The Abdus Salam
International Centre
for Theoretical Physics

2358-17

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

6 - 17 August 2012

Experimental Nuclear Physics II

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Kolkata
India

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Experimental Nuclear Physics II

VECC

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Kolkata, India

Computer does << *everything* >>

‼ Until Switching position ‼

I am very happy to learn that the computer understands the problem, but I would like to understand it too.

Eugene Wigner

Don't let your mouse to control your imagination

Some Useful Books

"Handbook of nuclear spectroscopy", J. Kantele,1995

"Radiation detection and measurements", G.F. Knoll, 1989

"In-beam gamma-ray spectroscopy", H. Morinaga and T. Yamazaki, 1976

"Gamma-ray and electron spectroscopy in Nuclear Physics", H. Ejiri and M.J.A. de Voigt, 1989

"Techniques in Nuclear Structure Physics", J.B.A. England, 1964

"Techniques for Nuclear and Particle Physics Experiments", W.R. Leo, 1987

"Nuclear Spectroscopy and Reactions", Ed. J. Cerny, Vol. A-C

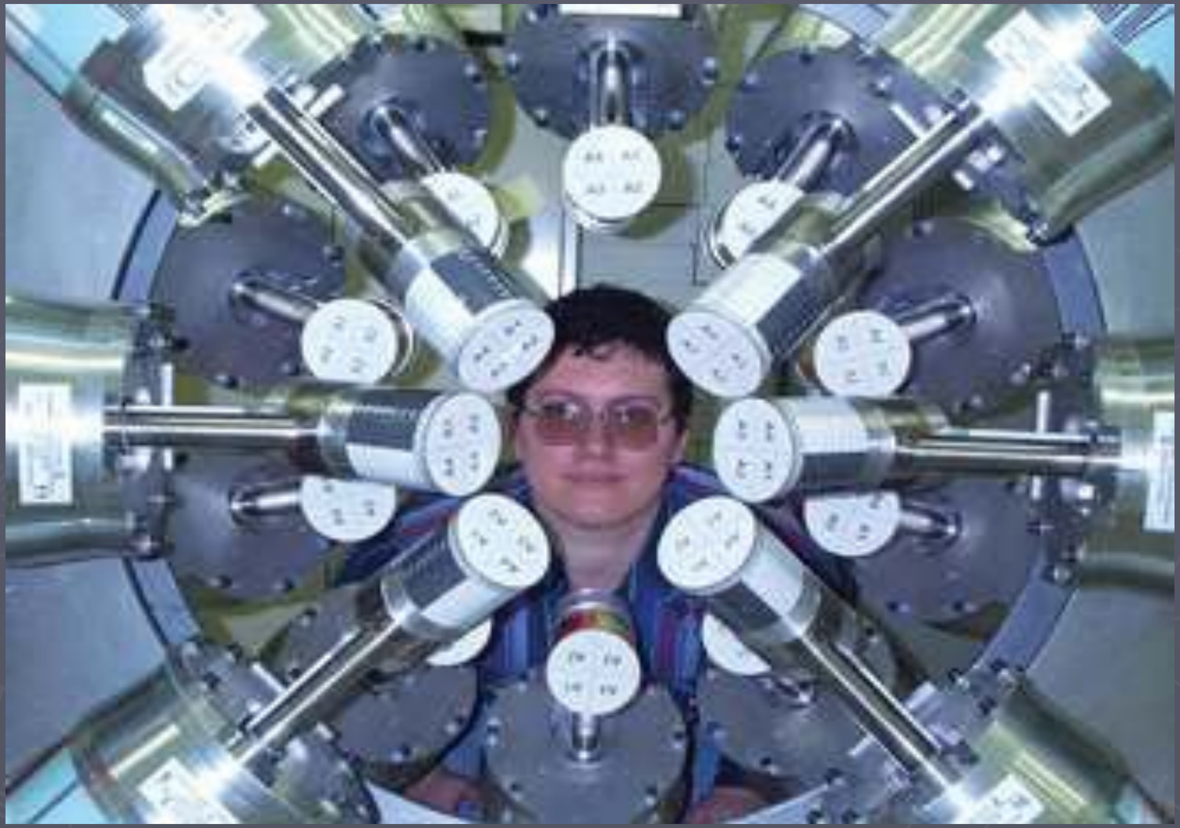
"Alpha-, Beta- and Gamma-ray Spectroscopy", Ed. K. Siegbahn, 1965

"The Electromagnetic Interaction in Nuclear Spectroscopy", Ed. W.D. Hamilton, 1975

