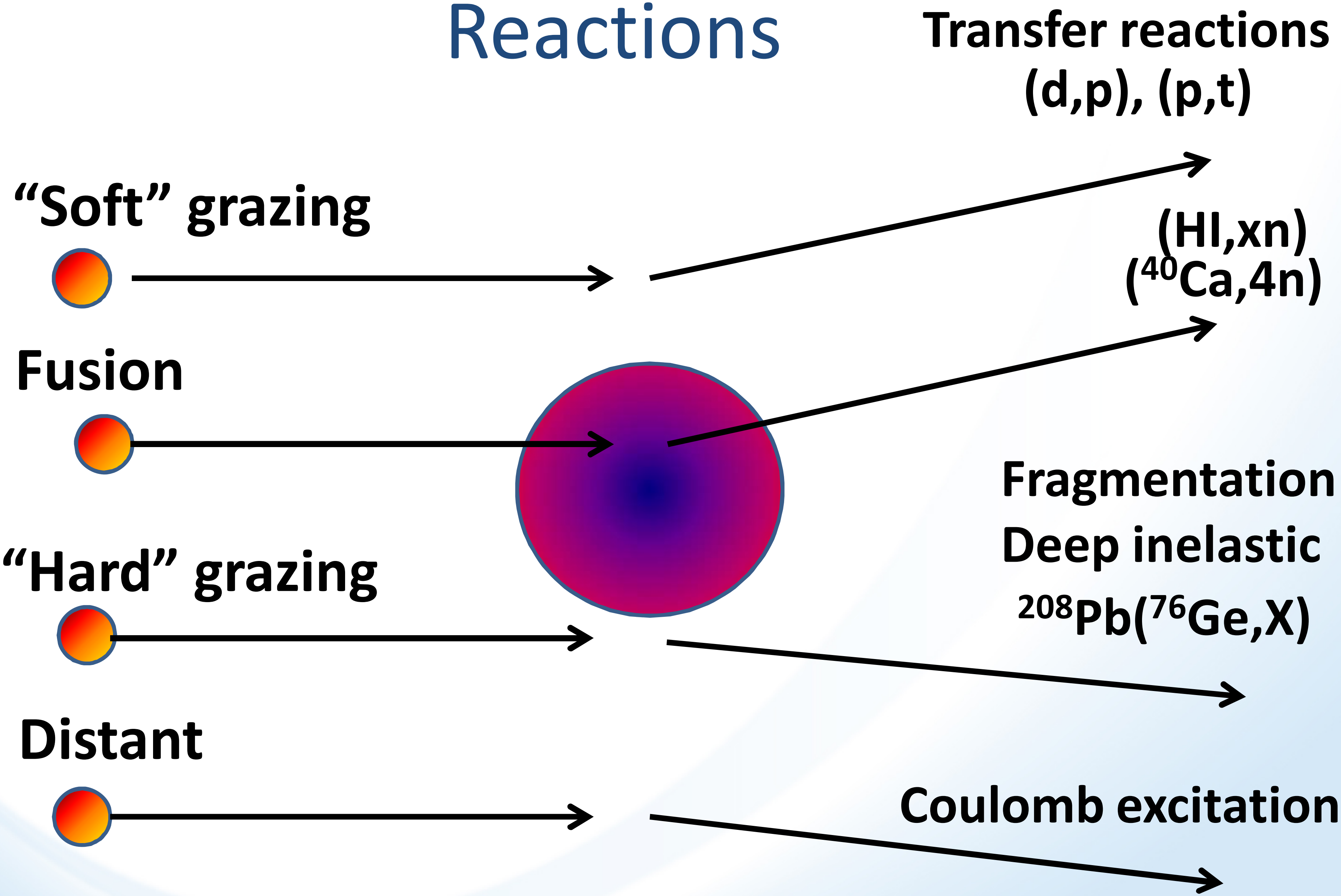
Schematic view of nuclear reactions



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



Reactions

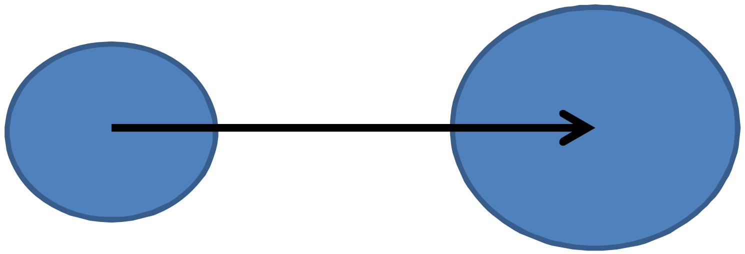

Transfer reactions
(d,p), (p,t)
“Soft” grazing
(HI,xn)
(^{40}Ca,4n)
Fusion
Fragmentation
Deep inelastic
^{208}Pb(^{76}Ge,X)
“Hard” grazing
Distant
Coulomb excitation

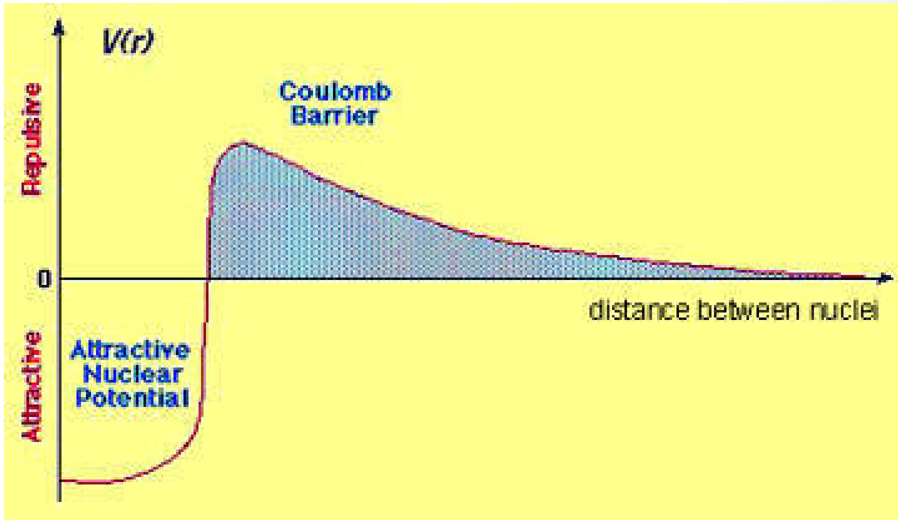
Heavy Ions at the Coulomb barrier:

VERY Classical

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

Need to overcome the Coulomb barrier

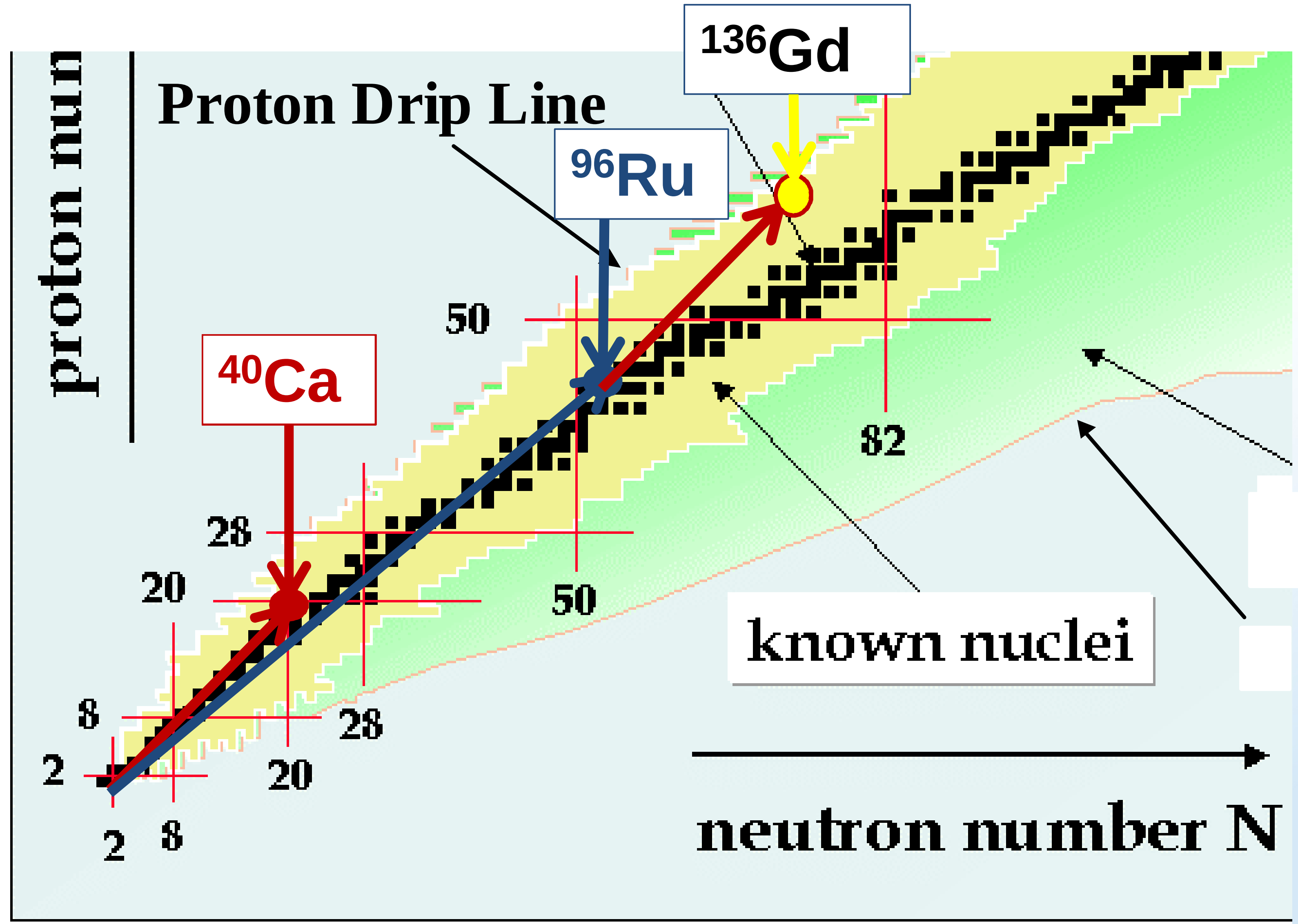




$$R = R_o A^{1/3}$$

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

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



(Almost) Always leads to proton-rich nuclei

Calculating the reaction yield

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

Typical beam current ~ 1-100 enA

$N_{beam} = 10\times10^{-9} / 1.6\times10^{-19}$ → 10^{10} particles/sec

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

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

$N_{target} = [\, 6\times10^{23}/100]^*1\times10^{-3}$ → 6×10^{18} particles/cm^2

Looks like we are winning …

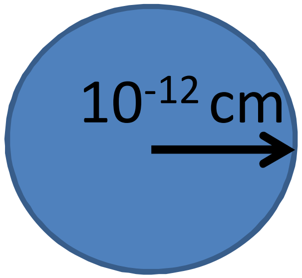
Calculating the reaction yield

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

N_{beam} = 10^{10} particles/sec

N_{target} = 6×10^{18} particles/cm^2

Cross section: remember the size of a nucleus



Probability of "hitting" the nucleus ~ πR^2

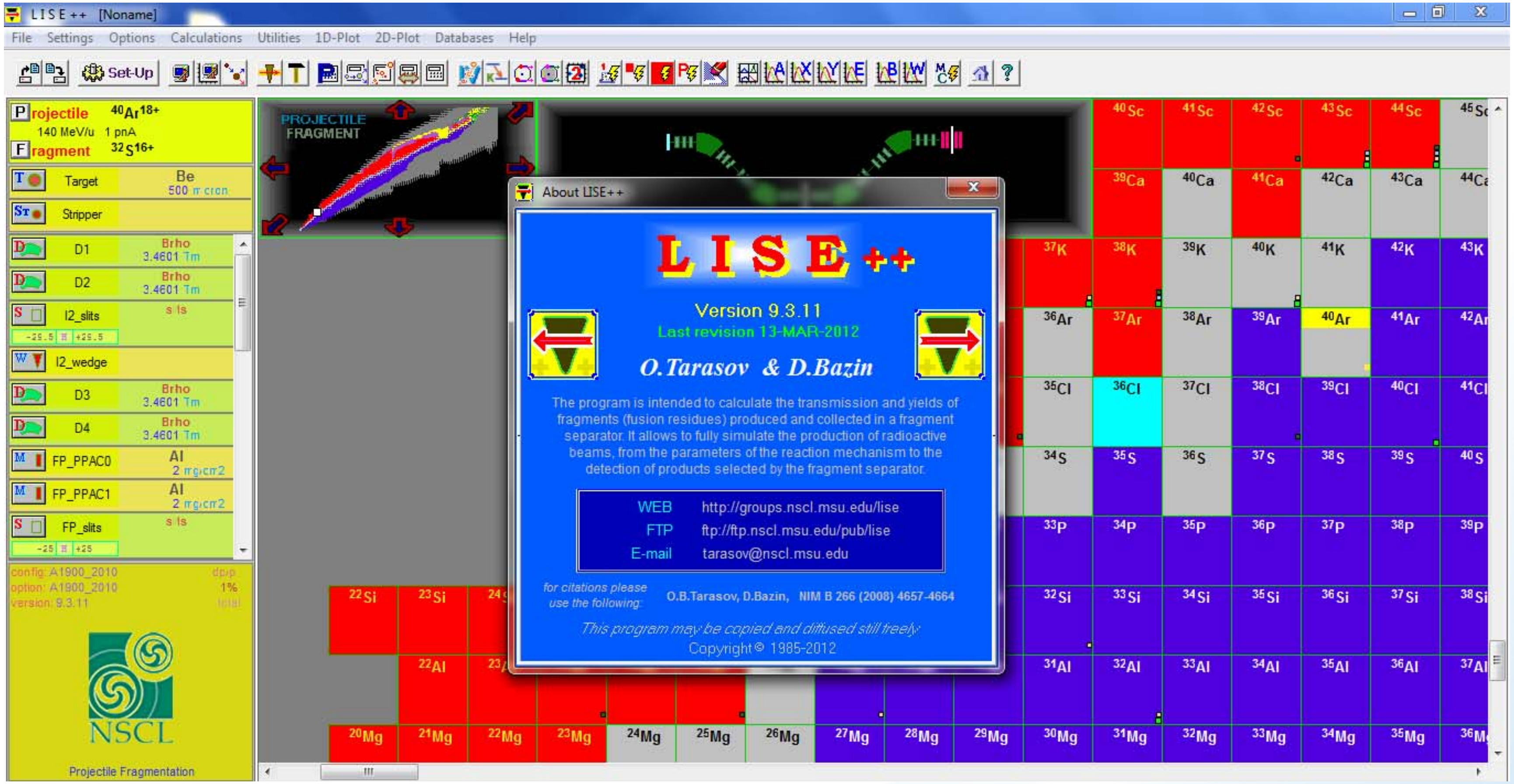
$$1 \text{ barn (b)} = 10^{-24} \text{ cm}^2$$

Typical fusion cross sections are in the mb's

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

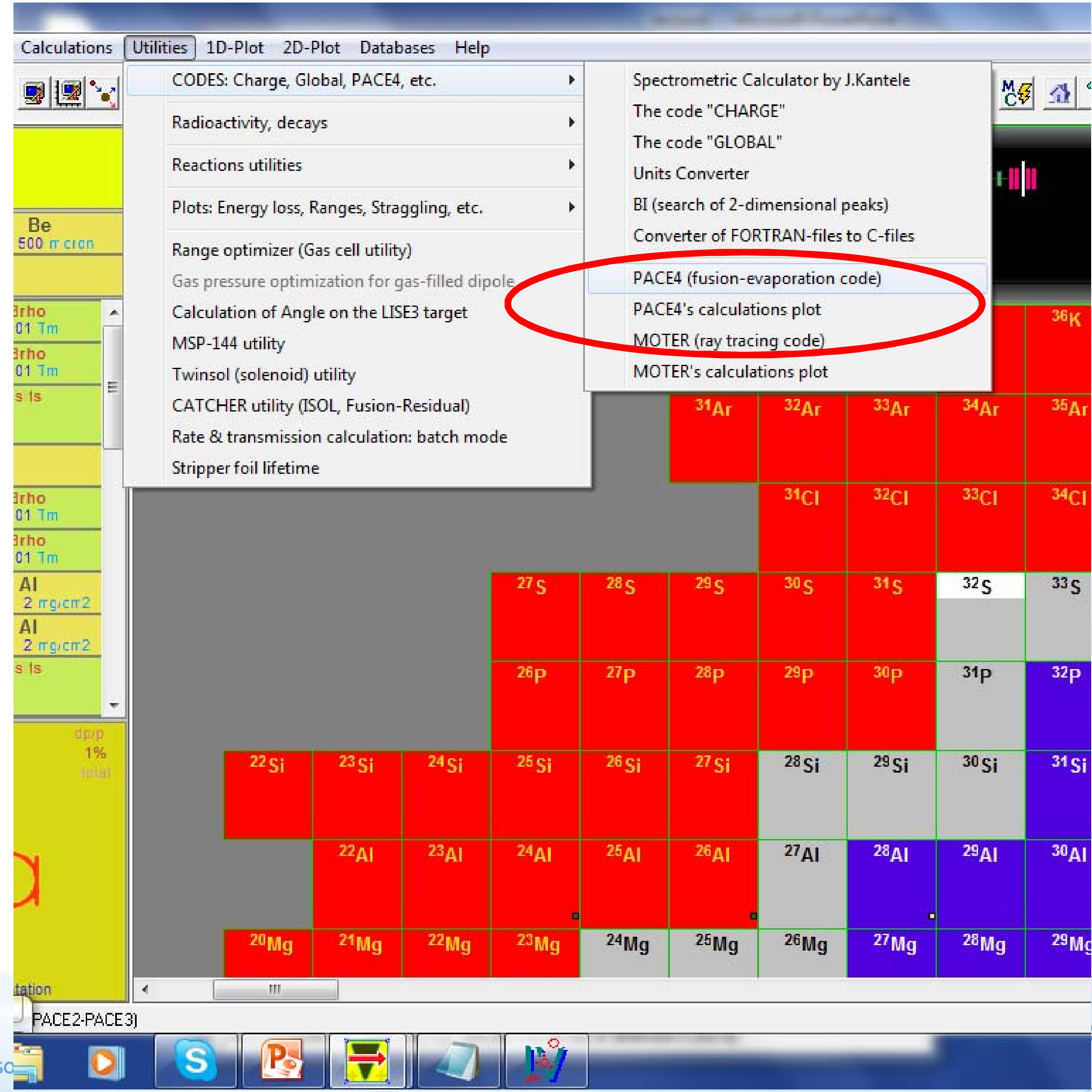
$$\# \text{ of reactions/sec} = 6000$$

A nice tool for planning experiments …



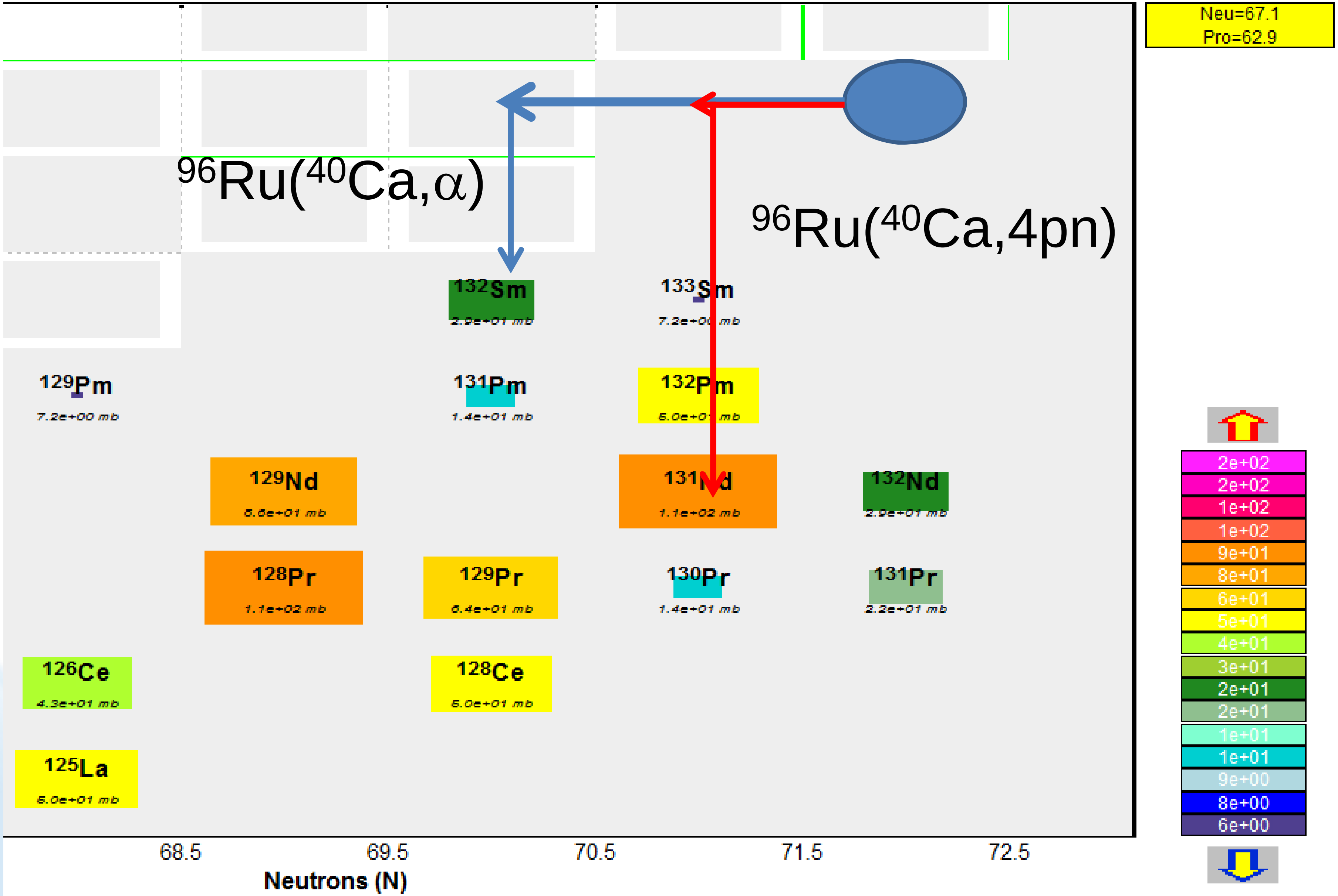
- Designed for fragmentation reactions
- Lots of good basic calculators

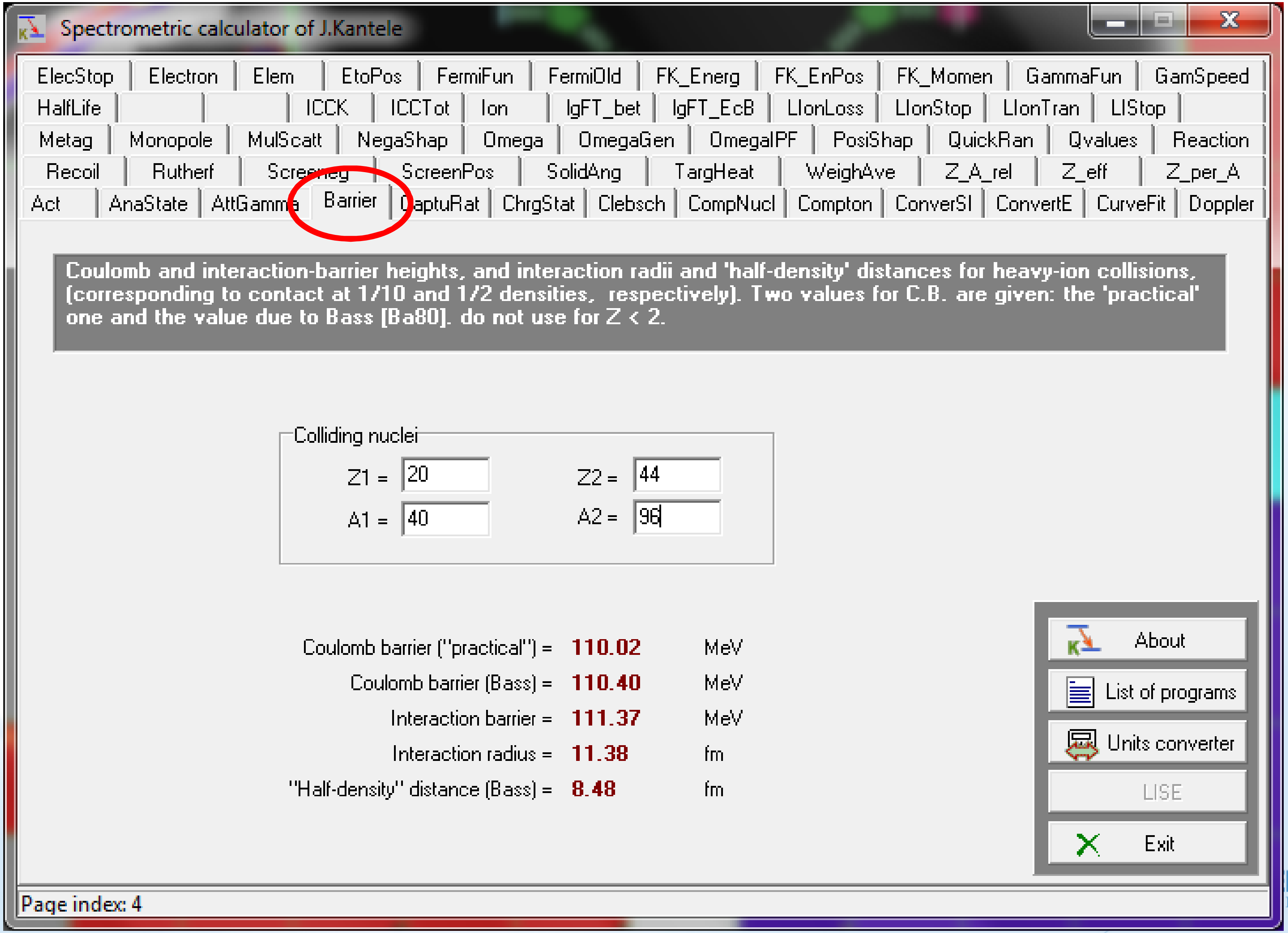
http://lise.nscl.msu.edu/lise.html


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
Be
500 micron
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
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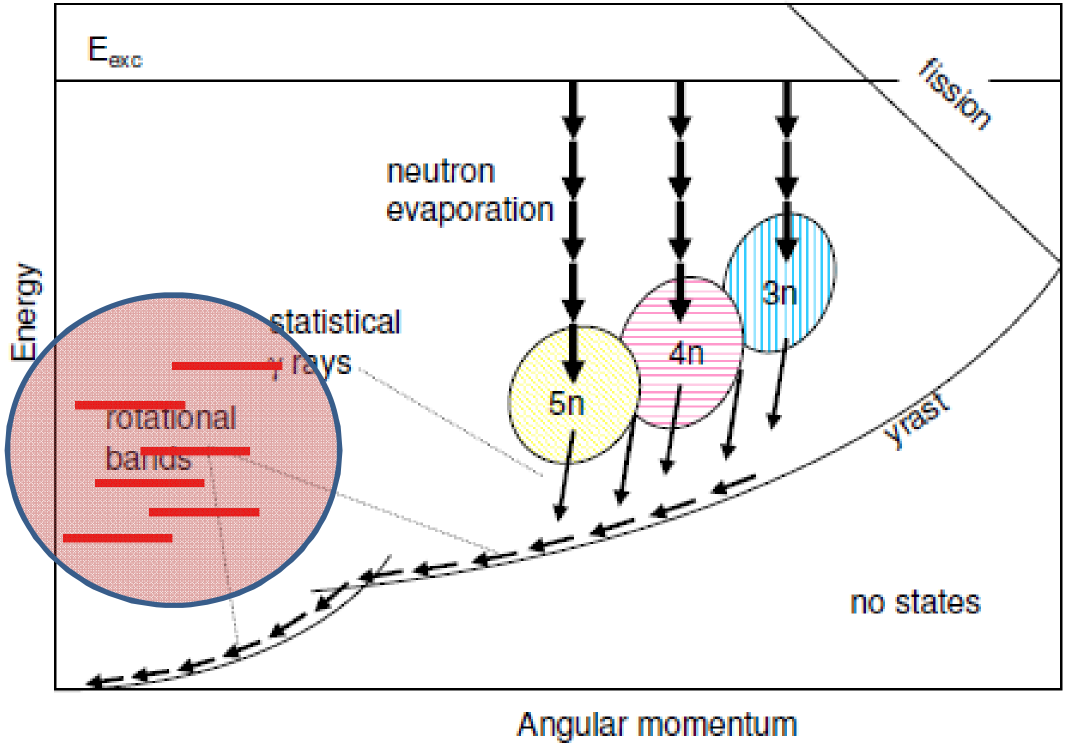
Decay of the Compound Nucleus

Heavy beam:

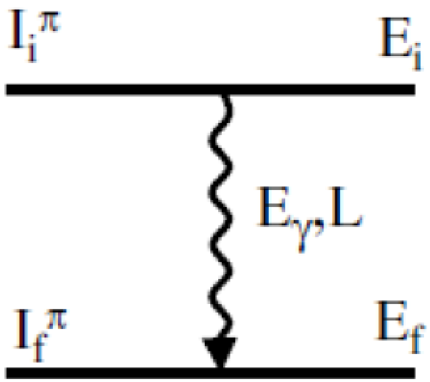
- Need high energy
- Brings in high angular momentum



Light beam:

- Can use lower E
- Brings in less angular momentum

Gamma-Ray Emission



$$E_{\gamma} = E_i - E_f$$

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

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

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

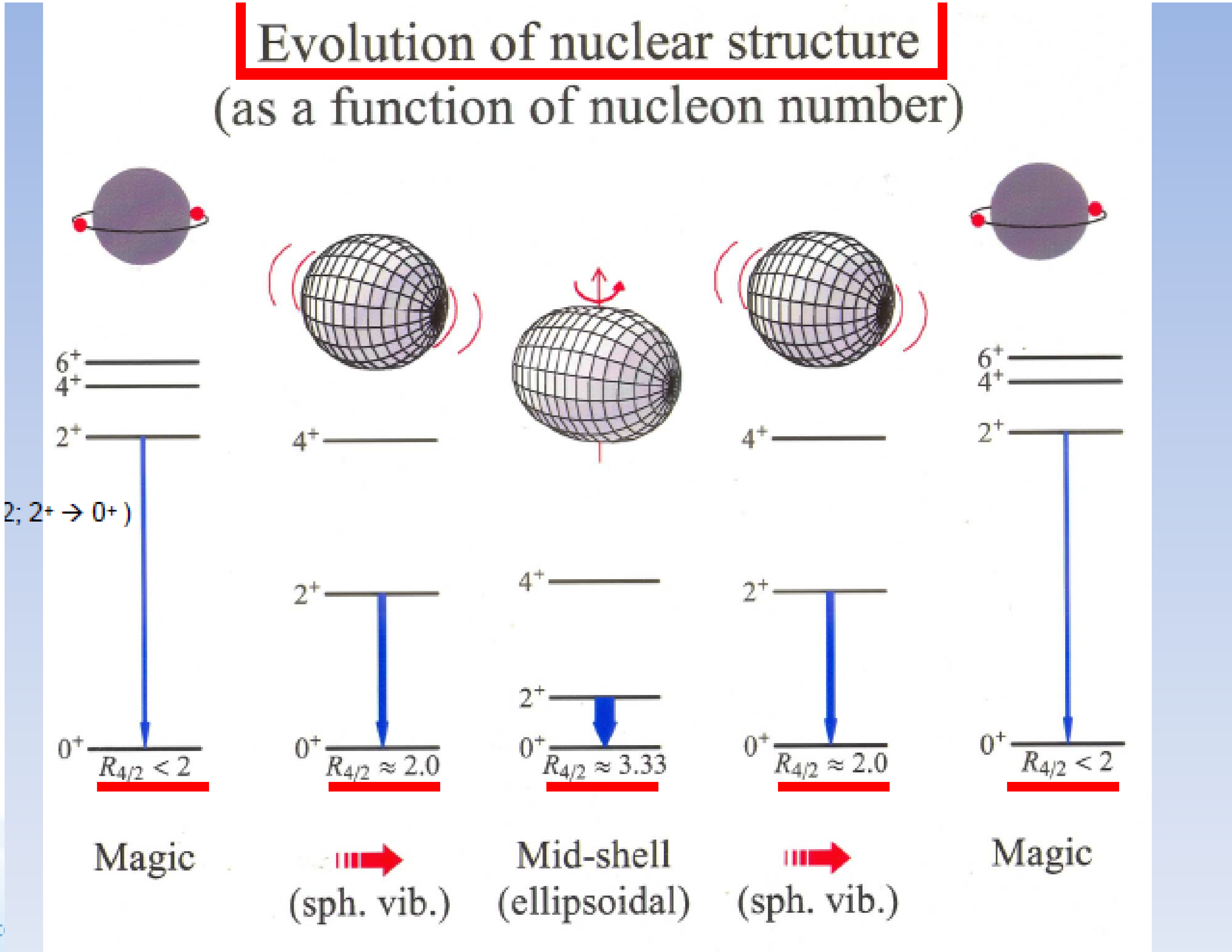
Possible decay modes:

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

Gamma-ray emission is usually the dominant decay mode

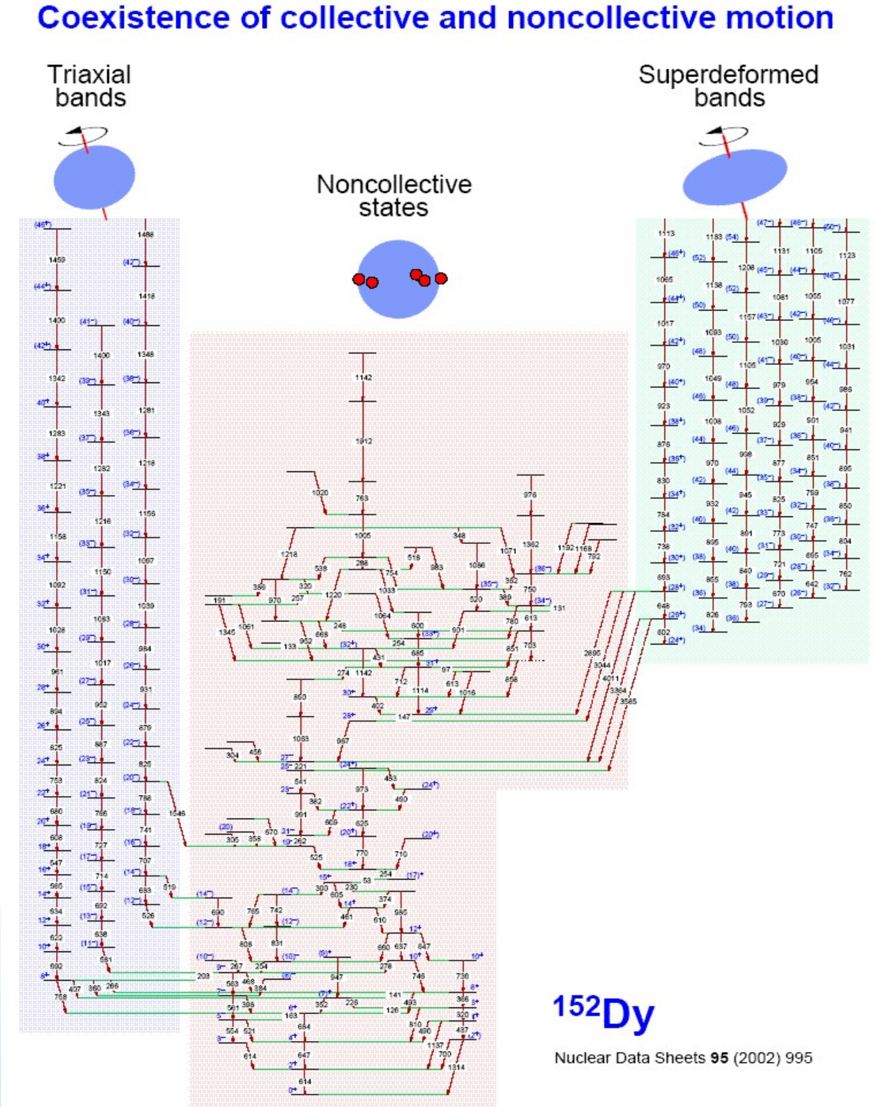
- Energy
- Spin, Parity
- Magnetic, quadrupole moment
- Lifetime
- …

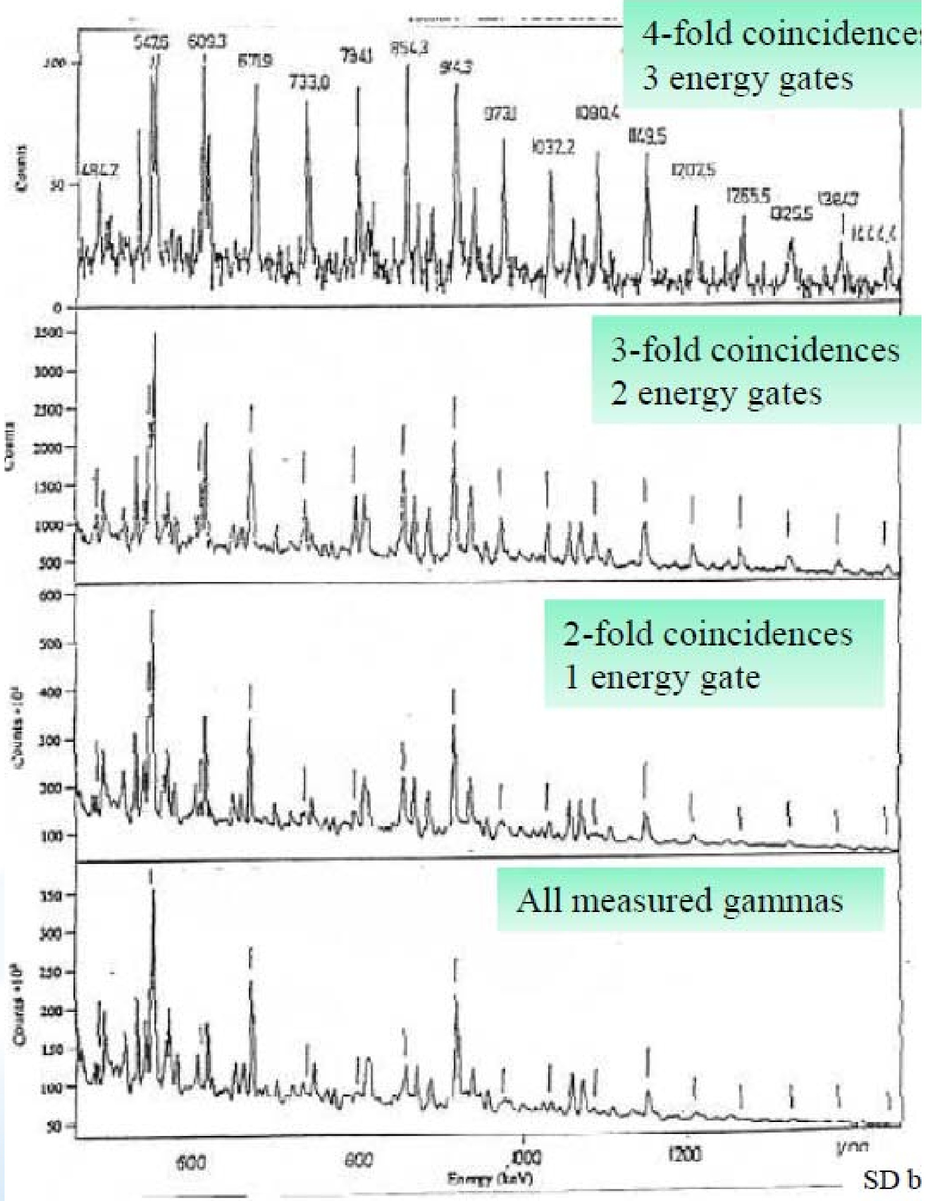
Gamma rays tell you something about shape



Partial Level Scheme of ^{152}Dy

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





Gamma-ray interactions with matter

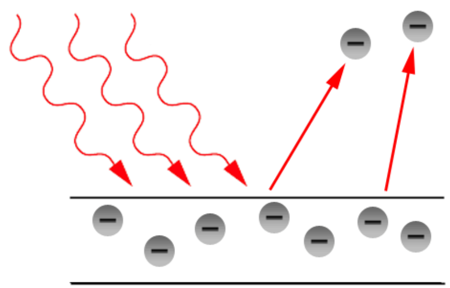
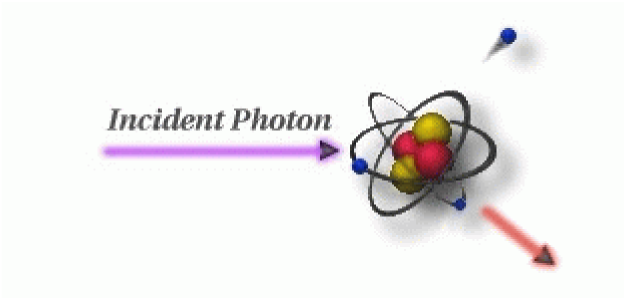
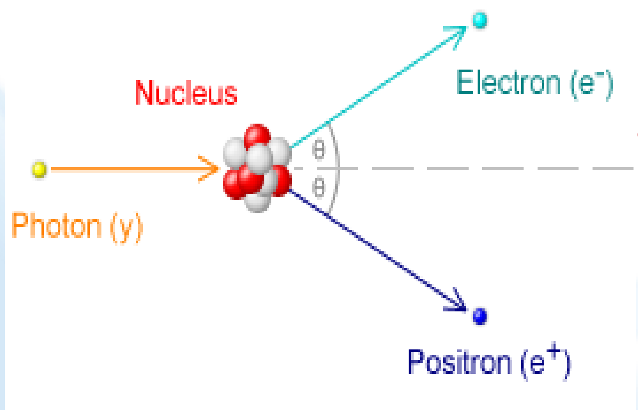


Photo effect – photoelectron is ejected carrying the total γ-ray energy



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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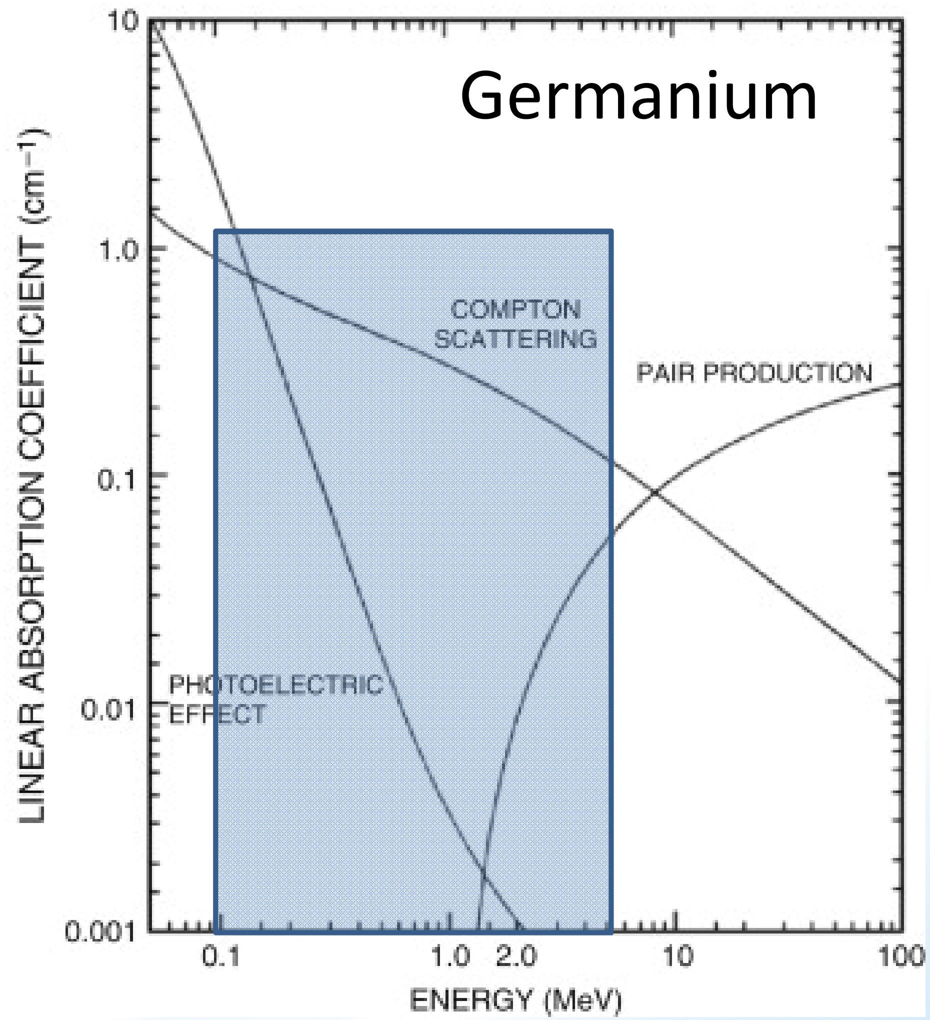
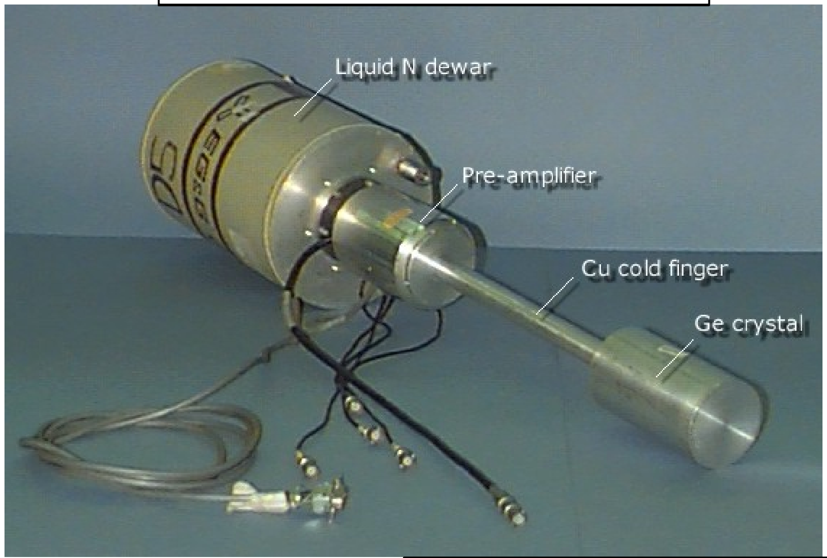
Gamma-ray interactions with matter

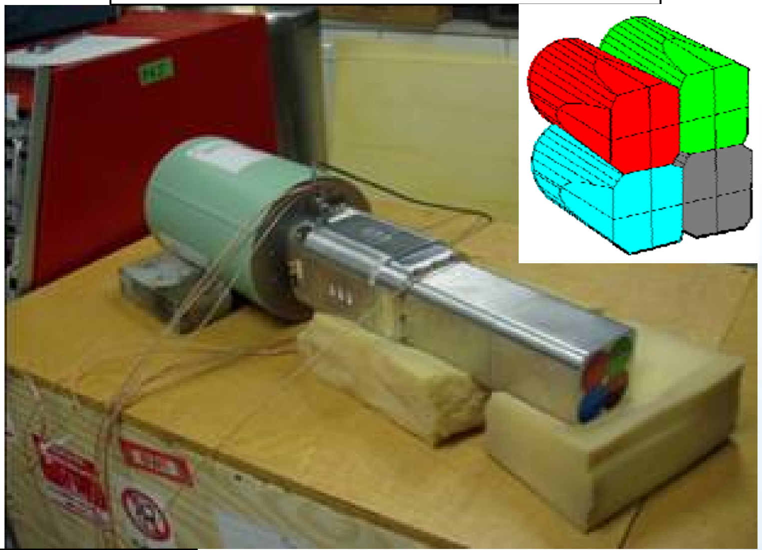


The “best” gamma-ray detector

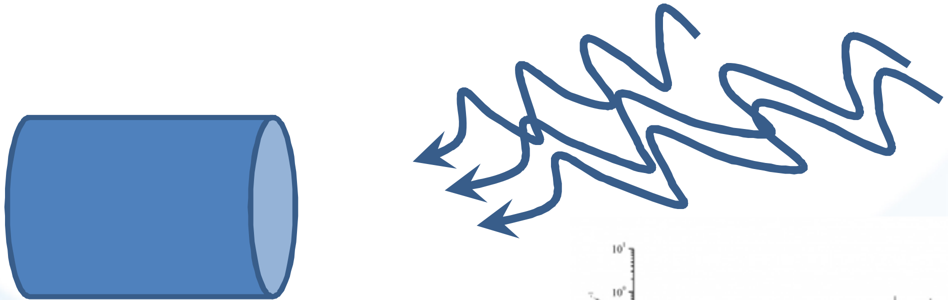
HPGe detector

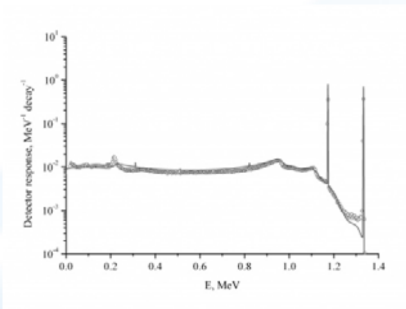


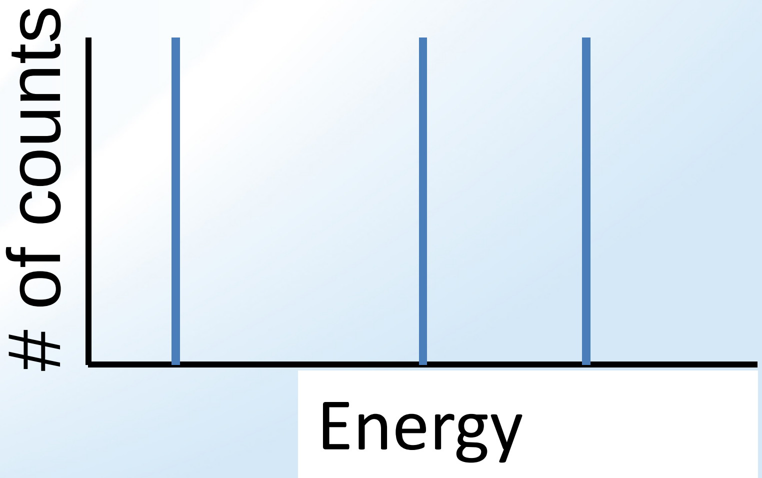
Clover detector



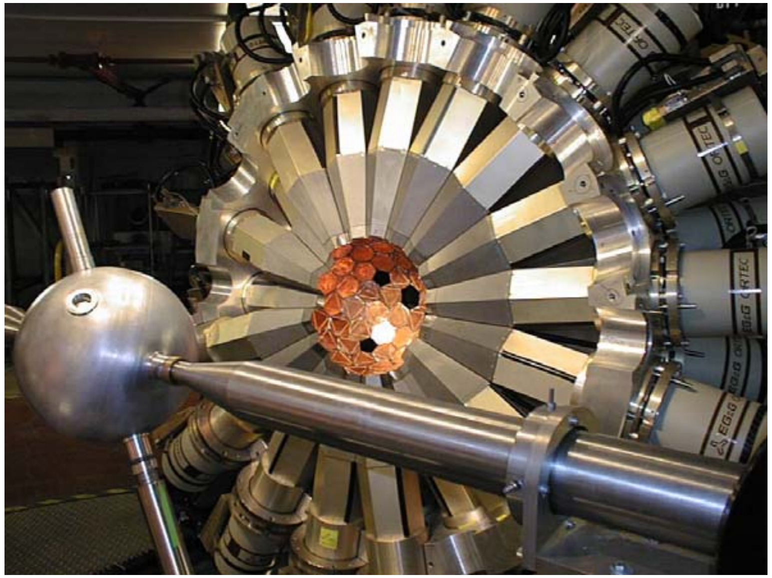
This happens about 70% of the time !!