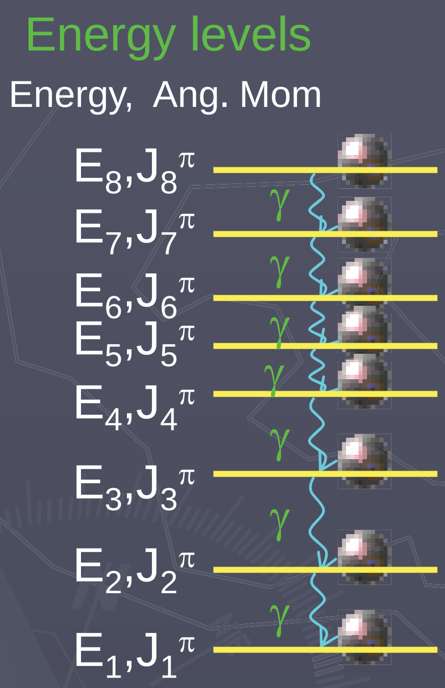
Plenty of information on the Web

Courtesy: F.G. Kondev

If you want to "see" the structure of a nucleus look through the "window" of γ-ray spectroscopy



γ-ray spectroscopy and nuclear structure



- ❖ How do nuclei respond when energy and angular momenta are increased ?
- ❖ What are different modes of excitations
- ❖ Are all the nuclei Spherical ? How can one experimentally determine ?
- ❖ Validity of Nuclear Model predictions

We can detect these gamma rays, measure their energies, intensities, angular distribution etc. and establish a level scheme

This gives information about the structure of a nucleus, modes of nuclear excitation and much more...

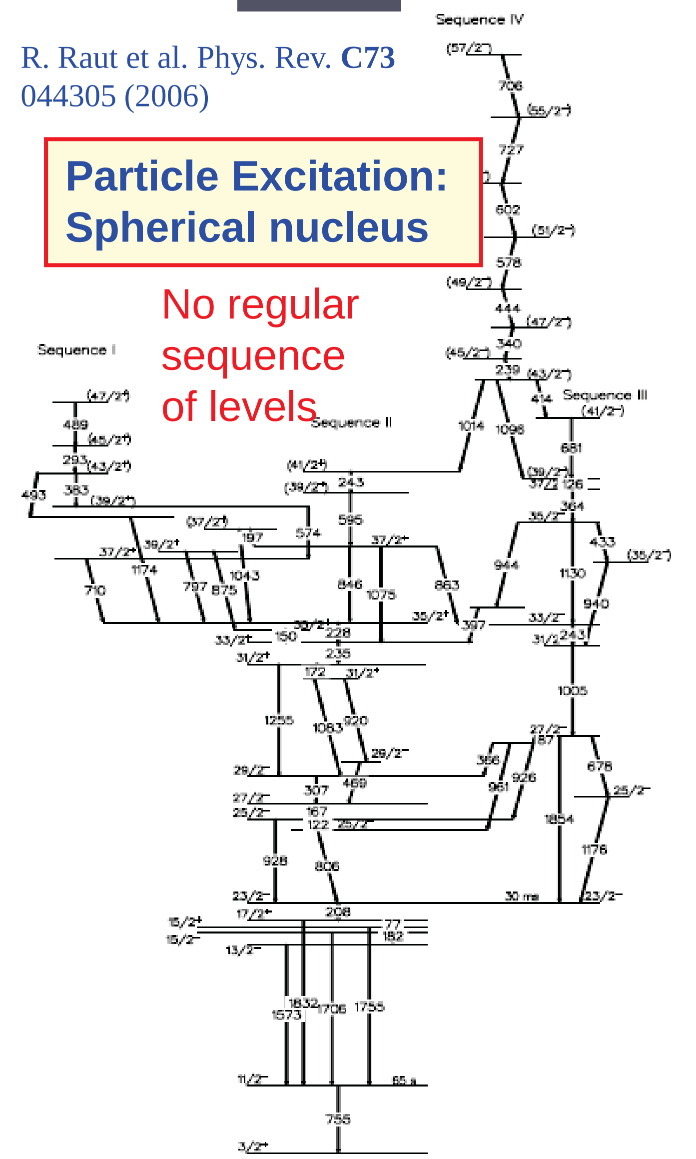
γ-ray spectroscopy and the structure of a nuclei