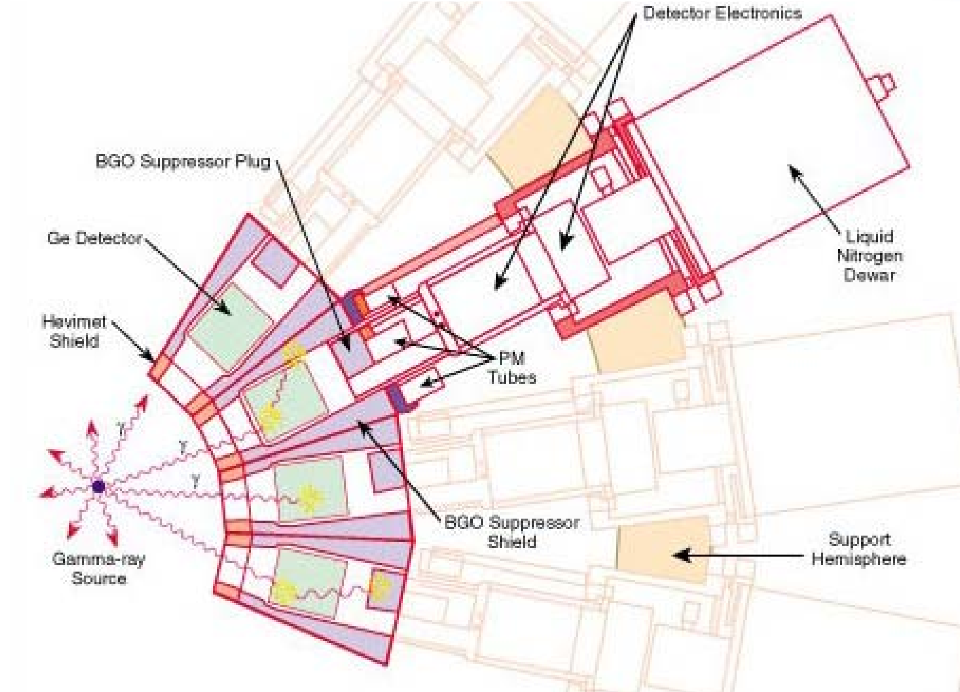


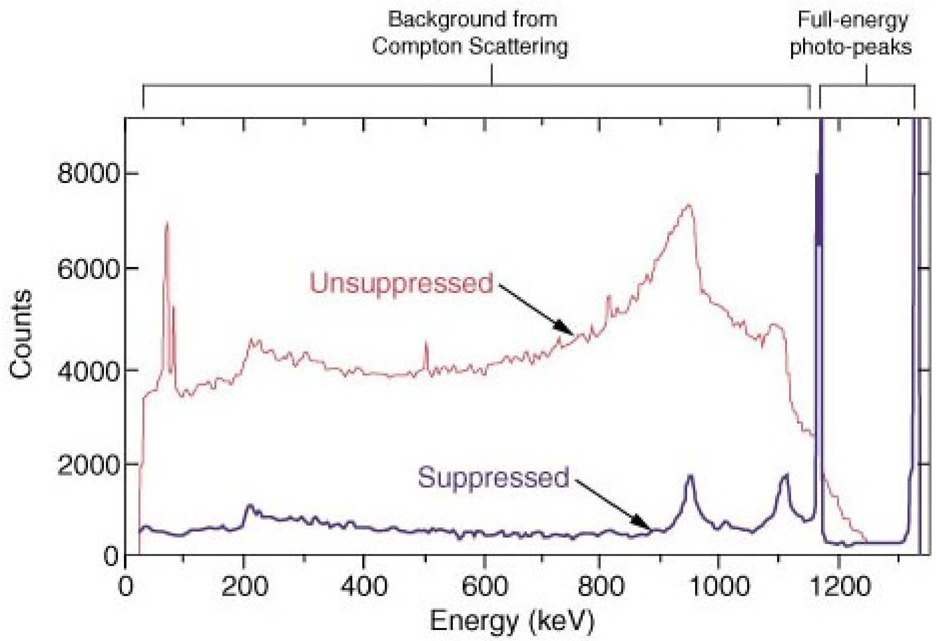


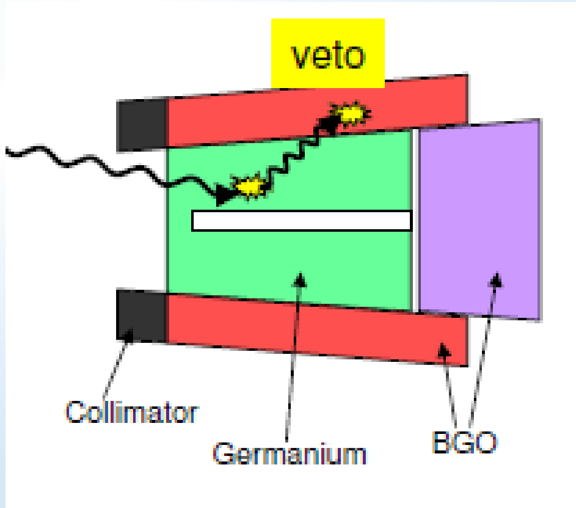


Compton Suppression



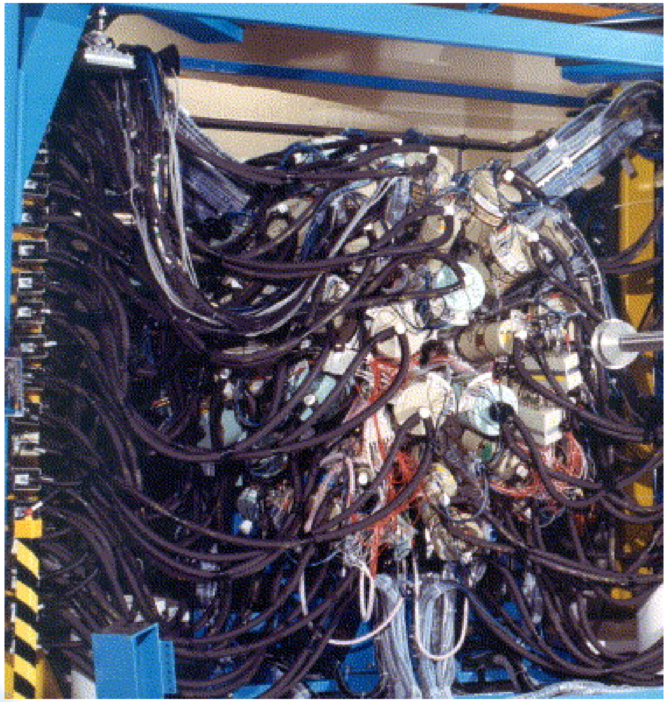




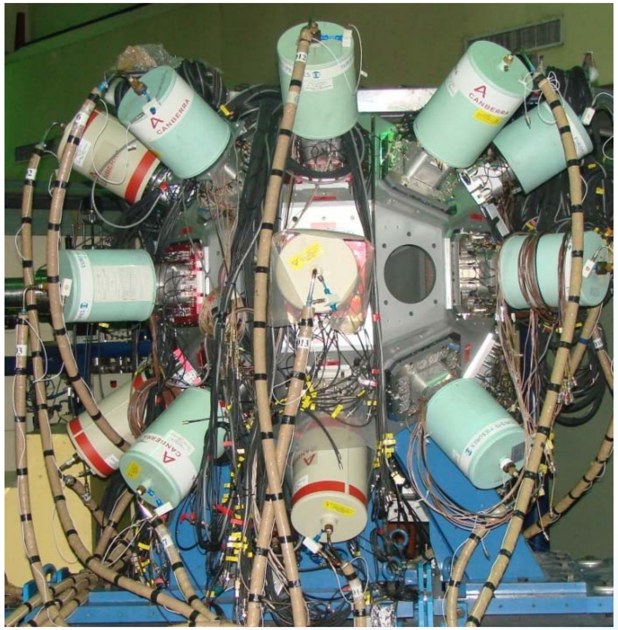


Compton Suppressed Arrays

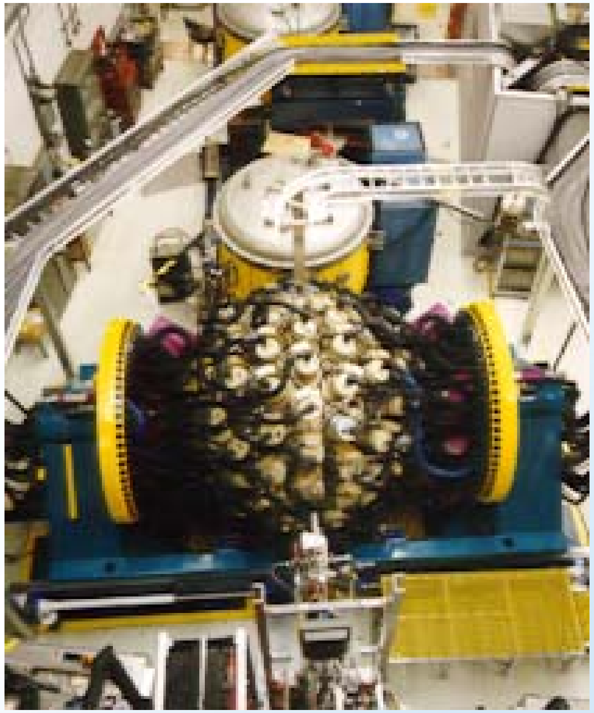
For the last ~ 15 - 20 years, large arrays of Compton-suppressed Ge detectors such as EuroBall, JUROBALL , GASP, EXOGAM, TIGRESS, INGA, Gammasphere and others have been the tools of choice for nuclear spectroscopy.



EUROBALL

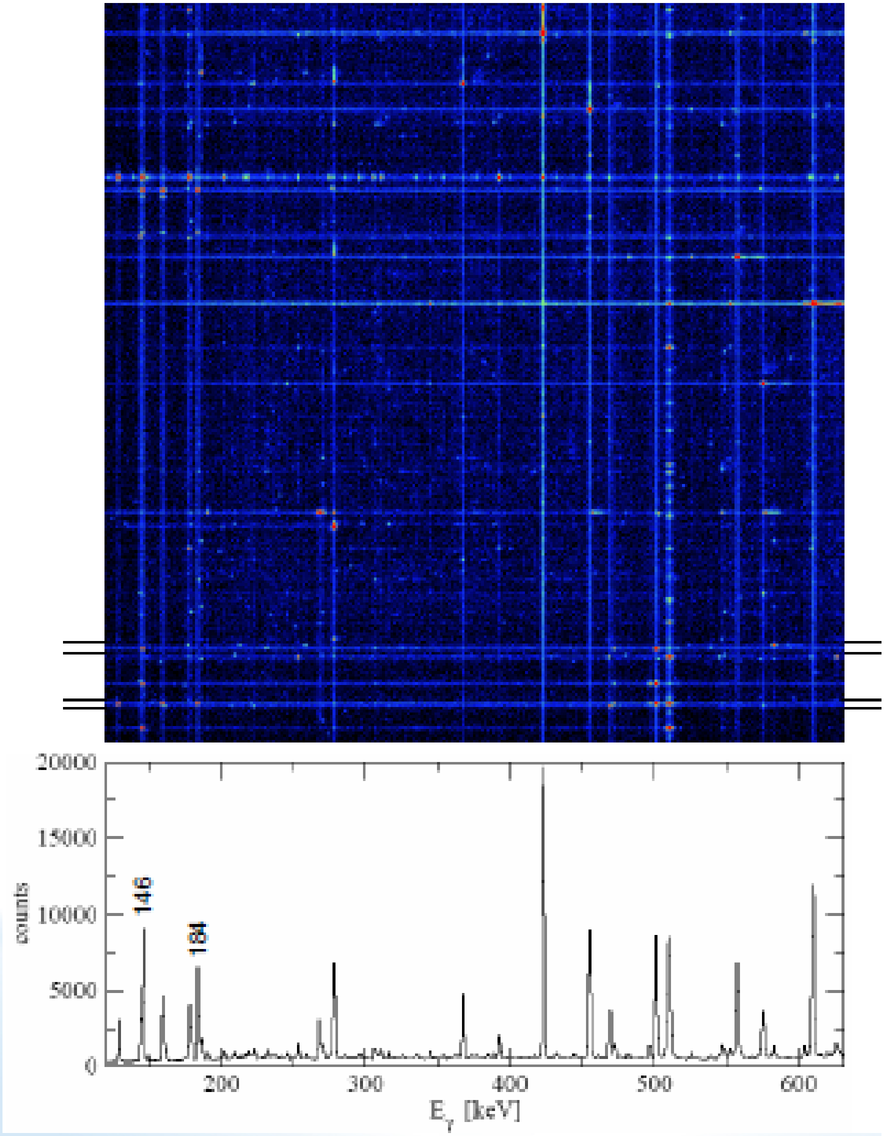


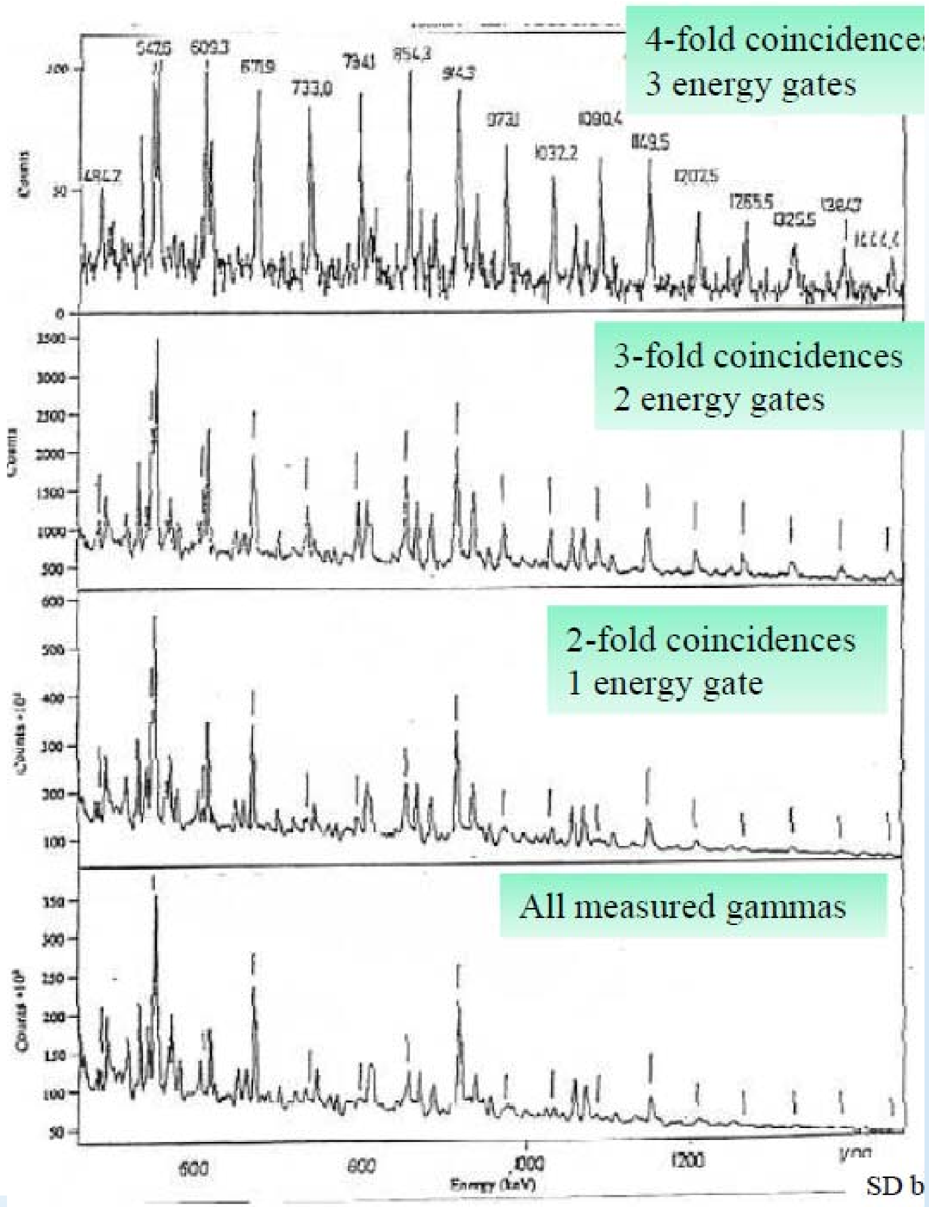
INGA



Gammasphere

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





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.

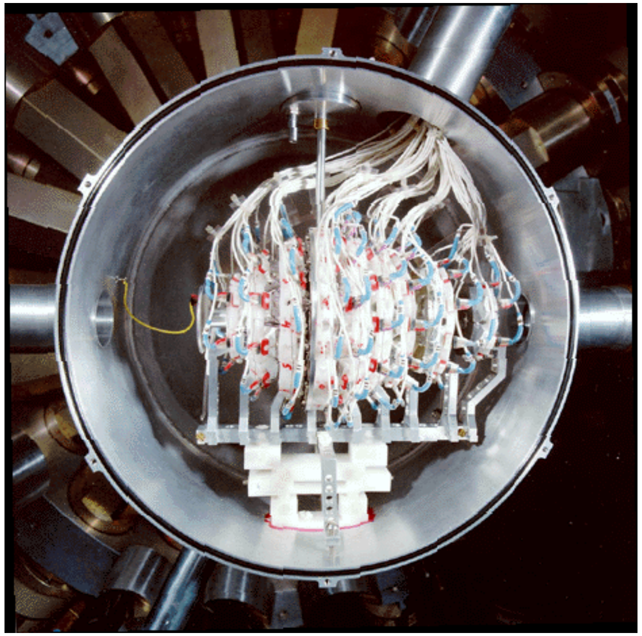
MINUS Low Efficiency

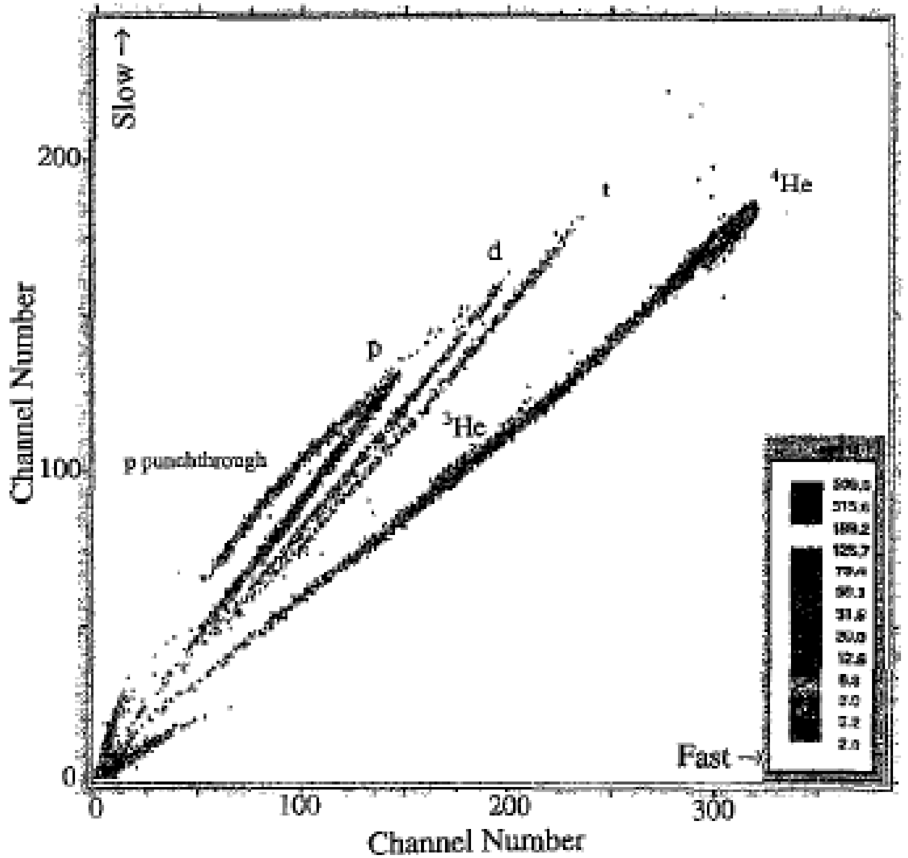
CROSS SECTION LOWER LIMIT ~100nb that is $\sim 10^{-7}$

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

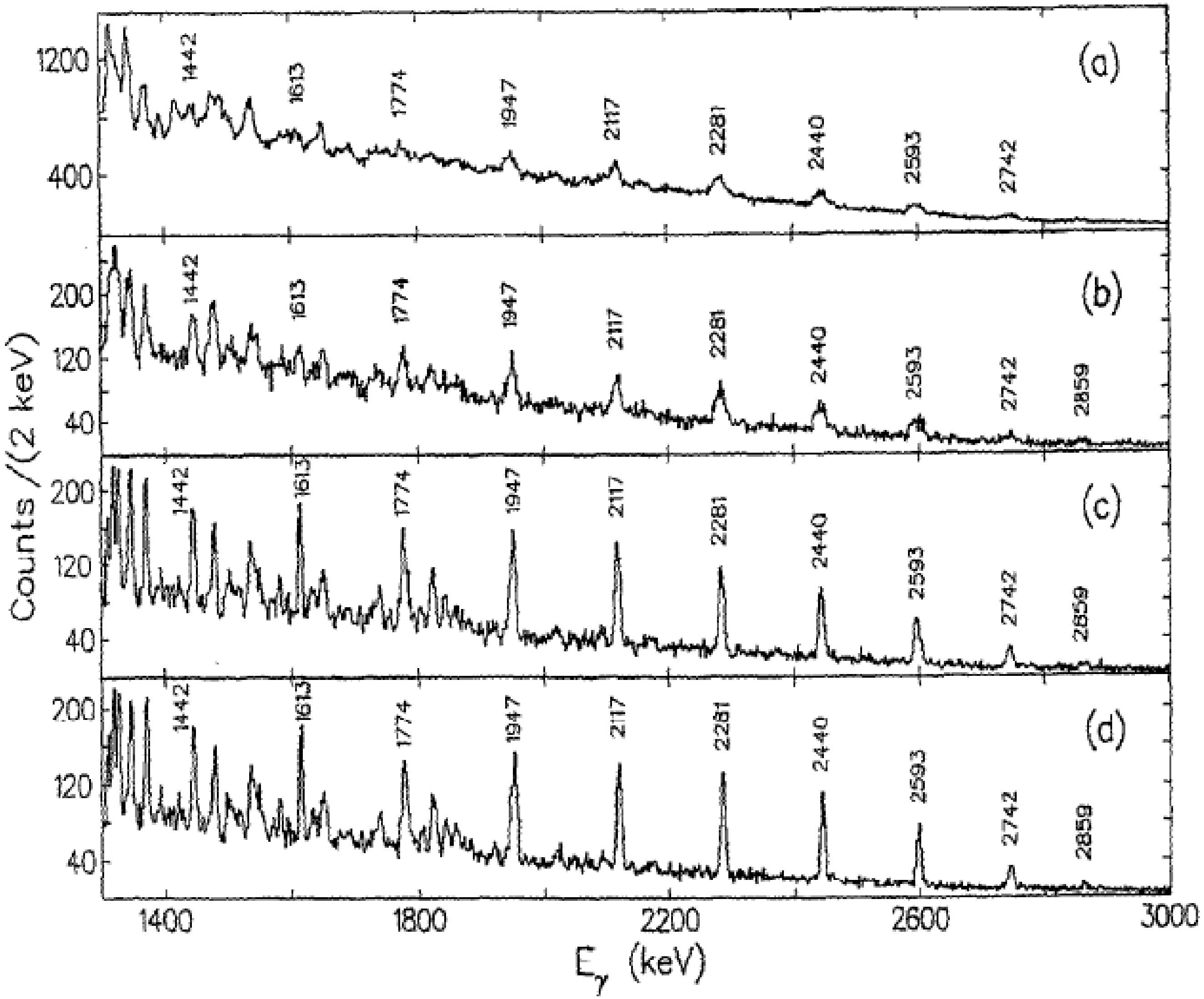




95 CsI(Tl) detectors

Nearly 4π coverage

Microball charged particle detector



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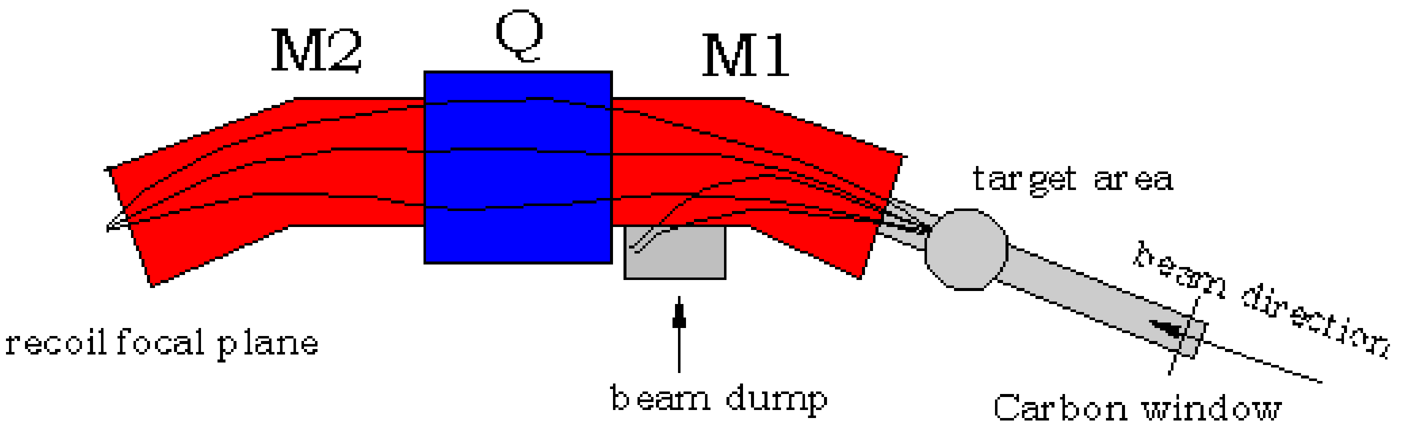
Recoil Separators

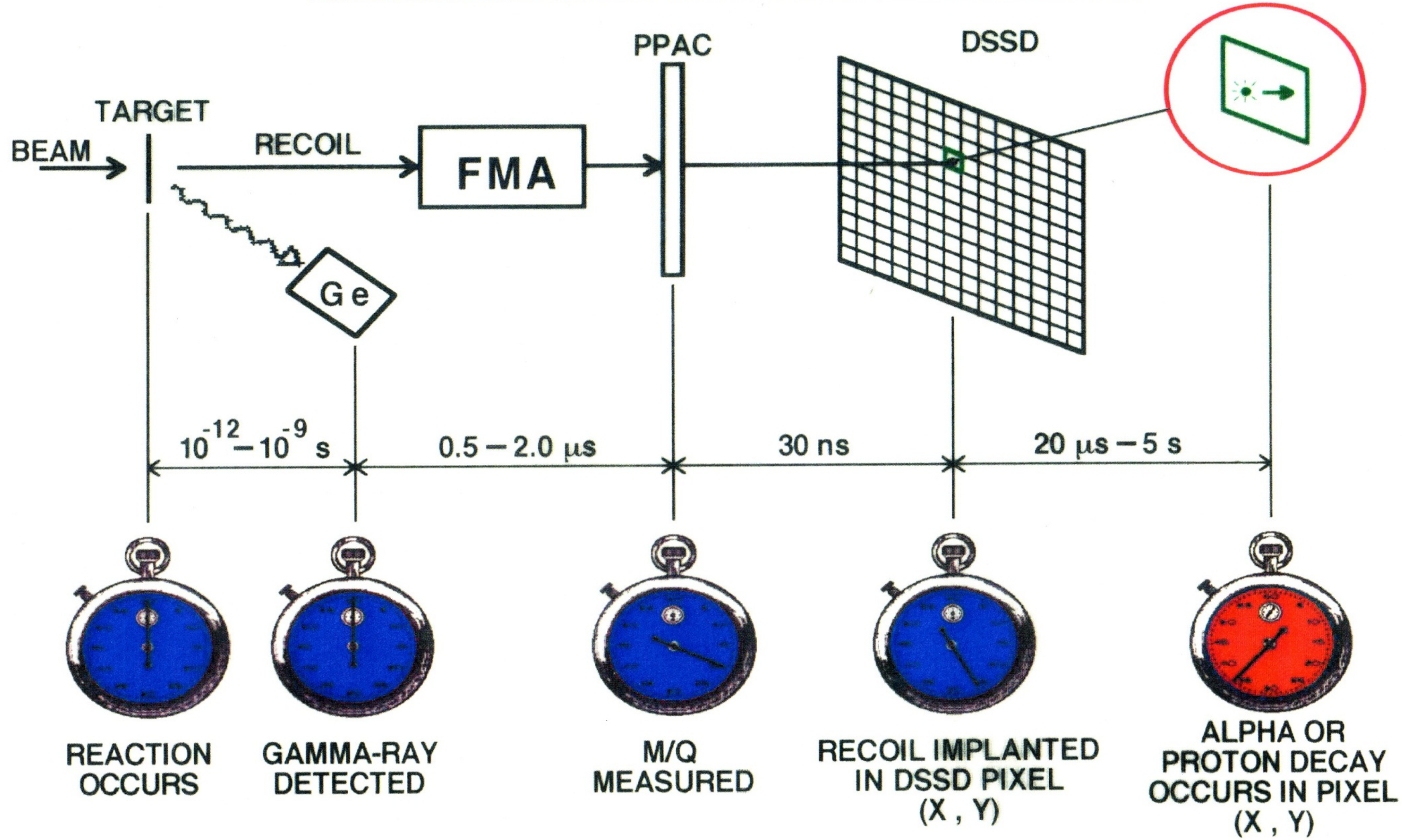
Works on basic principle of charged particle moving in magnetic or electric field



$$B\rho = mv/Q$$

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

RECOIL DECAY TAGGING METHOD

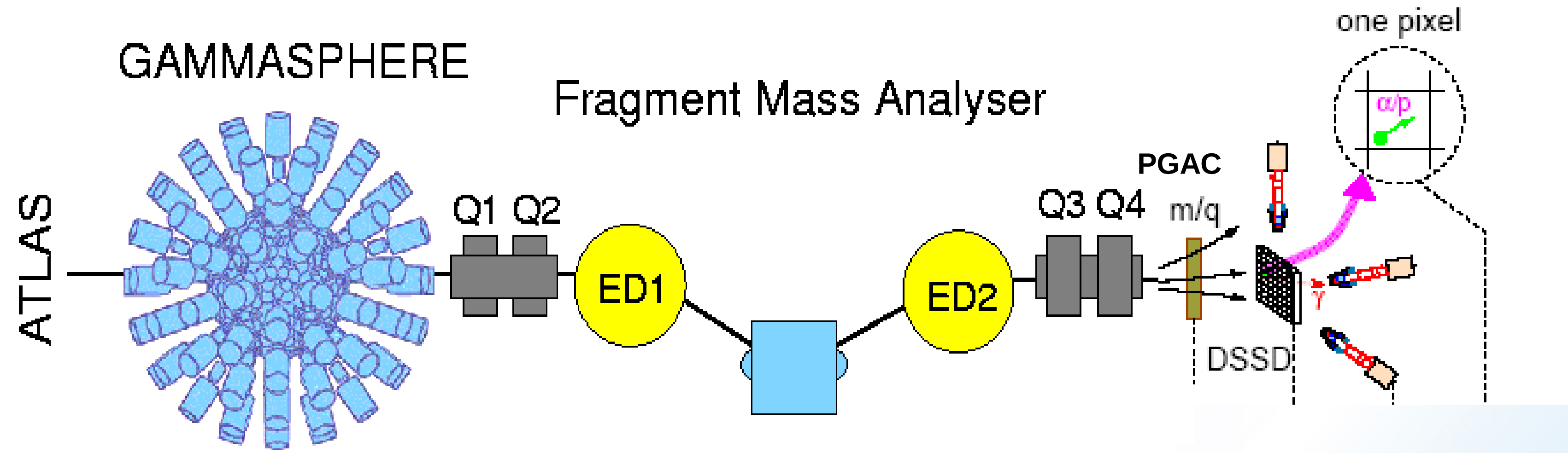


1. Prompt γ-rays correlated with M/Q and (X , Y) position of recoil in DSSD
2. Decay proton or alpha identifies nucleus that emitted the γ-rays

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]



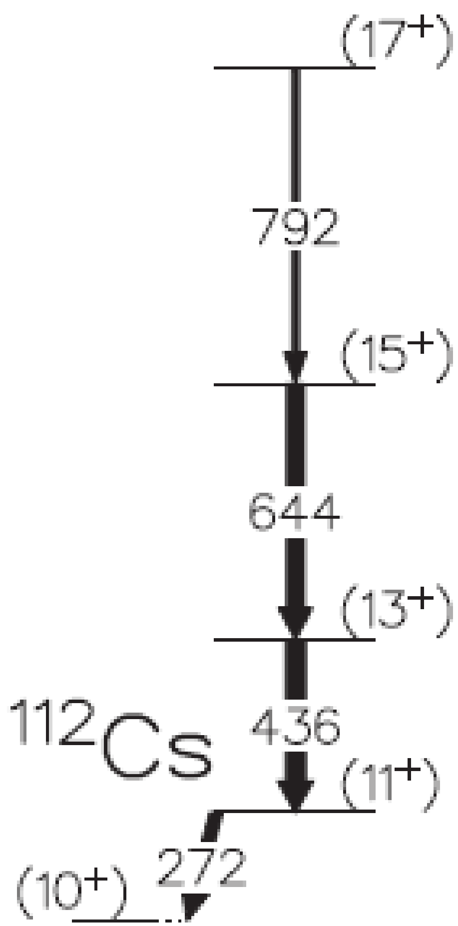
112Ba	113Ba	114Ba 0.43 S ε: 99.10% εp: 20.00%
	112Cs 0.5 MS P: 100.00%	113Cs 16.7 μS P: 100.00% α
110Xe 93 MS α: 64.00% εp	111Xe 0.81 S ε: 90.00% α: 10.00%	112Xe 2.7 S ε: 99.16% α: 0.84%

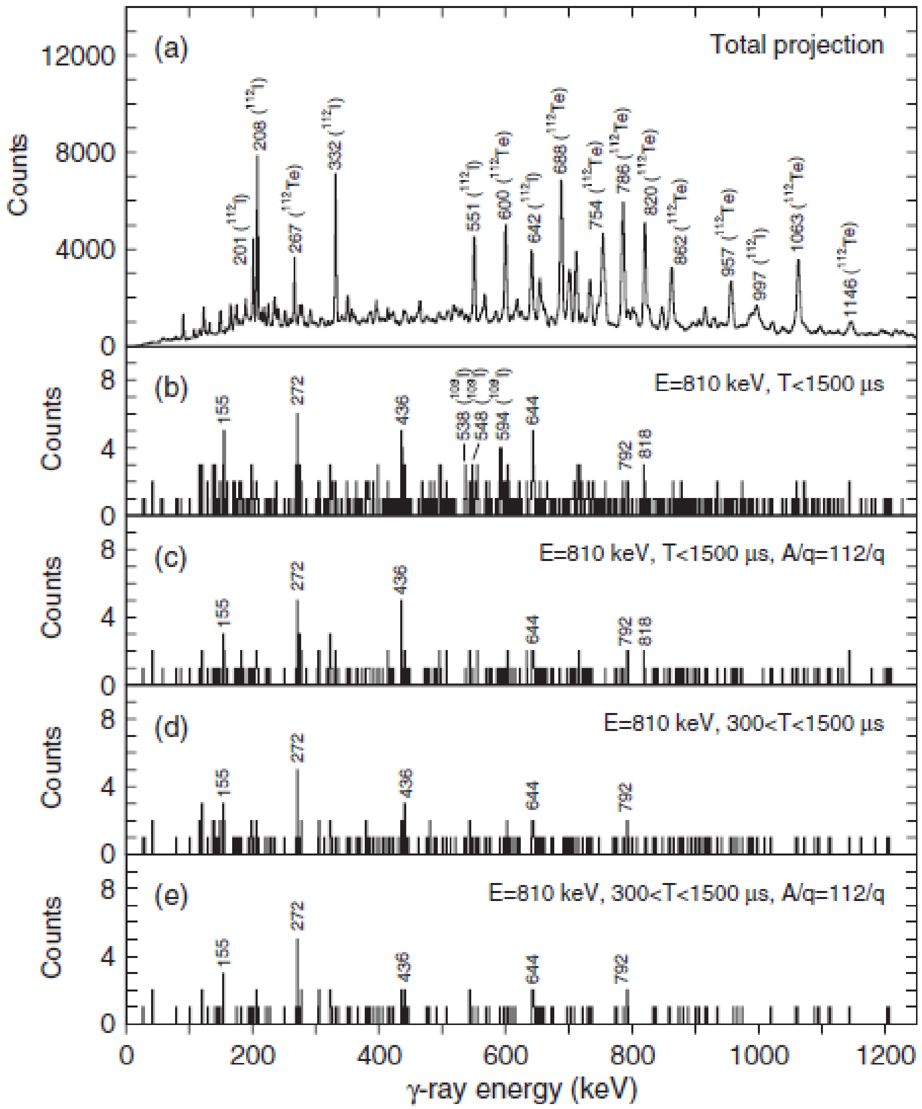
Measure recoil in DSSD
Recoil proton energy in same pixel

PHYSICAL REVIEW C **85**, 034329 (2012)

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

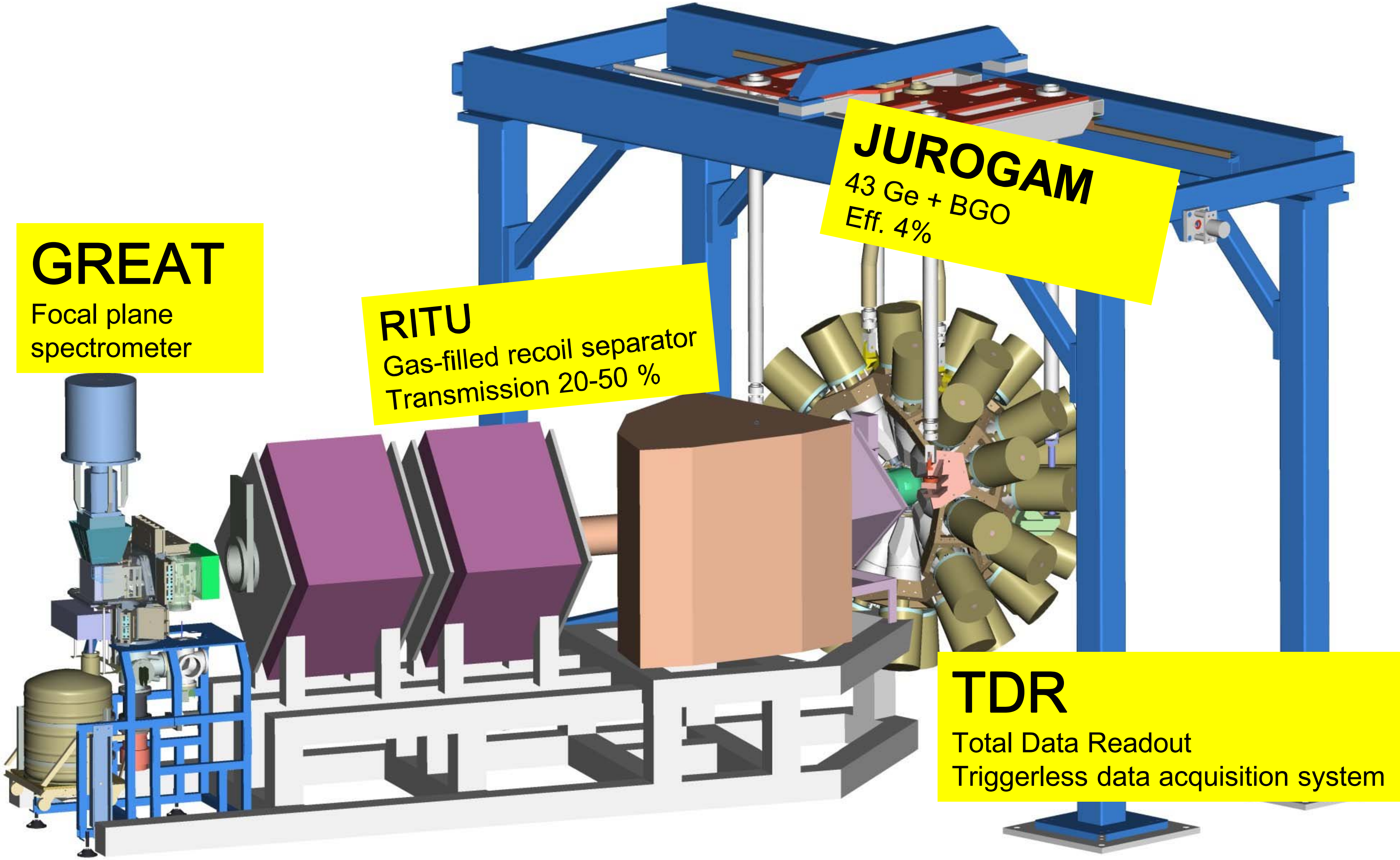
P. T. Wady,[1,2] J. F. Smith,[1,2,*] E. S. Paul,[3] B. Hadinia,[1,2,†] C. J. Chiara,[4,‡] M. P. Carpenter,[5] C. N. Davids,[5] A. N. Deacon,[6] S. J. Freeman,[6] A. N. Grint,[3] R. V. F. Janssens,[5] B. P. Kay,[6,§] T. Lauritsen,[5] C. J. Lister,[5] B. M. McGuirk,[3] M. Petri,[3,‖] A. P. Robinson,[5,¶]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





Brookhaven Science Associates

RDT Instrumentation at JYFL

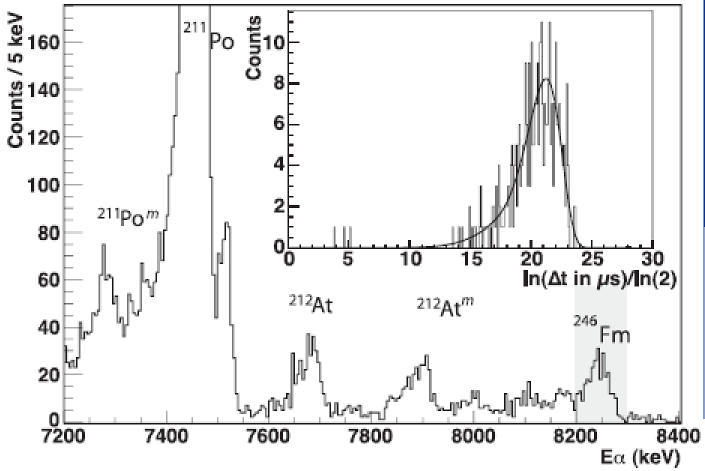


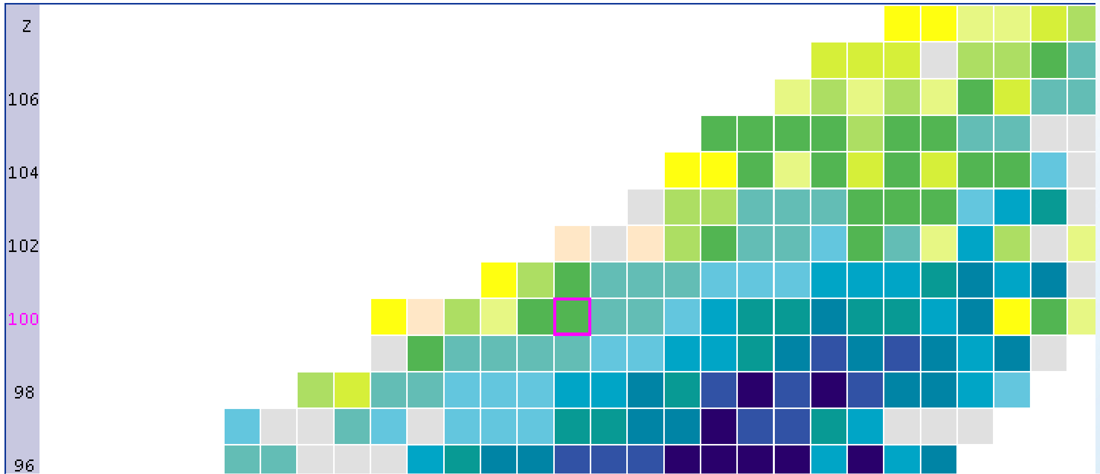
PHYSICAL REVIEW C 85, 041301(R) (2012)

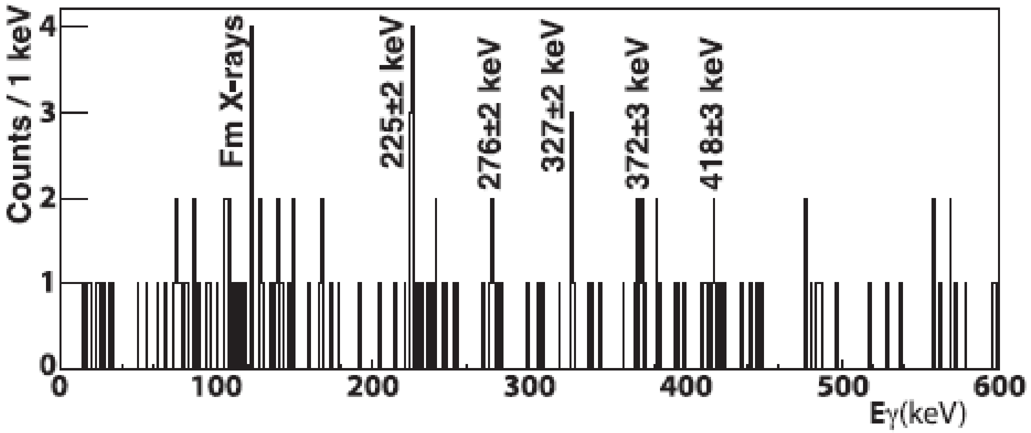
In-beam spectroscopy with intense ion beams: Evidence for a rotational structure in ^{246}Fm

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



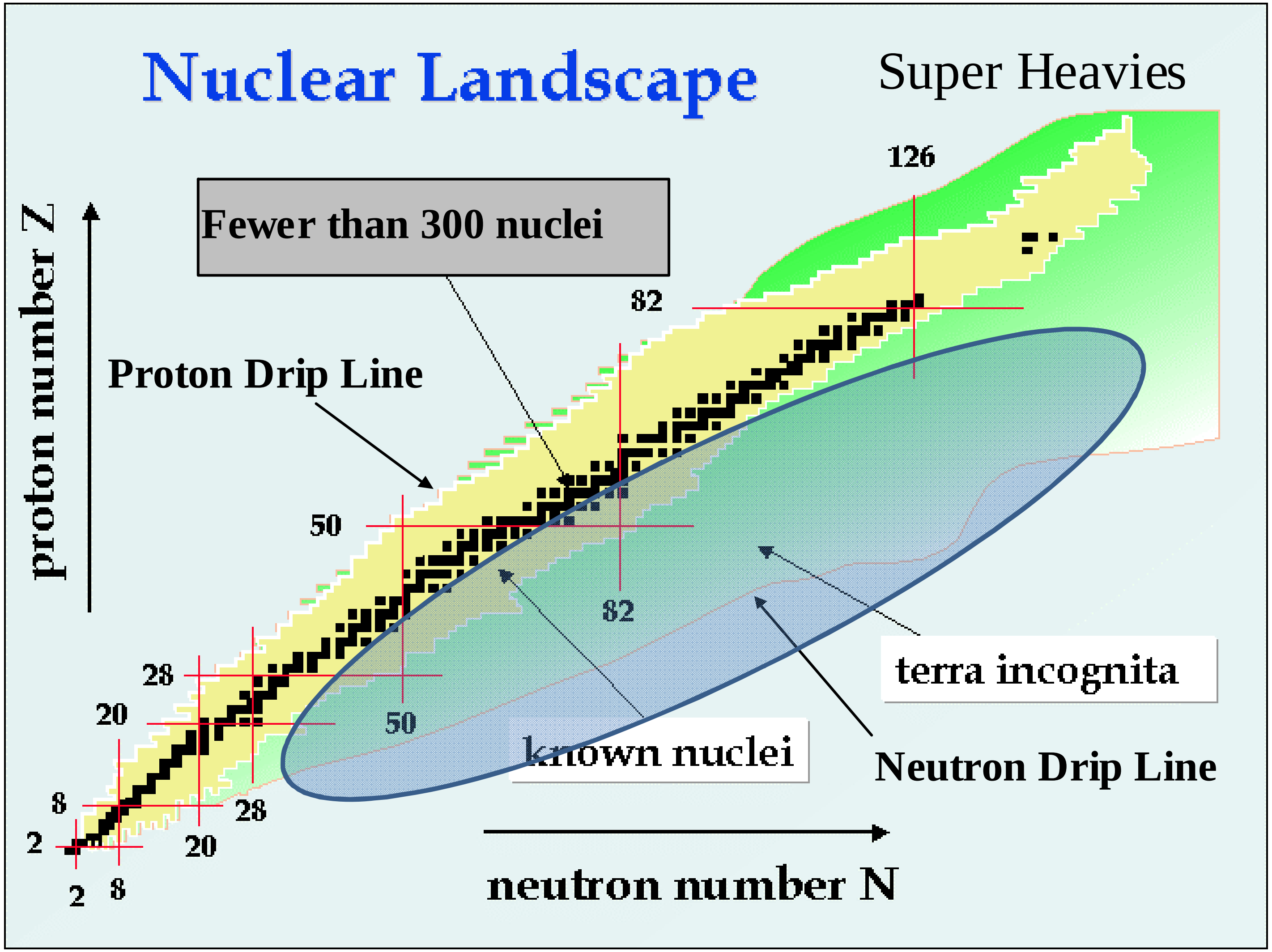




History : 100 years and counting

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 future



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

How Many ions/s do you need for Physics?

Remember that with a stable beam we had 10^{10} particles/sec

Well, it depends on what physics you want to do...

STOPPED BEAMS……Decays, masses, moments, harvesting.

(could be few/minute, or lower.. to macroscopic amounts [>10^{20} atoms)]

LOW ENERGY (~2MeV/u) …. Astrophysics and reactions.

(needs 10^8 p.p.s. …. or more)

RE-ACCELERATED (5-10 MeV/u) …. Structure.

(From 10^4 and upwards)

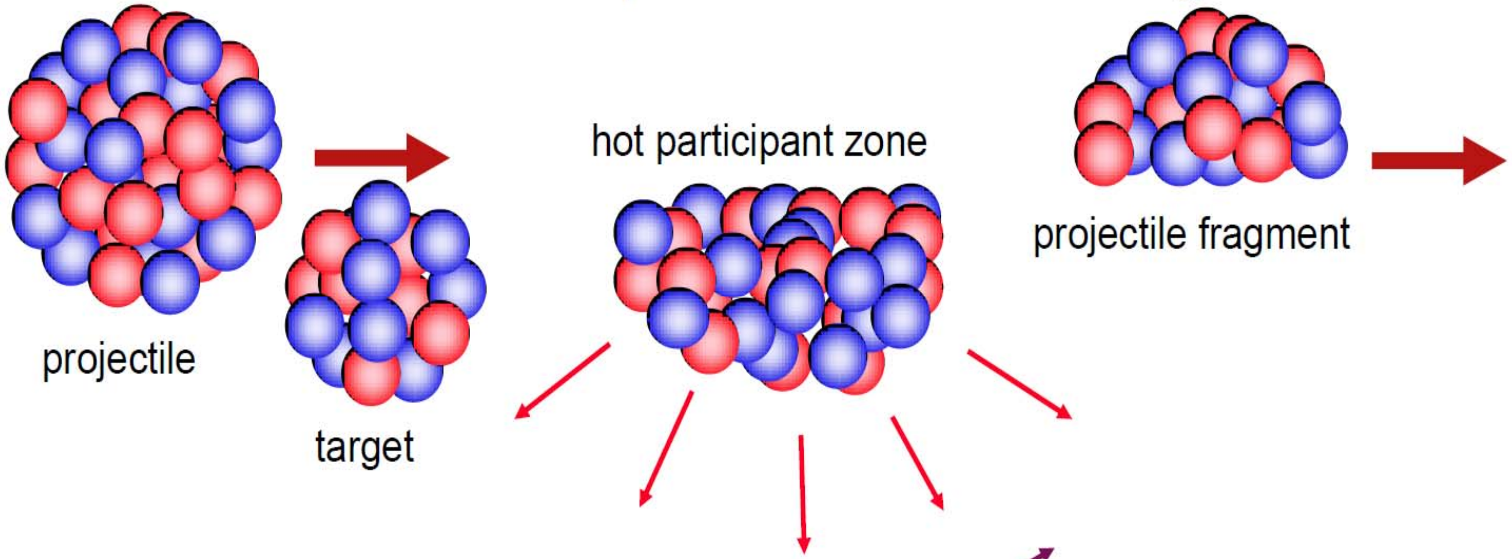
FAST (50-200MeV/u) …. Existence, whatever structure is possible.

(From few/week and up)

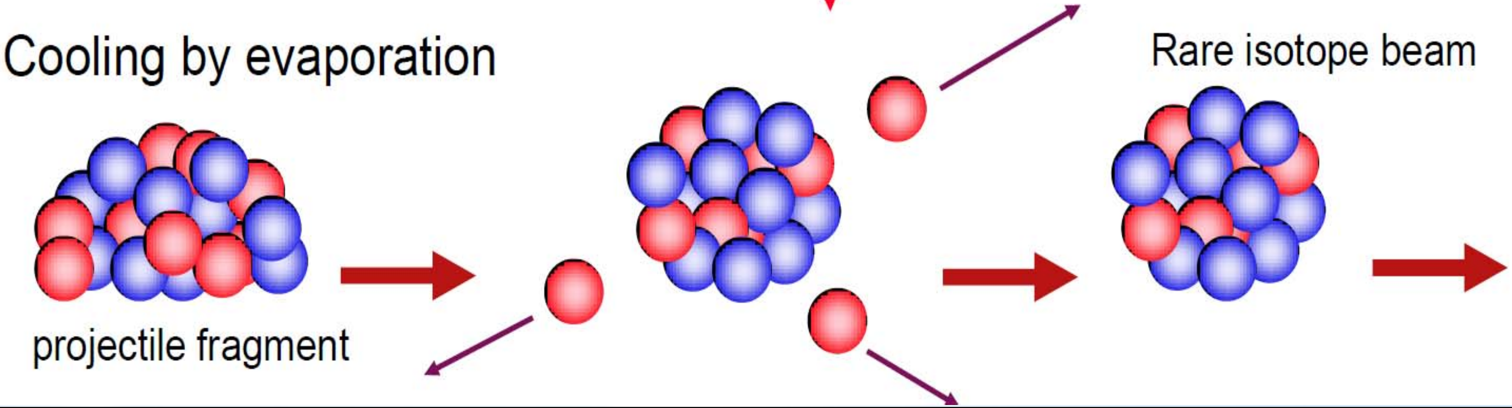
Production of Rare Isotopes in Flight

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

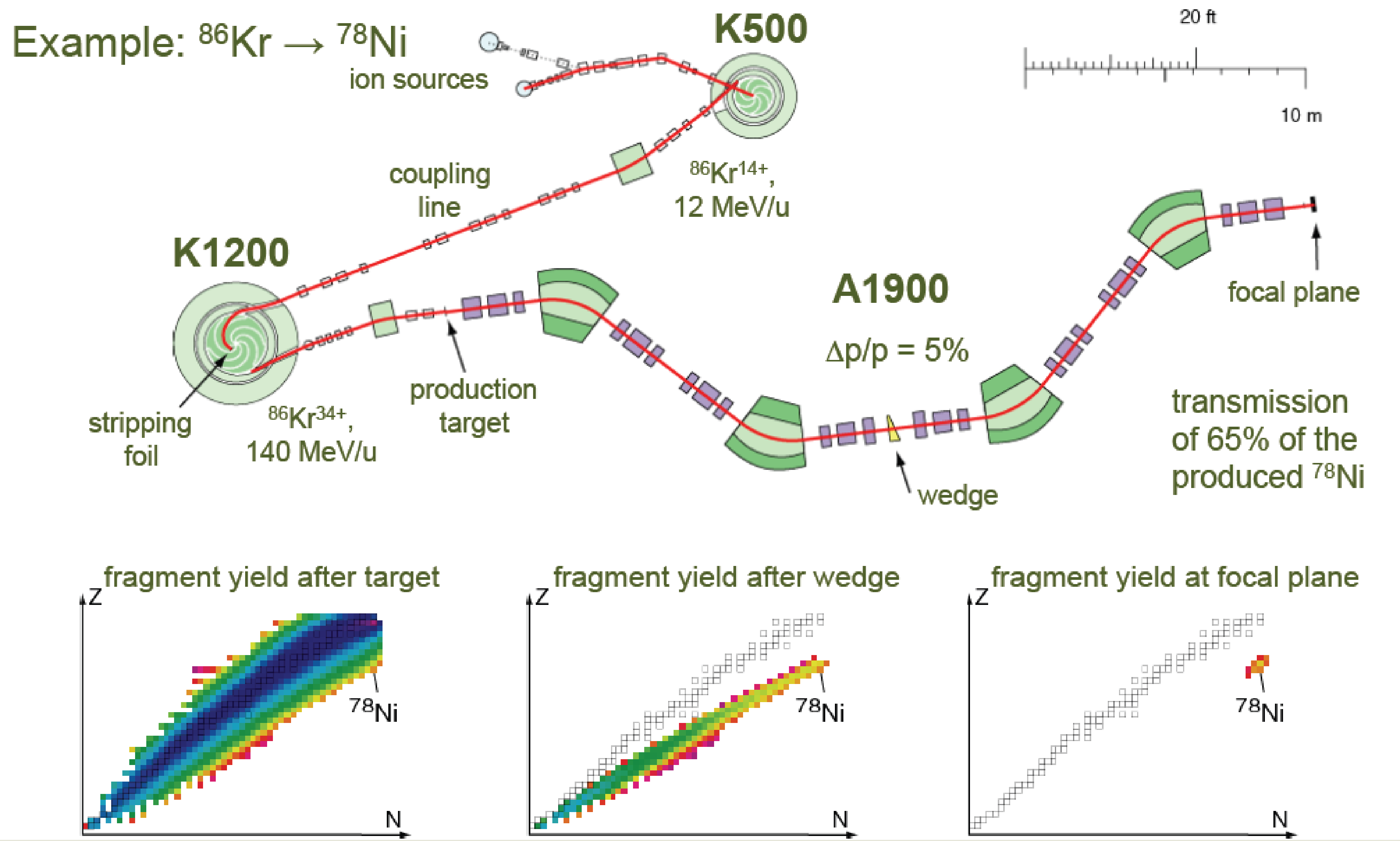


2. Cooling by evaporation



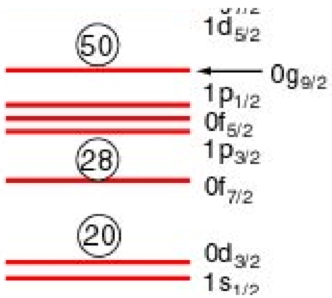
e.g., NSCL/FRIB (USA), RIKEN (Japan), GSI (Germany)

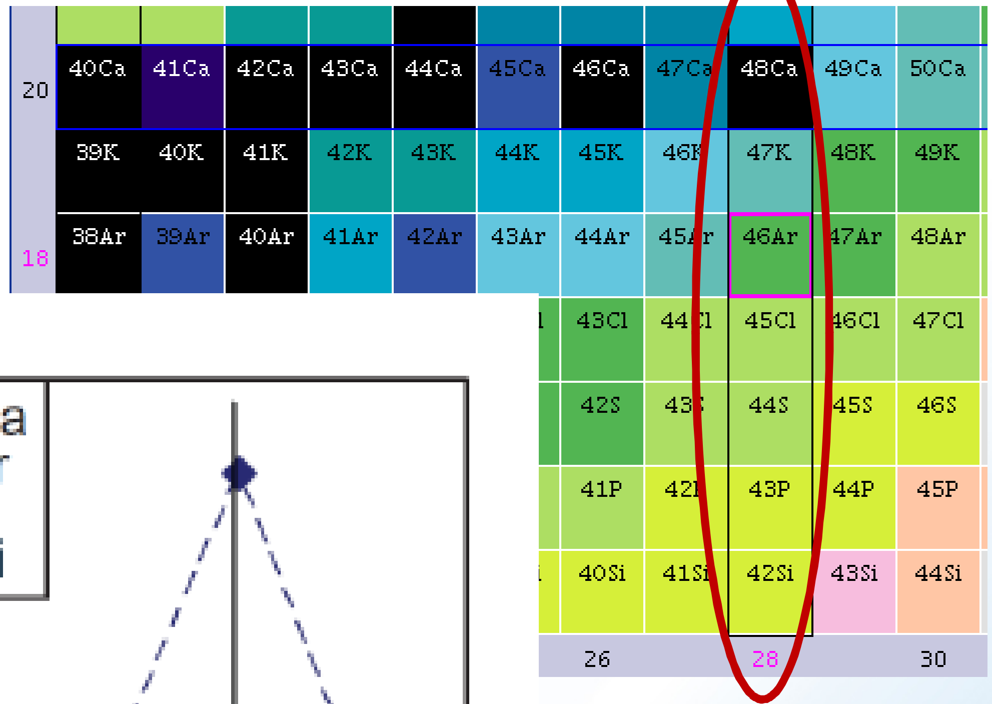
Example : In-Flight Production at NSCL

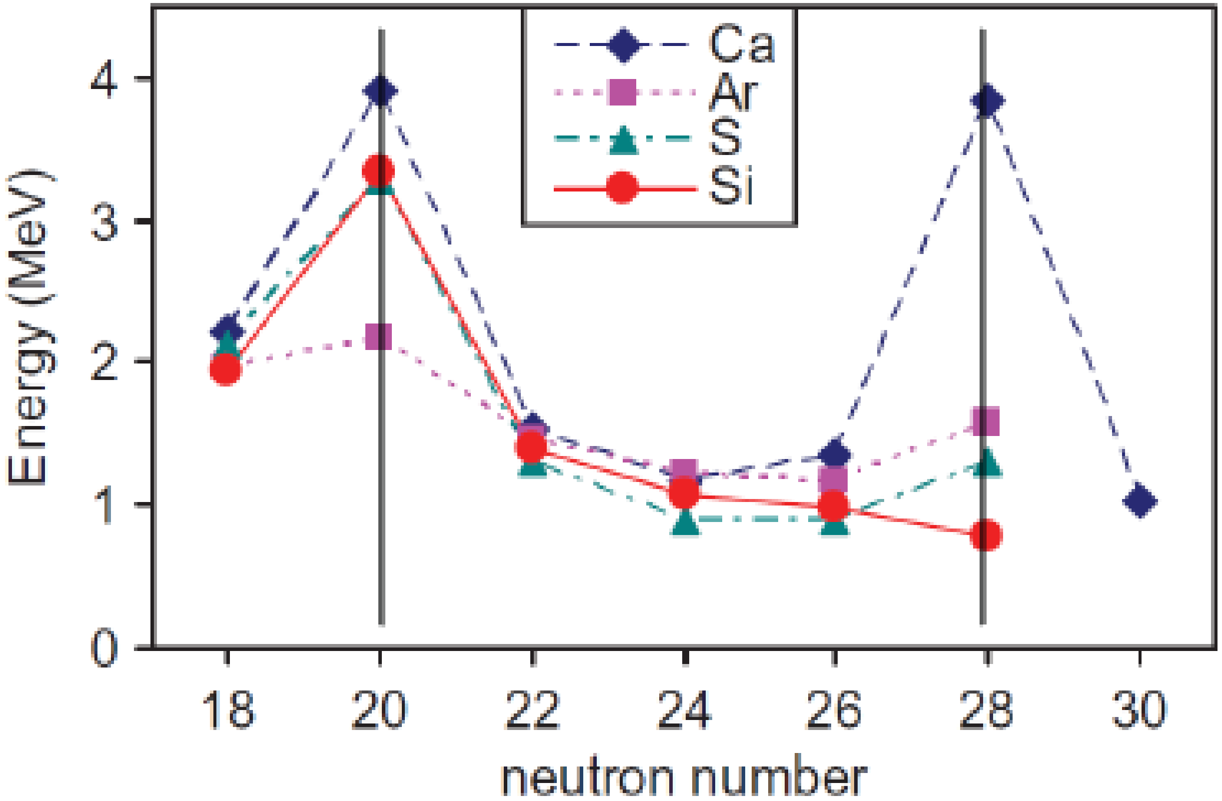


D.J. Morrissey, B.M. Sherrill, Philos. Trans. R. Soc. Lond. Ser. A Math Phys. Eng. Sci 356, 1985 (1998).

Neutron-Rich: Revealing New Physics







Gaudefroy and Grevy, Nucl. Phys. News 20, 13 (2010).

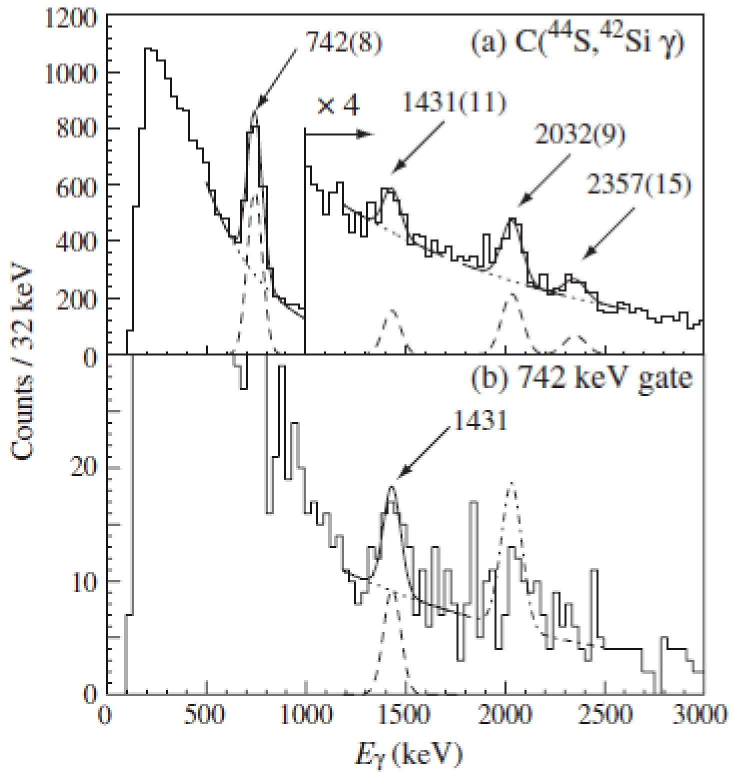
Neutron-Rich: Revealing New Physics

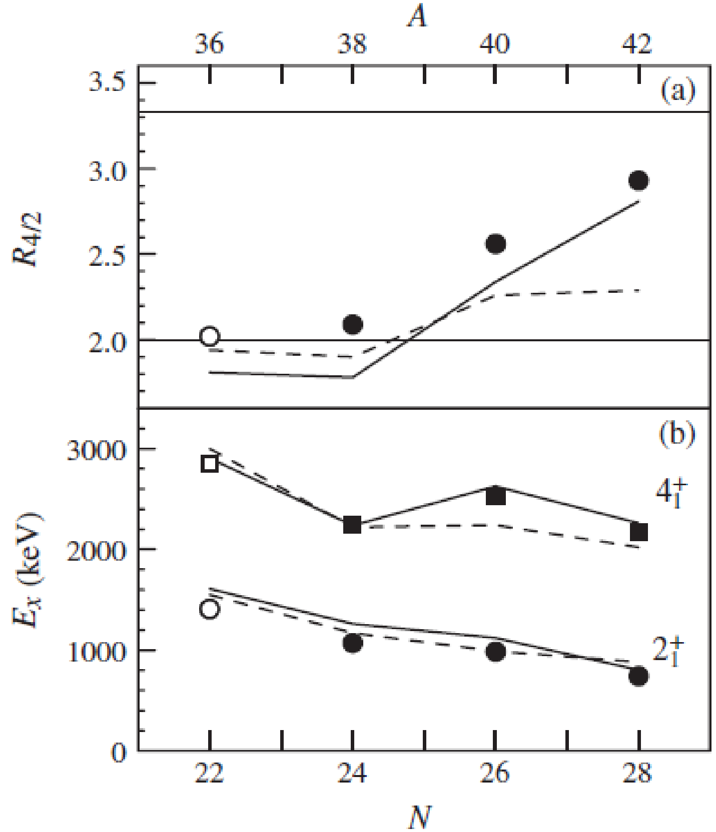
PRL 109, 182501 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

Well Developed Deformation in ^{42}Si

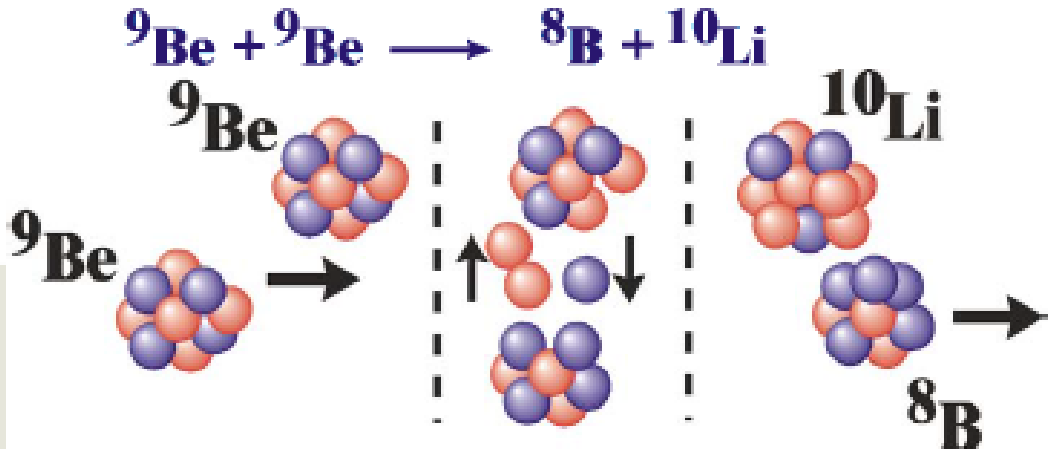
S. Takeuchi,[1,*] M. Matsushita,[1,2,†] N. Aoi,[1,‡] P. Doornenbal,[1] K. Li,[1,3] T. Motobayashi,[1] H. Scheit,[1,§] D. Steppenbeck,[1,†] H. Wang,[1,3] H. Baba,[1] D. Bazin,[4] L. Càceres,[5] H. Crawford,[6] P. Fallon,[6] R. Gernhäuser,[7] J. Gibelin,[8] S. Go,[9] S. Grévy,[5] C. Hinke,[7] C. R. Hoffman,[10] R. Hughes,[11] E. Ideguchi,[9,‡] D. Jenkins,[12] N. Kobayashi,[13] Y. Kondo,[13] R. Krücken,[7,||] T. Le Bleis,[14,15,¶] J. Lee,[1] G. Lee,[13] A. Matta,[16] S. Michimasa,[9] T. Nakamura,[13] S. Ota,[9] M. Petri,[6,§] T. Sako,[13] H. Sakurai,[1] S. Shimoura,[9] K. Steiger,[7] K. Takahashi,[13] M. Takechi,[1,**] Y. Togano,[1,**] R. Winkler,[4,††] and K. Yoneda[1]

^{44}S beam produced in fragmentation of ^{48}Ca
Two proton knockout to reach ^{42}Si



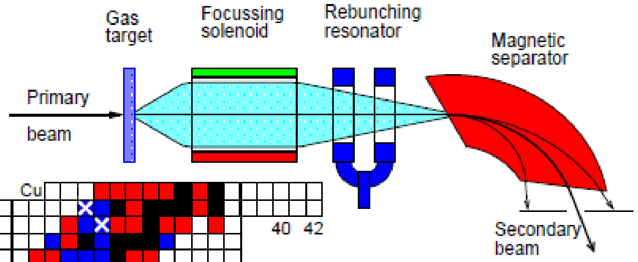


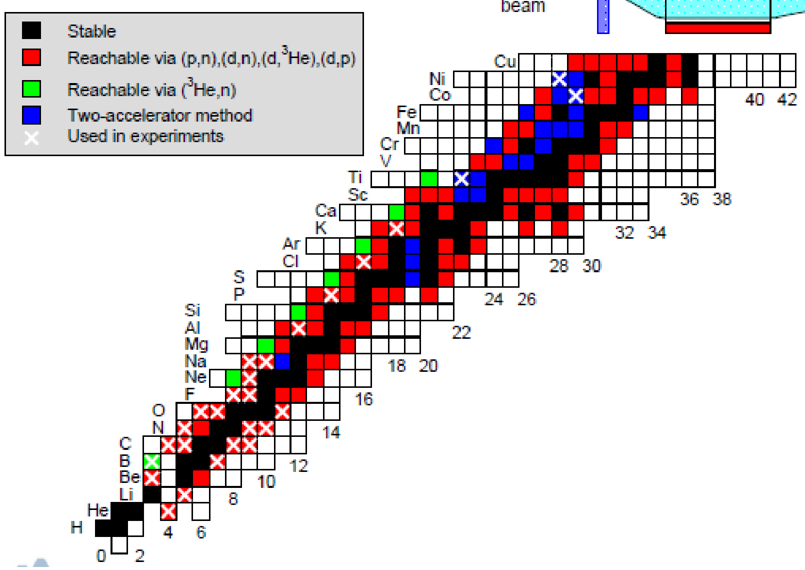
Transfer Reactions – in flight separation



8B 770 MS εα: 100.00% ε: 100.00%	9B 0.54 KeV 2α: 100.00% P: 100.00%	10B STABLE 19.9%	11B STABLE 80.1%	12B 20.20 MS β-: 100.00% B3A: 1.58%	13B 17.33 MS β-: 100.00%
7Be 53.24 D ε: 100.00%	8Be 5.57 eV α: 100.00%	9Be STABLE 100.%	10Be 1.387E+6 Y β-: 100.00%	11Be 13.81 S β-: 100.00% β-α: 3.1%	12Be 21.49 MS β-: 100.00% β-n≤ 1.00%
6Li STABLE 7.59%	7Li STABLE 92.41%	8Li 839.9 MS β-α: 100.00% β-: 100.00%	9Li 178.3 MS β-: 100.00% β-n: 50.80%	10Li N: 100.00%	11Li 8.75 MS β-: 100.00% β-n: 83.0%
5He 0.60 MeV N: 100.00% α: 100.00%	6He 801 MS β-: 100.00%	7He 150 KeV N	8He 119.1 MS β-: 100.00% β-n: 16.00%	9He N: 100.00%	10He 300 KeV N: 100.00%

Few nucleon transfer reactions
Inverse kinematics





- Argonne
- Notre Dame
- Florida State

Neutron-Rich: Testing Ab-initio Calculations

PHYSICAL REVIEW C **78**, 041302(R) (2008)

Structure of ^{7}He by proton removal from ^{8}Li with the (d, ^{3}He) reaction

A. H. Wuosmaa,[1] J. P. Schiffer,[2] K. E. Rehm,[2] J. P. Greene,[2] D. J. Henderson,[2] R. V. F. Janssens,[2] C. L. Jiang,[2] L. Jisonna,[3] J. C. Lighthall,[1] S. T. Marley,[1] E. F. Moore,[2] R. C. Pardo,[2] N. Patel,[4] M. Paul,[5] D. Peterson,[2] Steven C. Pieper,[2] G. Savard,[2] R. E. Segel,[3] R. H. Siemssen,[6] X. D. Tang,[2] and R. B. Wiringa[2]
[1]*Physics Department, Western Michigan University, Kalamazoo, Michigan 49008-5252, USA*

8B 770 MS εα: 100.00% ε: 100.00%	9B 0.54 KeV 2α: 100.00% P: 100.00%	10B STABLE 19.9%	11B STABLE 80.1%	12B 20.20 MS β-: 100.00% B3A: 1.58%	13B 17.33 MS β-: 100.00%
7Be 53.24 D ε: 100.00%	8Be 5.57 eV α: 100.00%	9Be STABLE 100.%	10Be 1.387E+6 Y β-: 100.00%	11Be 13.81 S β-: 100.00% β-α: 3.1%	12Be 21.49 MS β-: 100.00% β-n≤ 1.00%
6Li STABLE 7.59%	7Li STABLE 92[illegible]	8Li [illegible]9.9 MS β[illegible]00.00% β-: 1[illegible]0.00%	9Li 178.3 MS β-: 100.00% β-n: 50.80%	10Li N: 100.00%	11Li 8.75 MS β-: 100.00% β-n: 83.0%
5He 0.60 MeV N: 100.00% α: 100.00%	6He 801 MS β-: 100.00%	7[illegible]e 150 KeV N[illegible]	8He 119.1 MS β-: 100.00% β-n: 16.00%	9He N: 100.00%	10He 300 KeV N: 100.00%

- Start with ^{7}Li beam
- (d,p) to make ^{8}Li
- (d,^{3}He) to make ^{7}He

Neutron-Rich: Testing Ab-initio Calculations

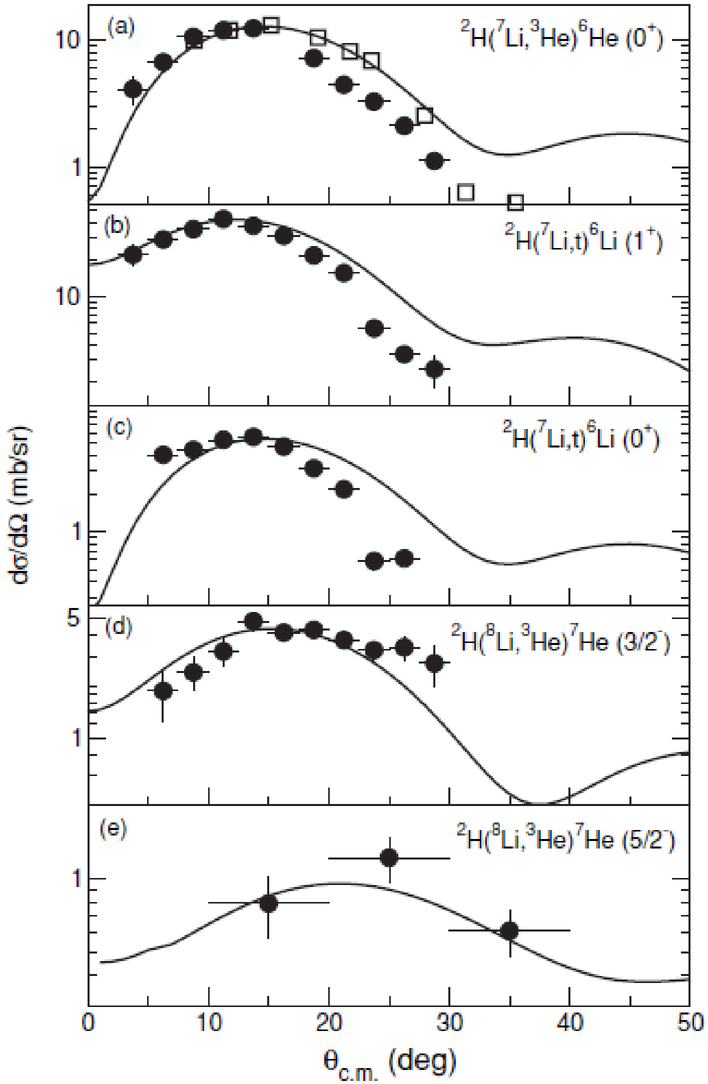


TABLE III. Comparison of experimental and theoretical spectroscopic factors for the (d, t) and $(d, {}^3\mathrm{He})$ reactions; σ denotes the cross section at the angular-distribution maximum.

Reaction	σ (Exp) (mb/sr)	C^2S (Exp)[a]	C^2S (VMC)
$^7\mathrm{Li}(d, {}^3\mathrm{He})\,{}^6\mathrm{He}(0^+)$	12.3(2.0)	0.44(6)	0.42
$^7\mathrm{Li}(d, t)\,{}^6\mathrm{Li}(1^+)$	41.2(6.0)	0.74(11)	0.68
$^7\mathrm{Li}(d, t)\,{}^6\mathrm{Li}(0^+)$	5.6(0.9)	0.19(3)	0.21
$^8\mathrm{Li}(d, {}^3\mathrm{He})\,{}^7\mathrm{He}(3/2^-)$	4.5(0.9)	0.36(7)	0.58
$^8\mathrm{Li}(d, {}^3\mathrm{He})\,{}^7\mathrm{He}(5/2^-)$	1.0(0.5)	0.29(15)	0.17

[a] Values obtained from $(\sigma_{\mathrm{Exp}}/\sigma_{\mathrm{DWBA}}) \times 0.32$.

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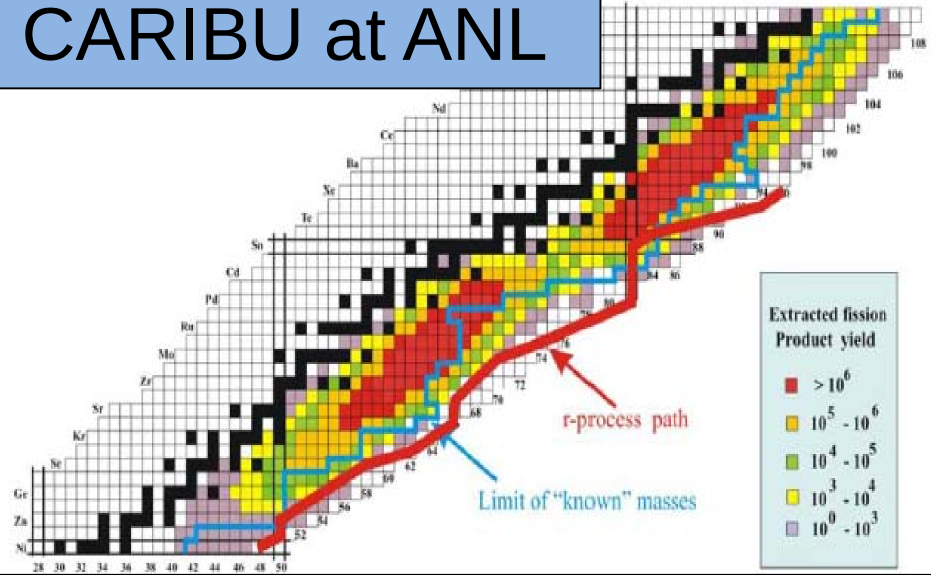
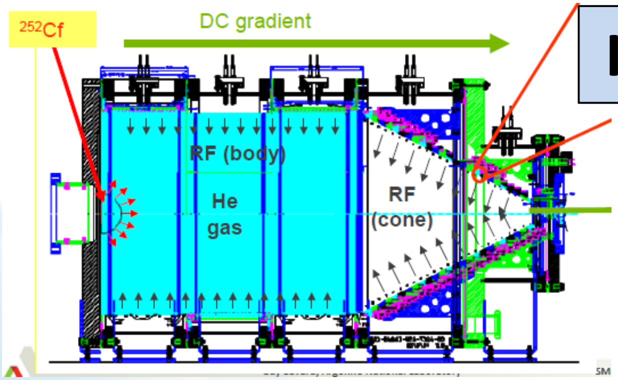
Fission

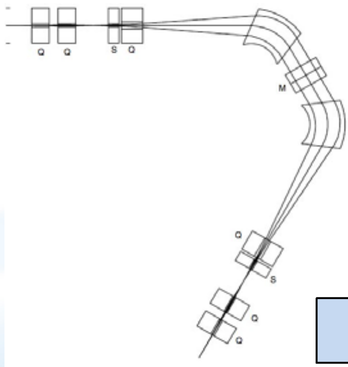
CARIBU at ANL



Spontaneous Fission Source: ^{252}Cf



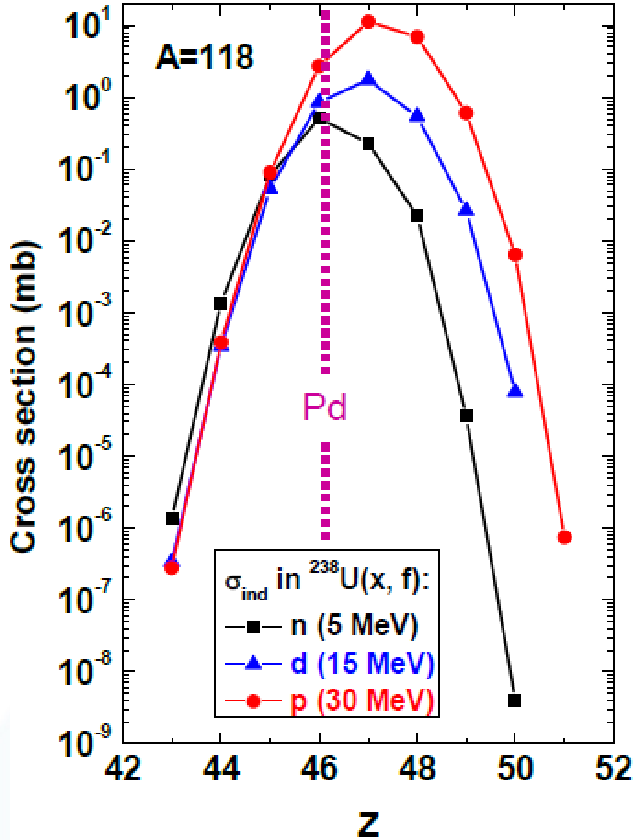
Isobar Separator

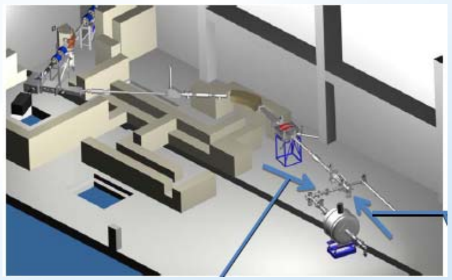


Gas Catcher

Univ. of Jyvaskyla

Proton-induced fission of Uranium

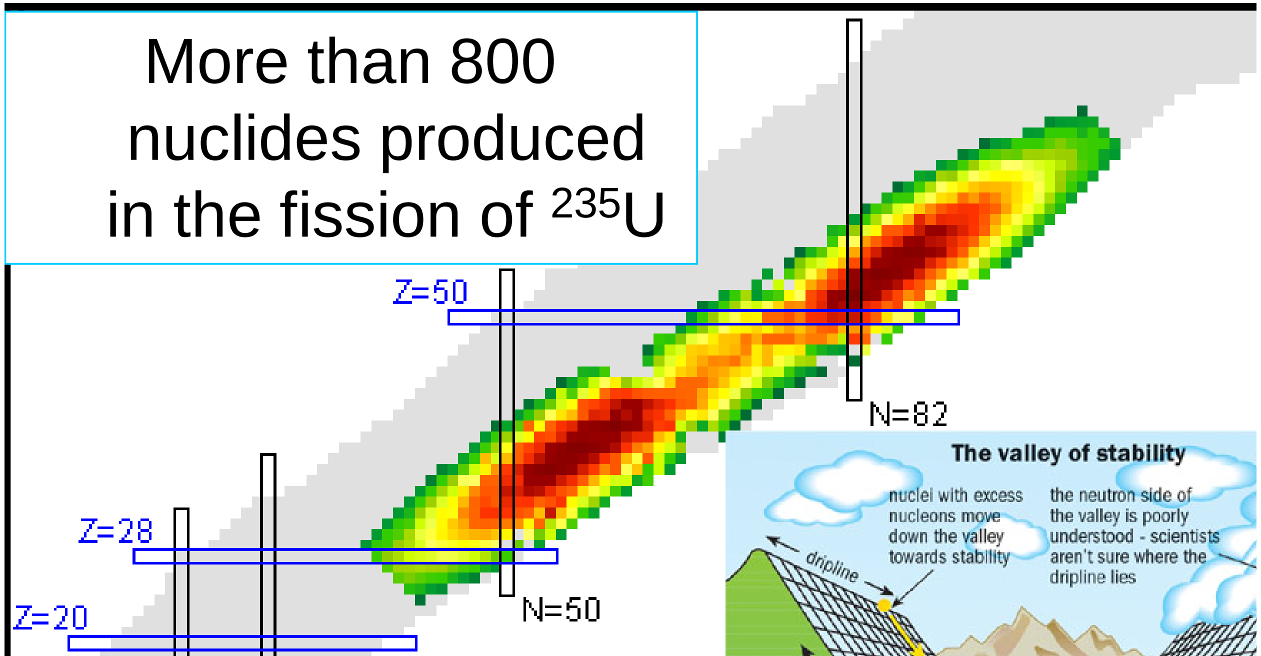


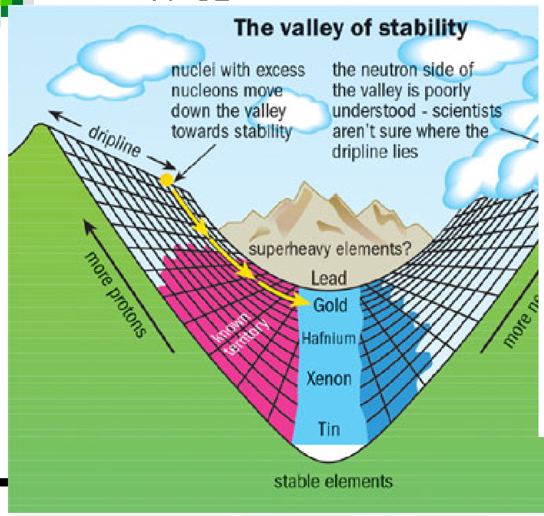


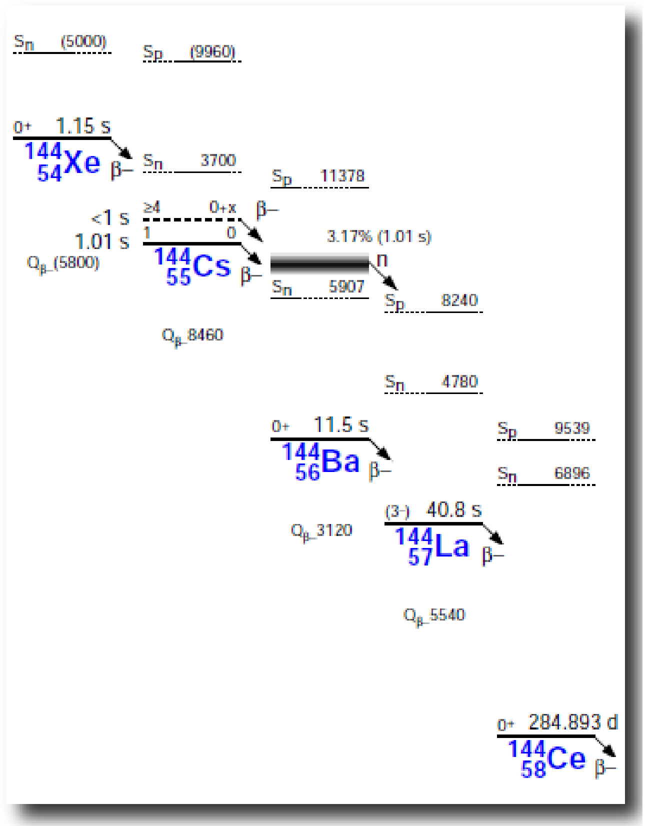
Ion Guide, Mass Separator, Penning Trap

Neutron-Rich: For Applications

More than 800 nuclides produced in the fission of ^{235}U

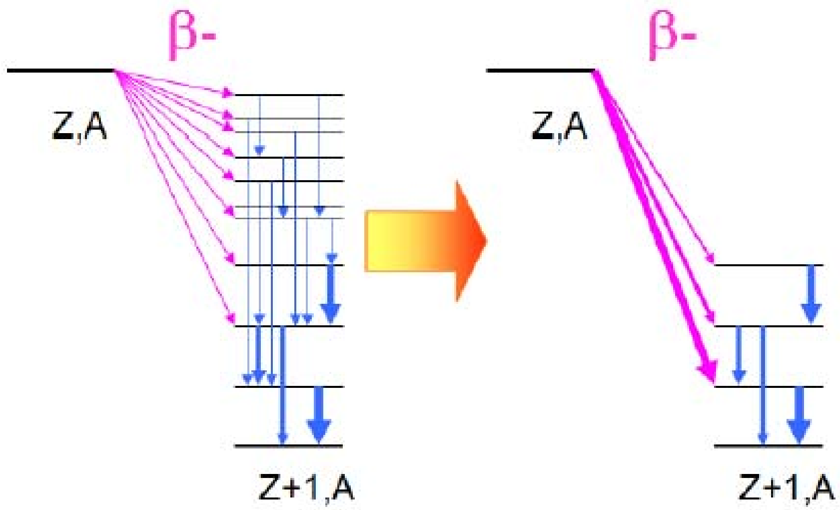






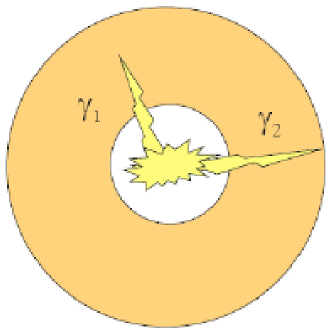
Neutron-Rich: For Applications

Pandemonium leads to incorrect average β and γ energies



How do we fix that? Use a detector that "catches" everything

Total Absorption Gamma Spectrometer (TAGS)



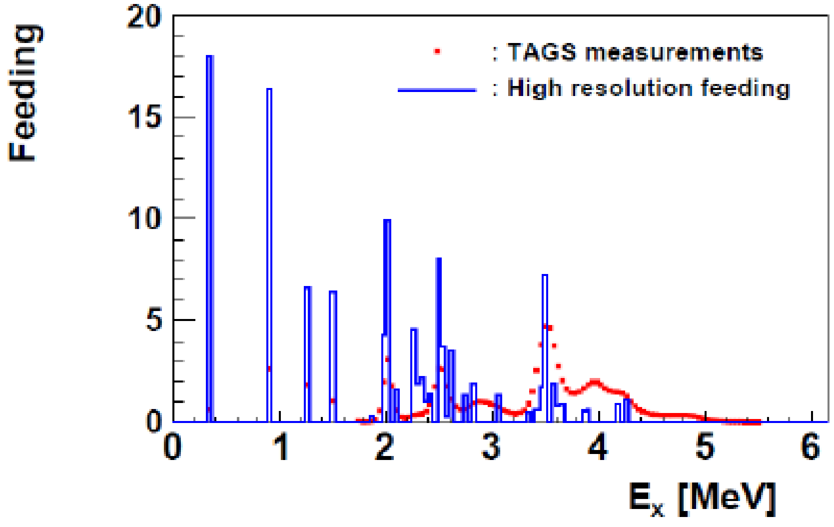
- Full 4π coverage
- High efficiency
- Calorimeter

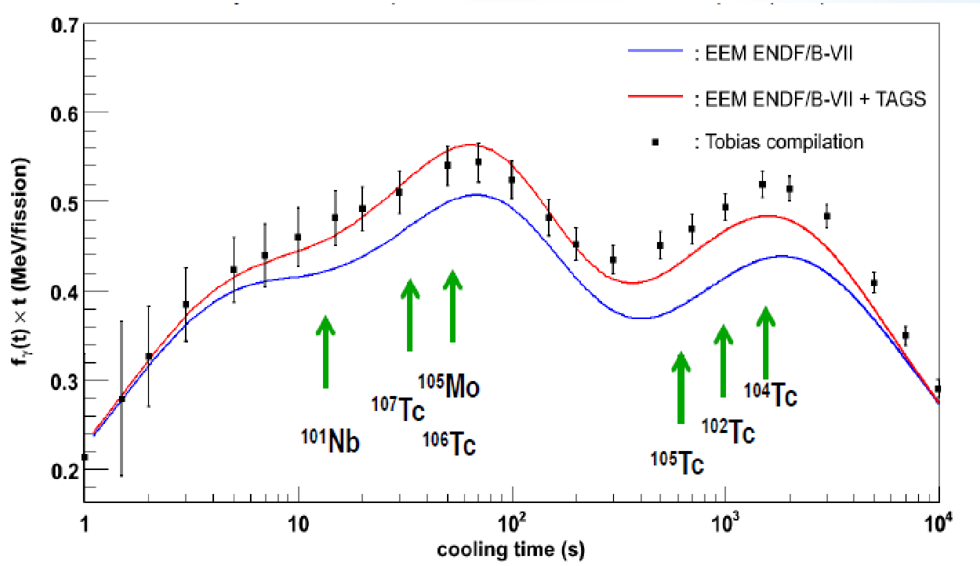
Neutron-Rich: For Applications

Selected for a Viewpoint in *Physics*
PRL 105, 202501 (2010) PHYSICAL REVIEW LETTERS week ending 12 NOVEMBER 2010

Reactor Decay Heat in ^{239}Pu: Solving the γ Discrepancy in the 4–3000-s Cooling Period

A. Algora,[1,2,*] D. Jordan,[1] J. L. Taín,[1] B. Rubio,[1] J. Agramunt,[1] A. B. Perez-Cerdan,[1] F. Molina,[1] L. Caballero,[1] E. Nácher,[1] A. Krasznahorkay,[2] M. D. Hunyadi,[2] J. Gulyás,[2] A. Vitéz,[2] M. Csatlós,[2] L. Csige,[2] J. Äysto,[3] H. Penttilä,[3] I. D. Moore,[3] T. Eronen,[3] A. Jokinen,[3] A. Nieminen,[3] J. Hakala,[3] P. Karvonen,[3] A. Kankainen,[3] A. Saastamoinen,[3] J. Rissanen,[3] T. Kessler,[3] C. Weber,[3] J. Ronkainen,[3] S. Rahaman,[3] V. Elomaa,[3] S. Rinta-Antila,[3] U. Hager,[3] T. Sonoda,[3] K. Burkard,[4] W. Hüller,[4] L. Batist,[5] W. Gelletly,[6] A. L. Nichols,[6] T. Yoshida,[7] A. A. Sonzogni,[8] and K. Peräjärvi[9]





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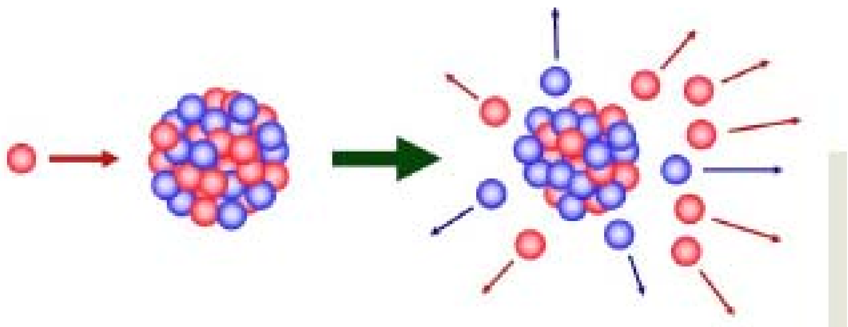
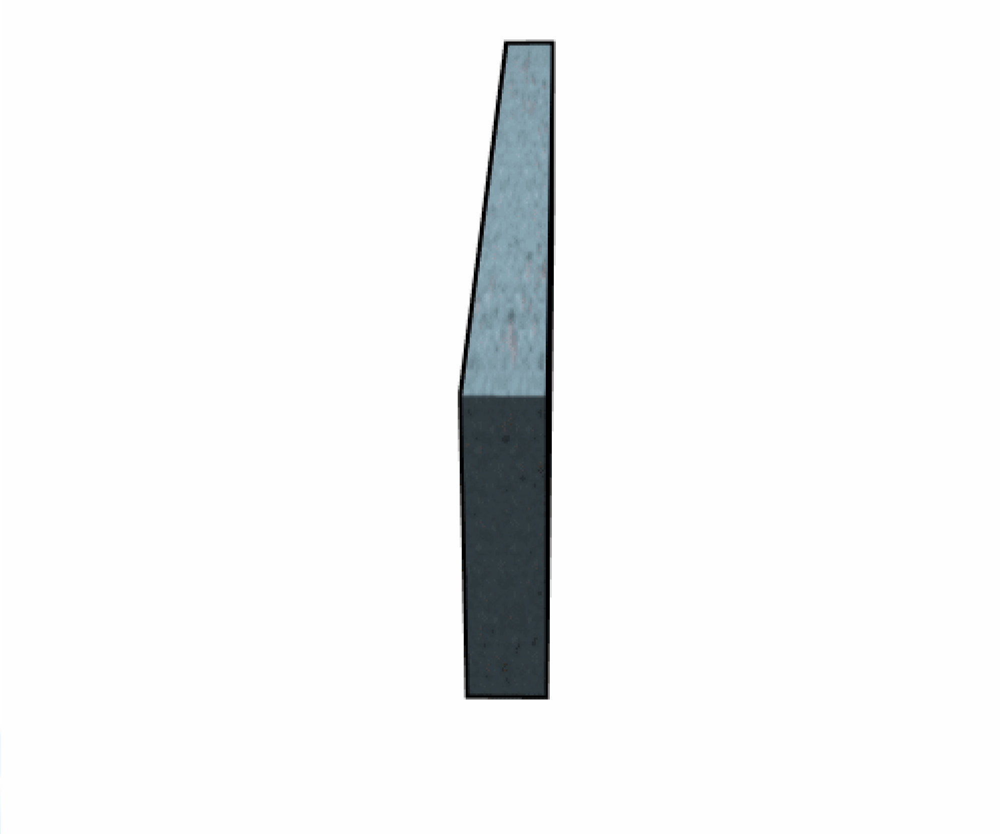
Spallation

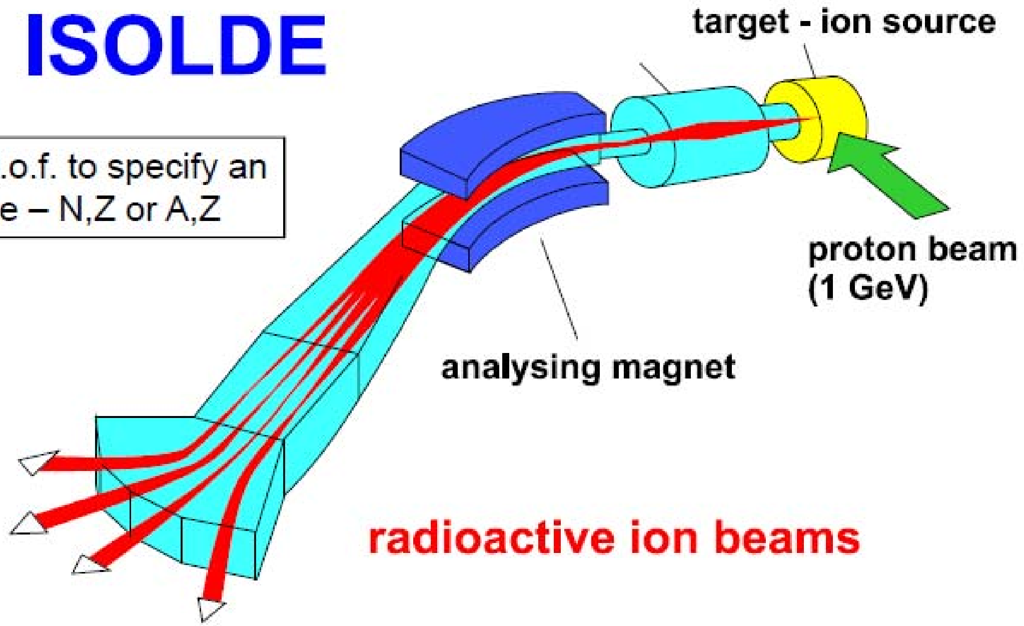


Removal of protons and neutrons from heavy target by light energetic particles

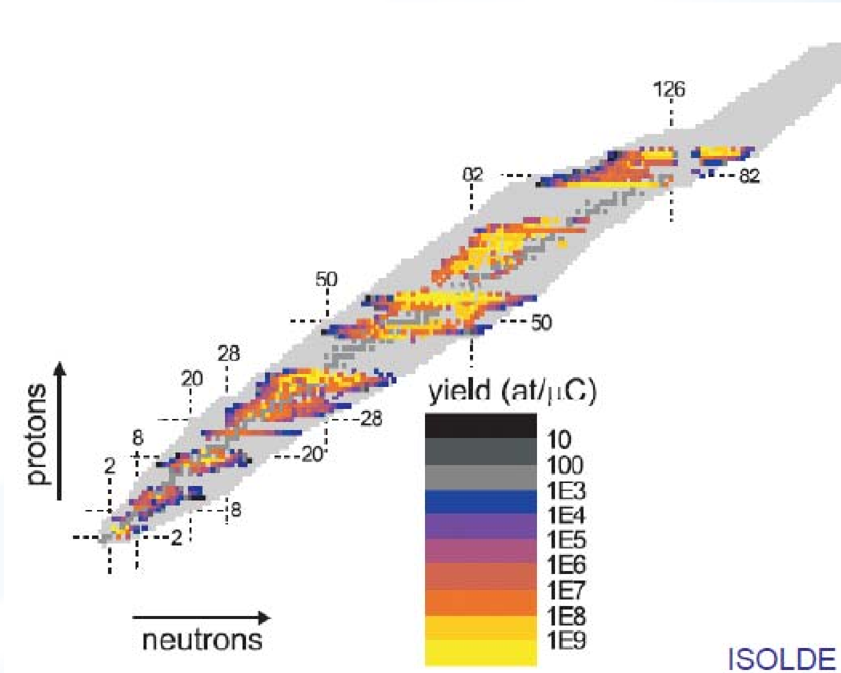


Spallation

Two d.o.f. to specify an isotope – N,Z or A,Z



ISOLDE @ CERN
SPIRAL2 @ GANIL
ISAC @ TRIUMF



Exotic Nuclei: For Other Fields

ARTICLE

Studies of pear-shaped n accelerated radioactive b

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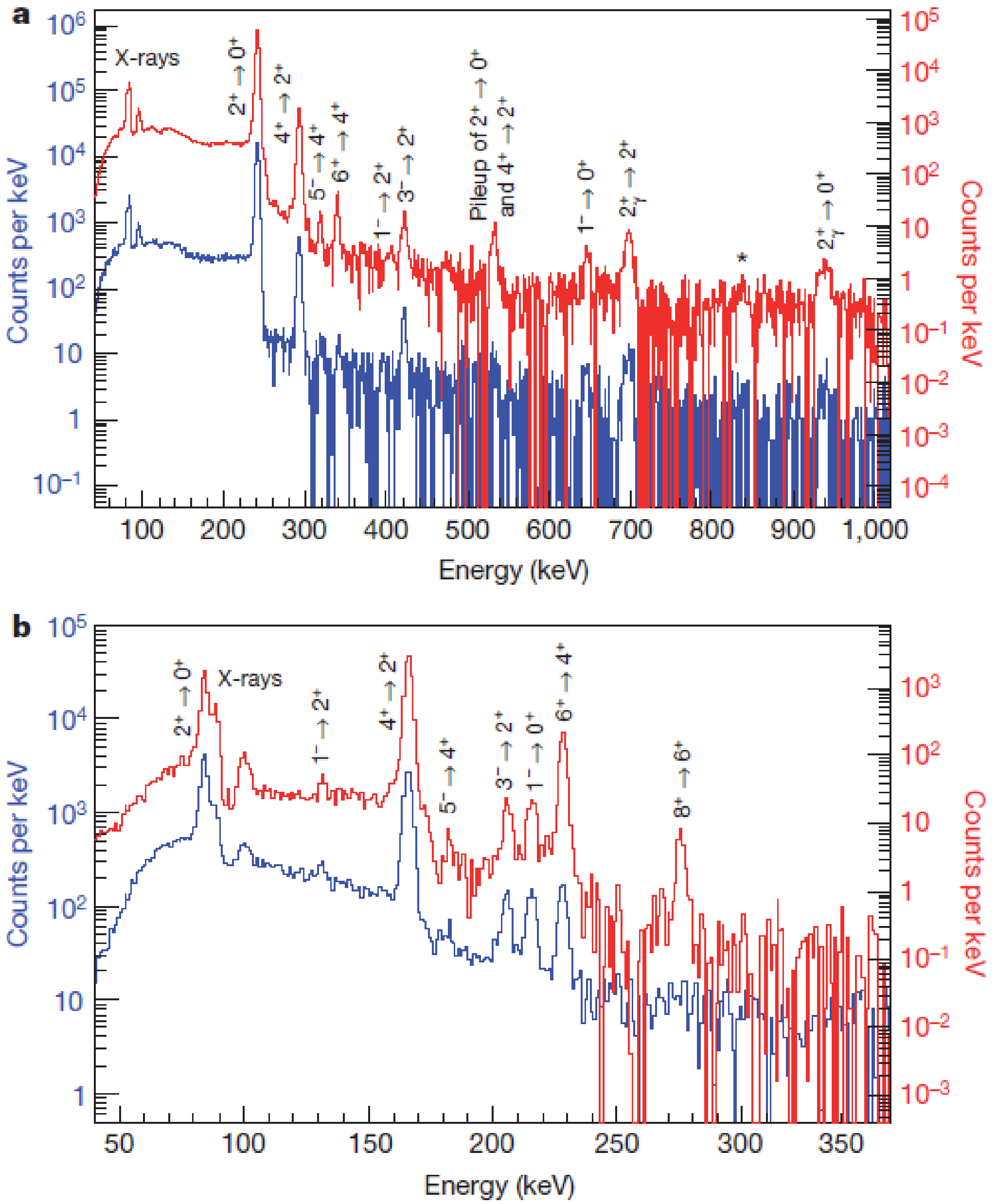
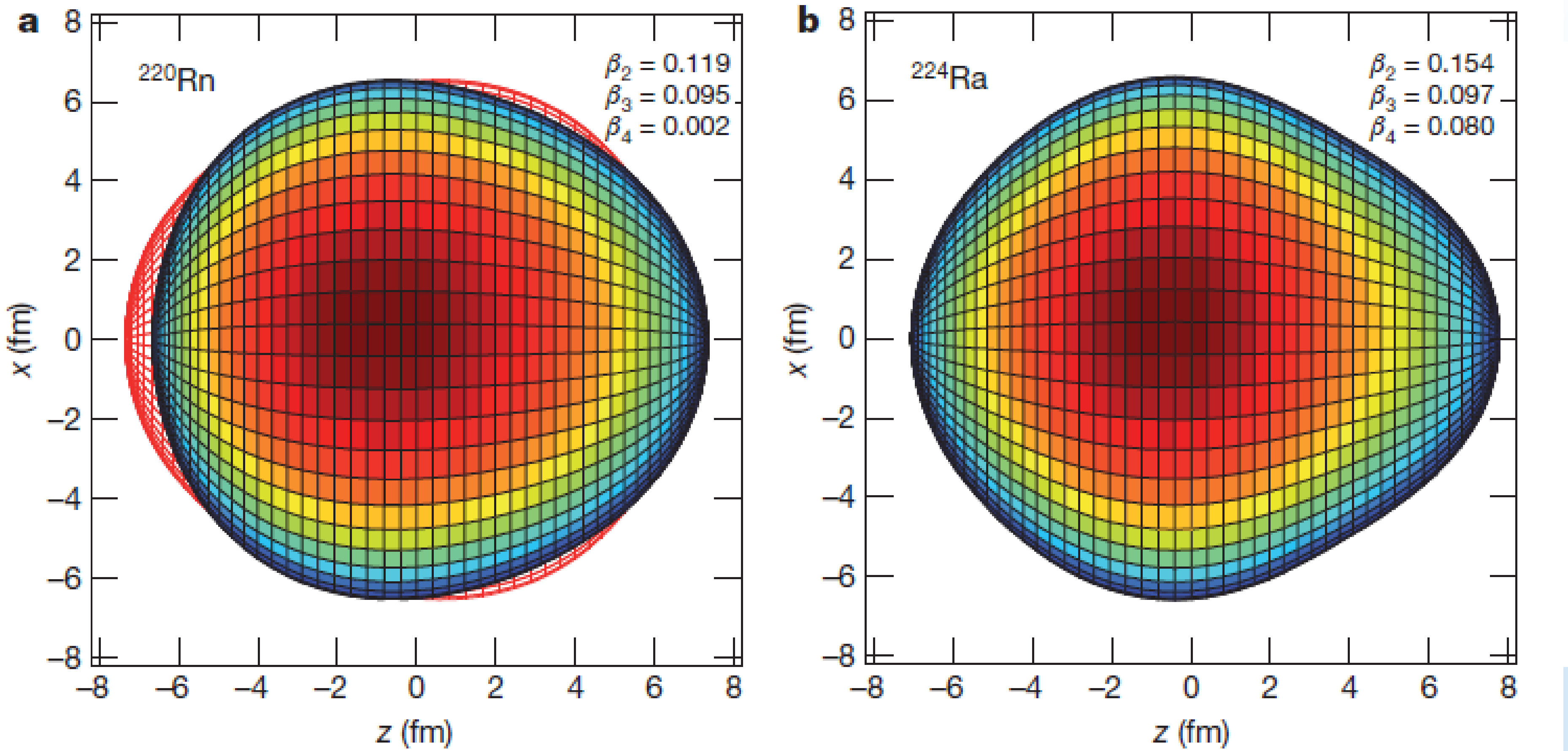
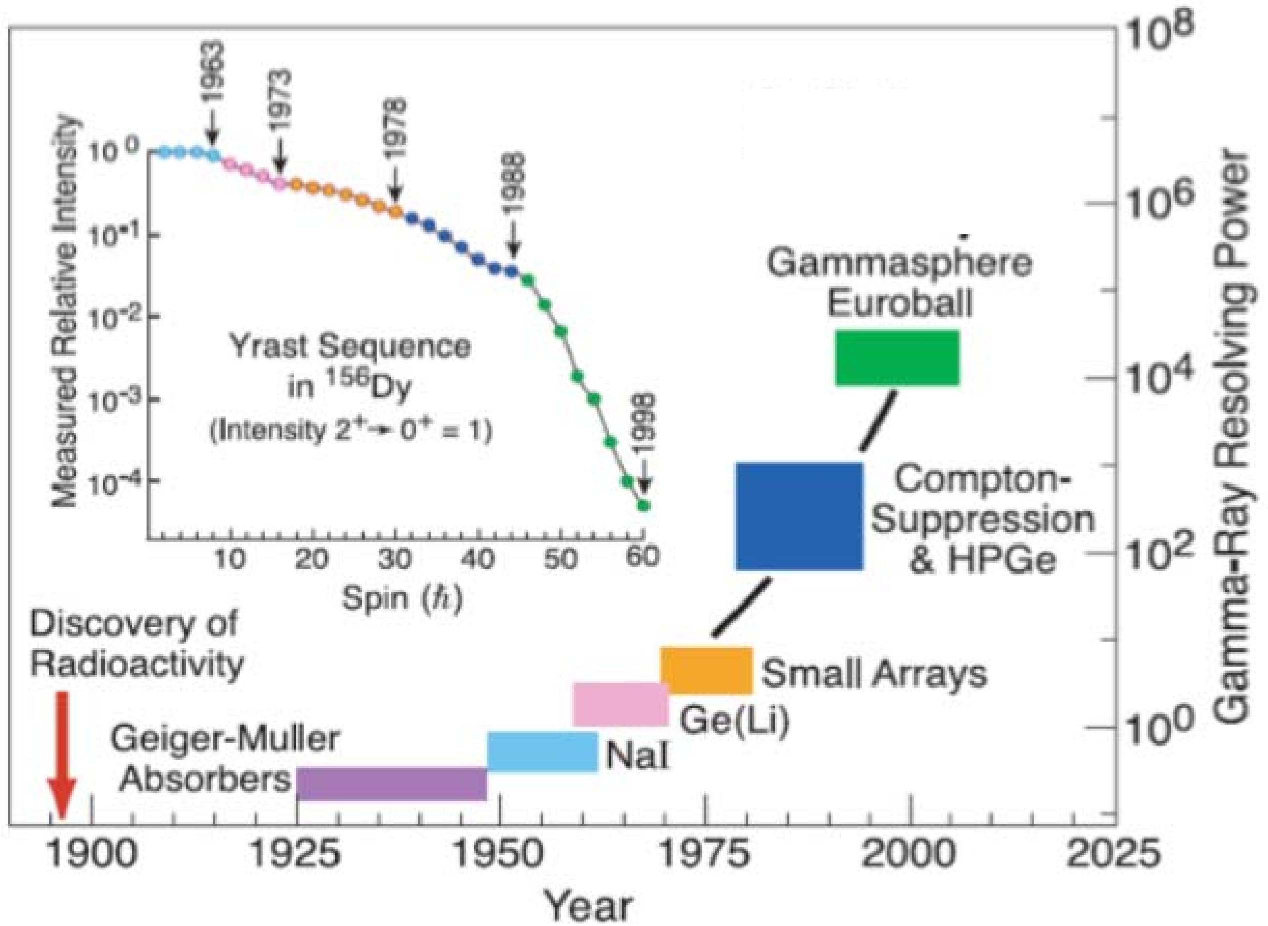


Exotic Nuclei: For Other Fields

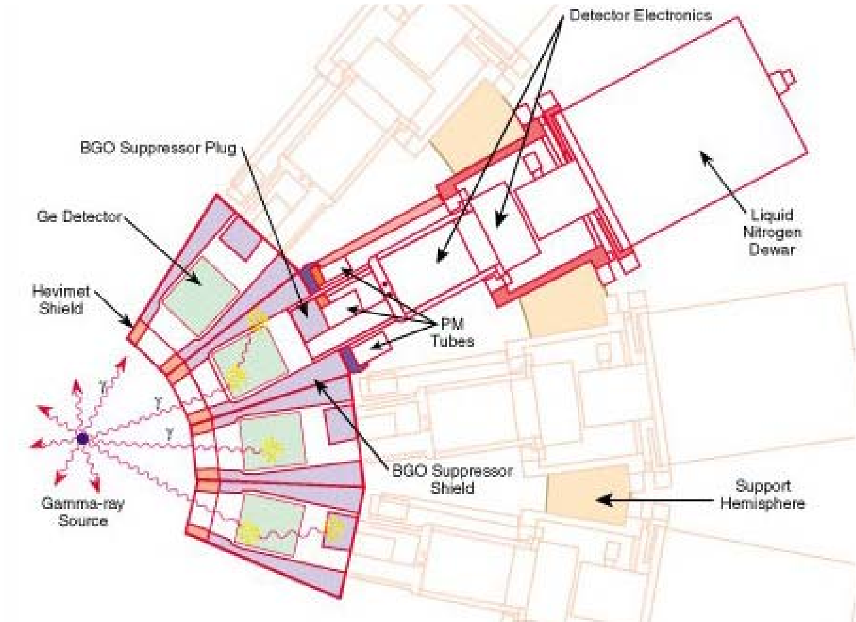


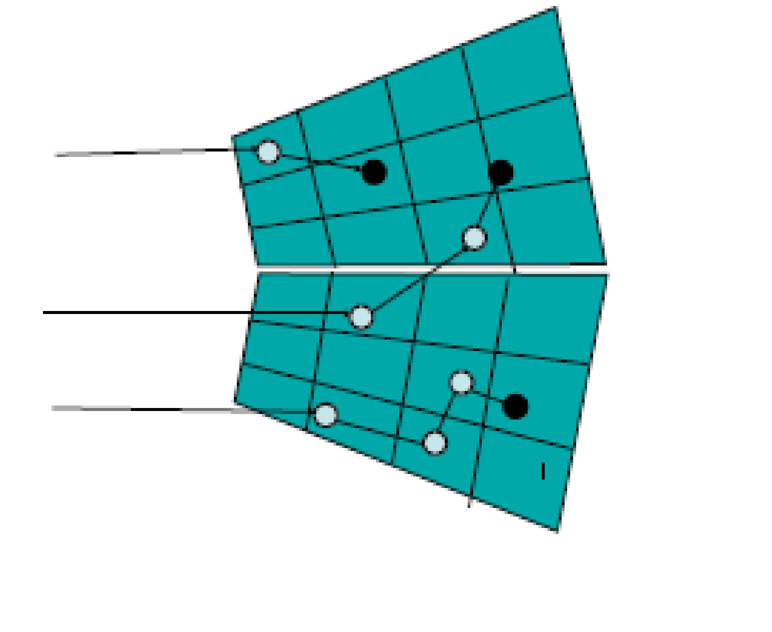
Next generation of γ-ray spectrometers



Next generation of γ-ray spectrometers

Current arrays limited by all the other "stuff"	Ideally, want just a sphere of Germanium





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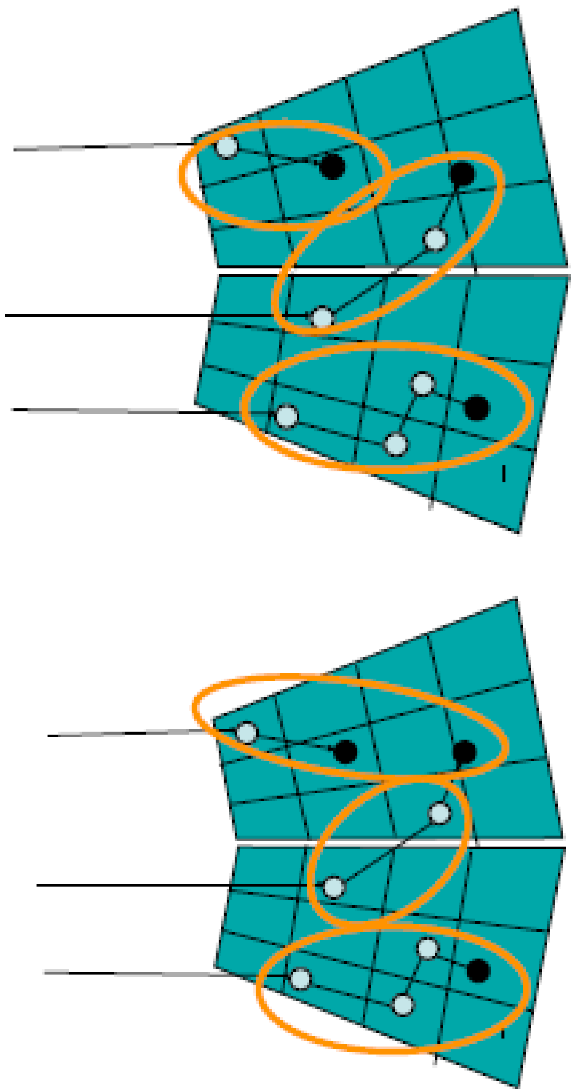
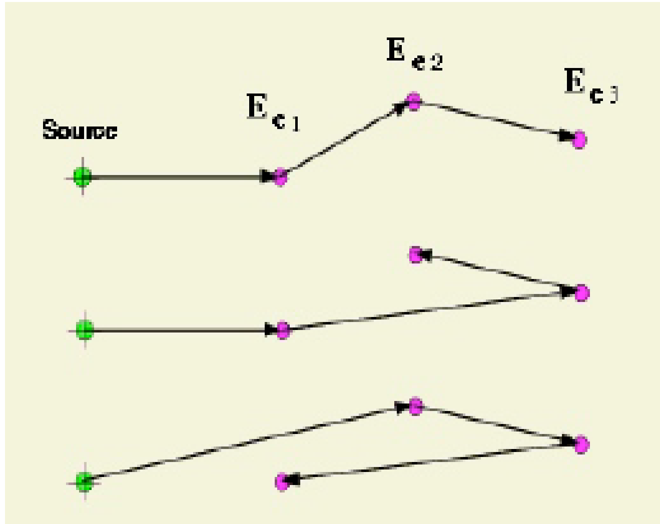
Need Compton Tracking



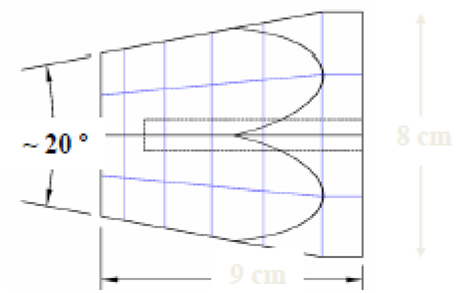
$$E_\gamma = E_{e1} + E_{e2} + E_{e3}$$

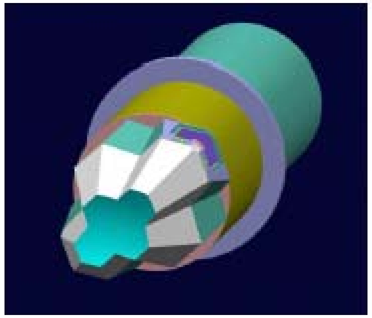
$$\cos\theta_C = 1 + \frac{0.511}{E_\gamma} - \frac{0.511}{E'_\gamma}$$



- Fit all permutations with Compton scattering
- Lowest χ^2 gives most probable sequence

Building Gretina

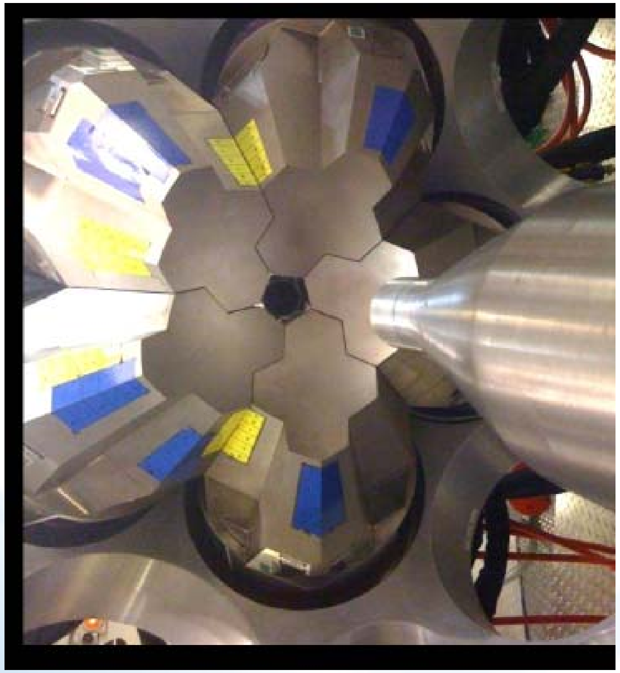


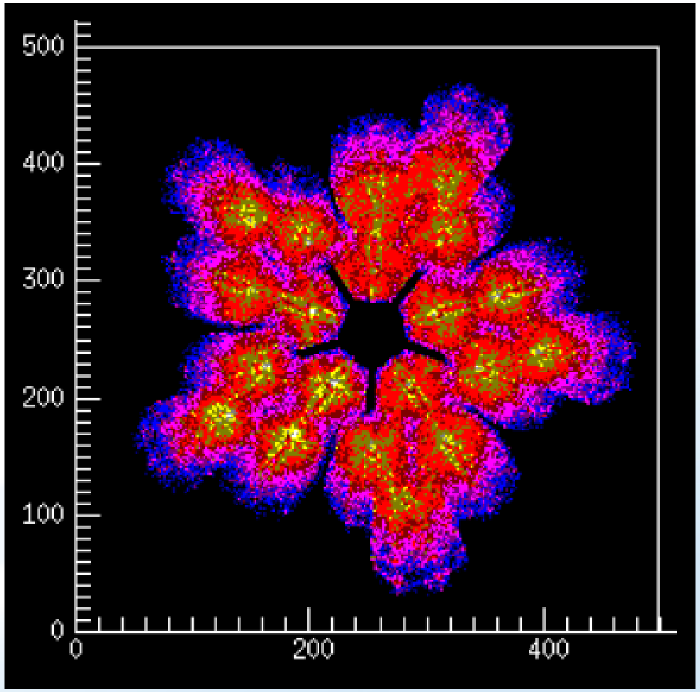


36 segments per Ge crystal

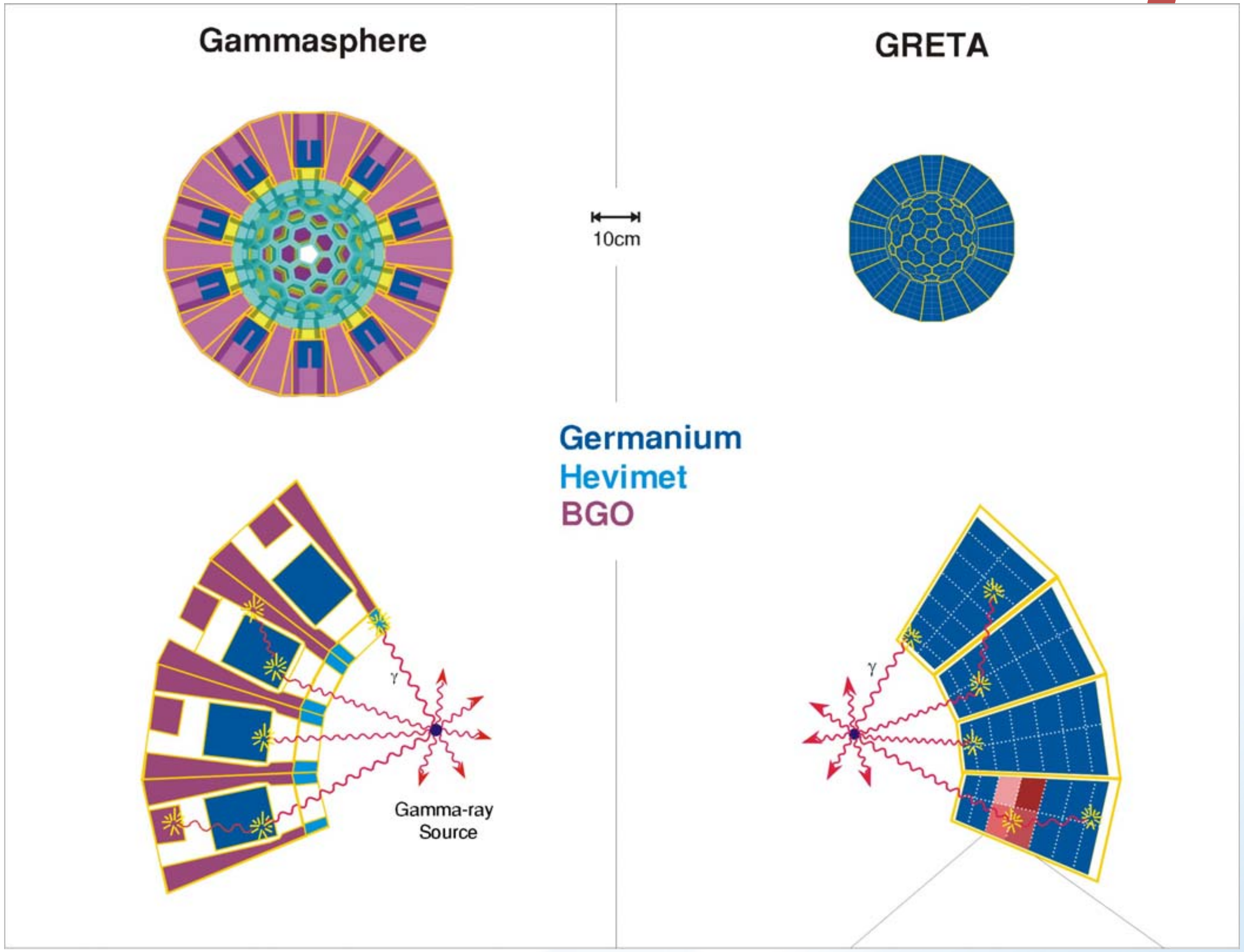
4 crystals per module

30 modules for 4π





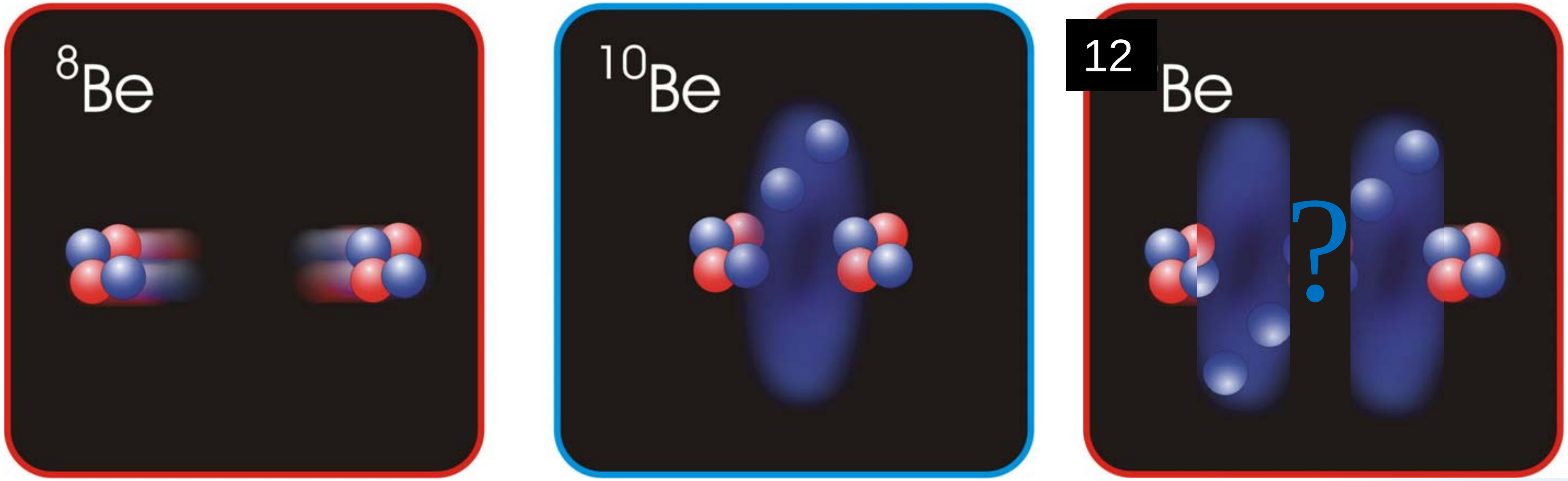
Compare GRETA with Gammasphere



Efficiency (1 MeV)	8%	55%
Efficiency (15 MeV)	0.5%	12%
Peak/Total (1 MeV)	55%	85%
Position resolution	20mm	1 mm

An example related to data evaluators

What do extra neutrons do?



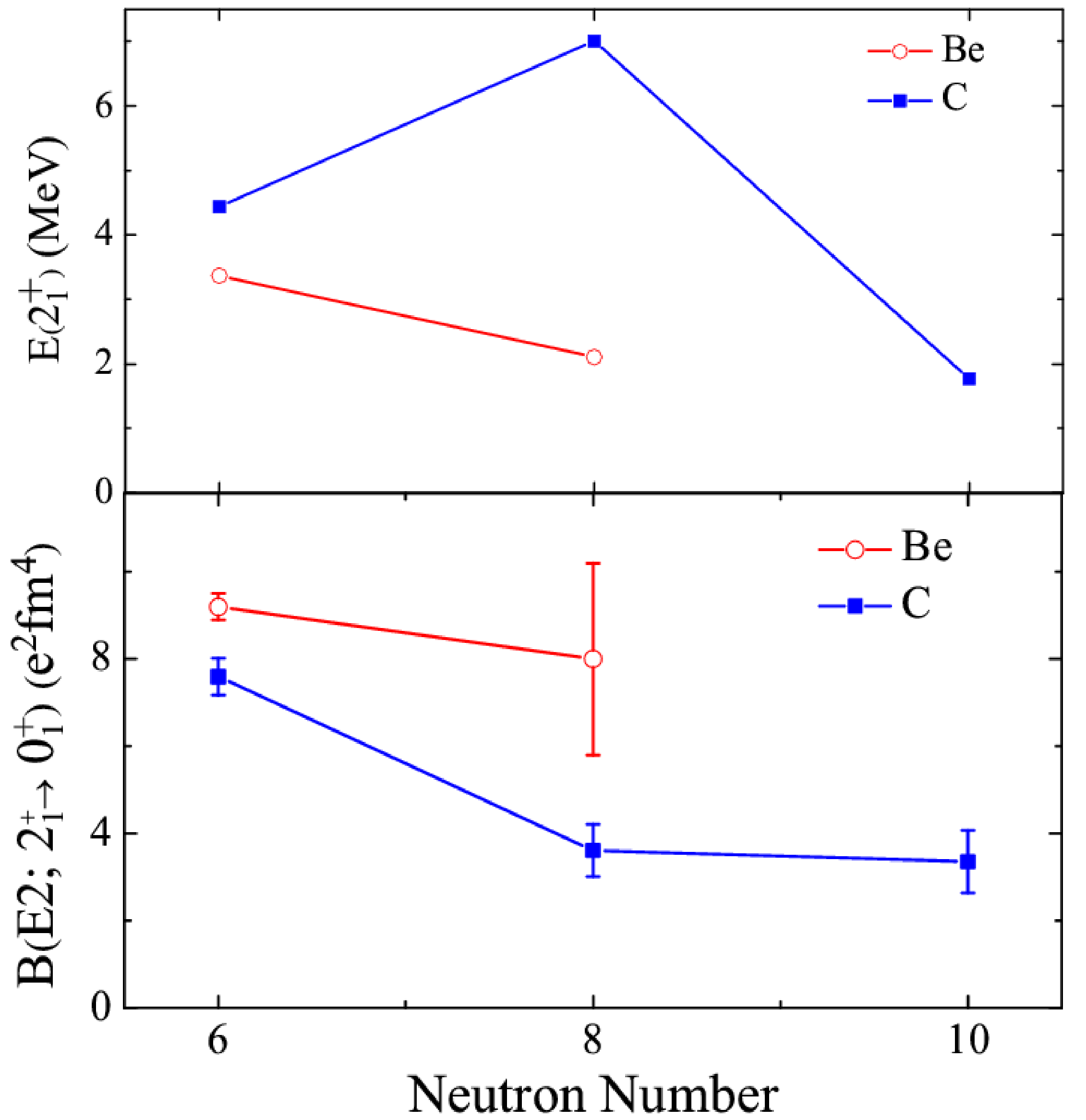
Make a "Nuclear Molecule"?

B(E2) increases

Make a "N=8" spherical cloud?

B(E2) decreases

Systematics



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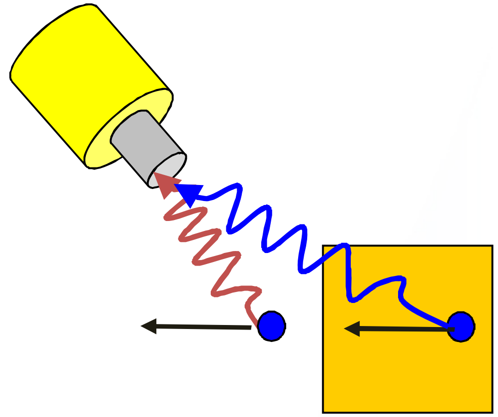
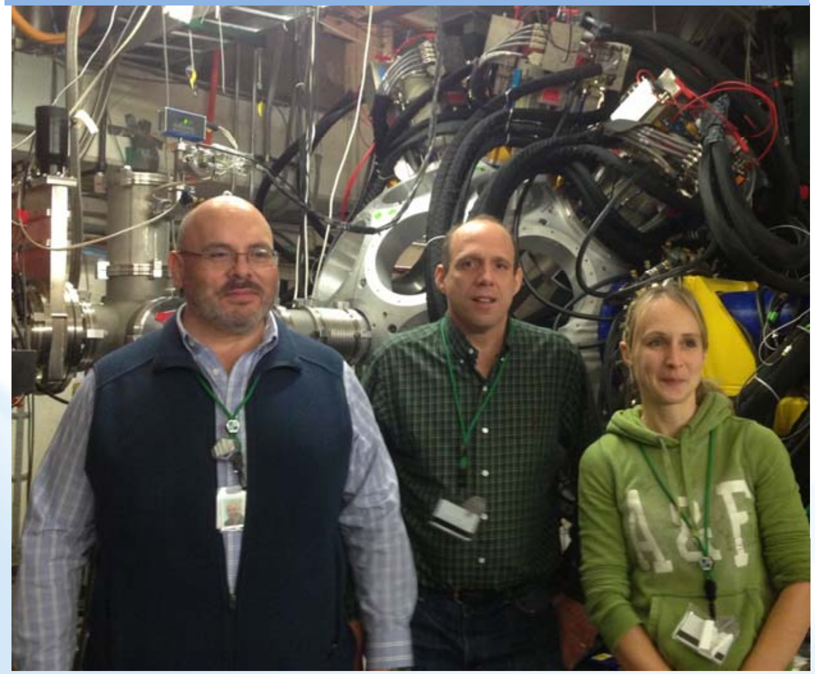
A precise measurement of the B(E2; $2^+ \to 0^+$) in ^{12}Be

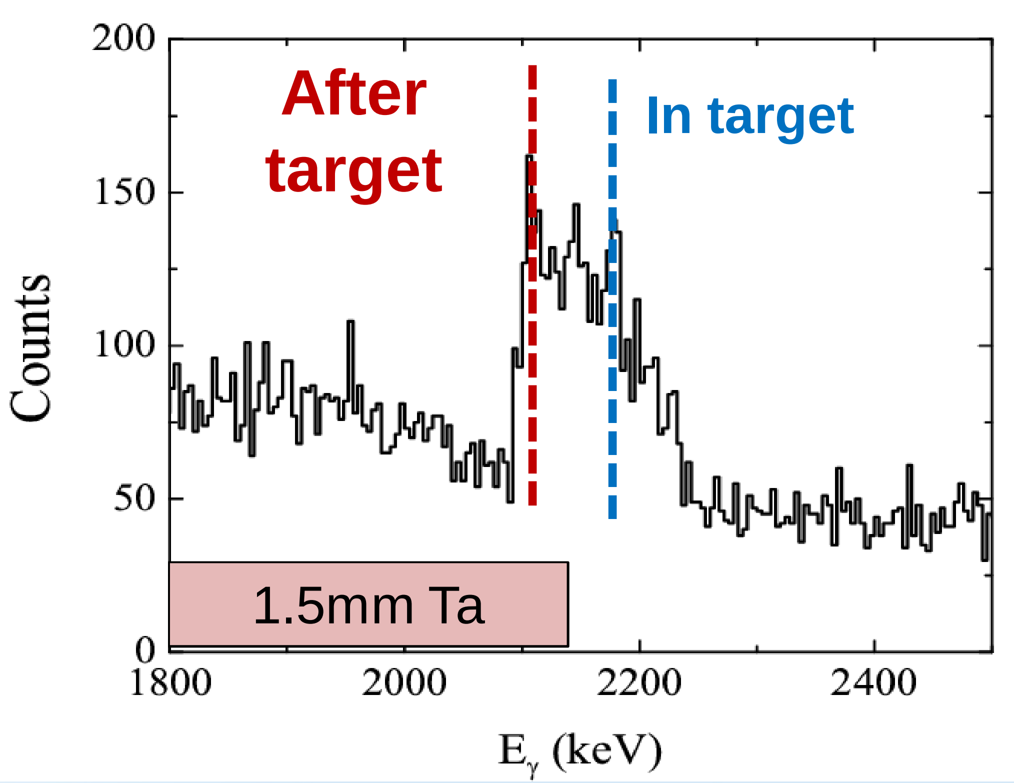
Fast, thick target DSAM

- 55 MeV/A ^{12}Be beam
- 3 different targets
- GRETINA + S800

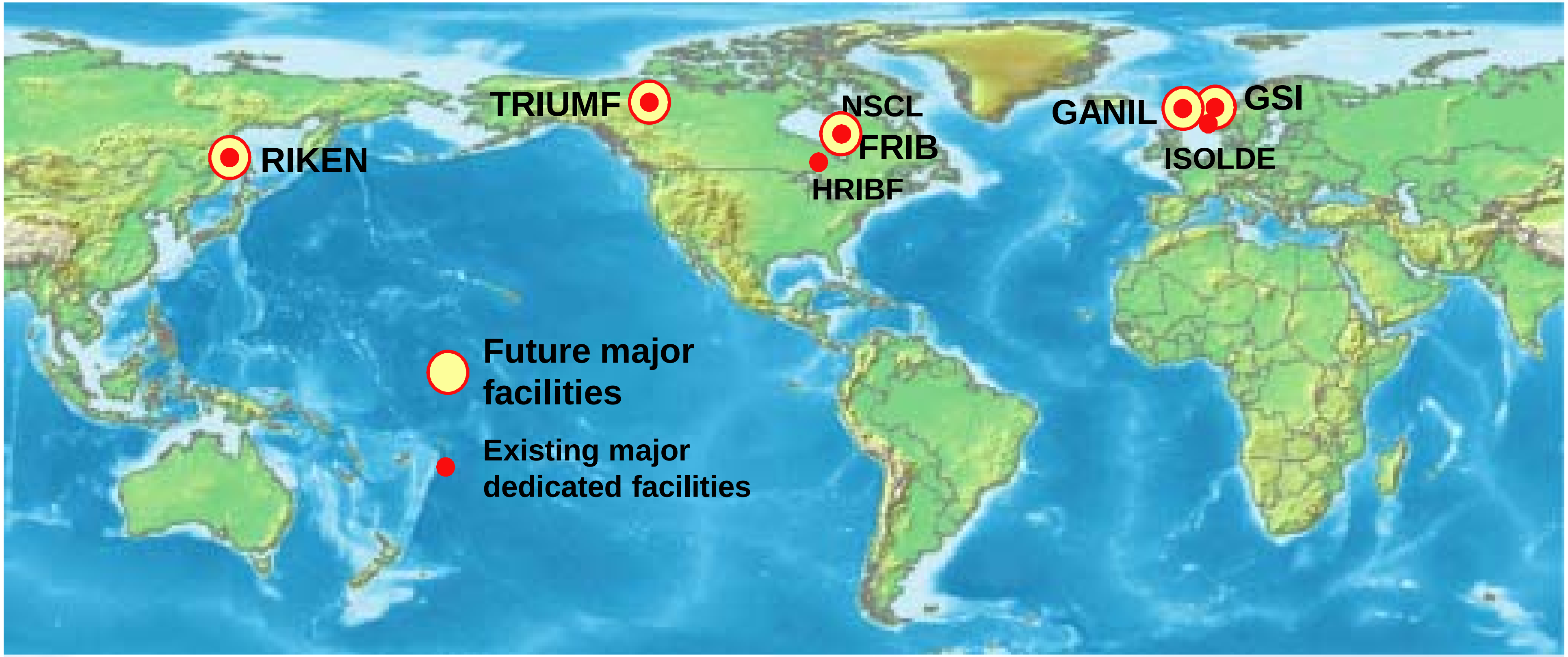


Gretina at MSU/NSCL





Radioactive Ion Beam Facilities Worldwide



Lots of new, exciting data on the horizon !!