^{143}Sm

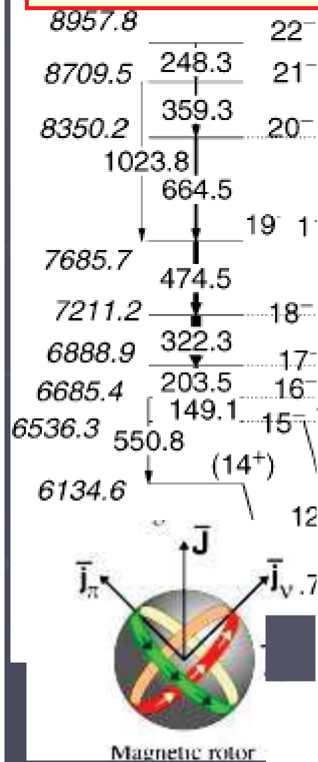
R. Raut et al. Phys. Rev. **C73** 044305 (2006)

Particle Excitation: Spherical nucleus

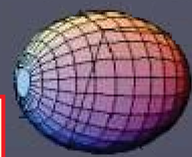
No regular sequence of levels



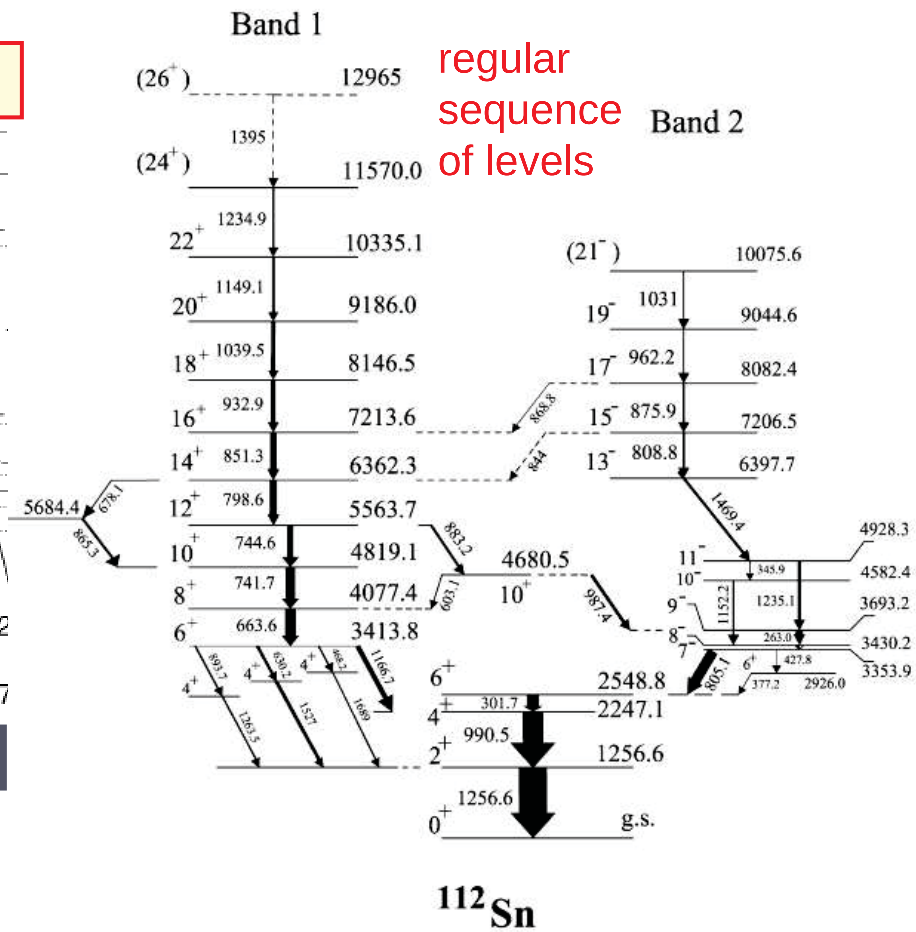
Shears band



Rotational bands: Deformed nucleus



regular sequence of levels



T. Bhattacharjee et al. Nucl. Phys. **A825** 16 (2009)

S. Ganguly et al. Nucl. Phys. **A789** 1 (2007)

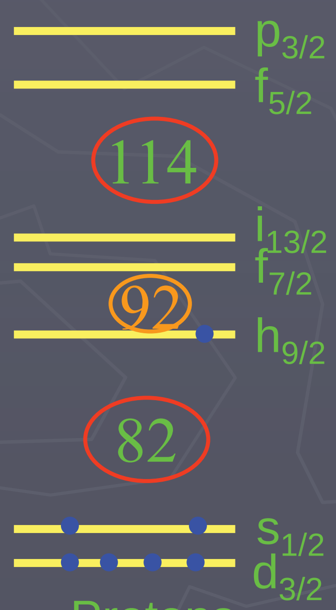
Modes of excitation in nuclei

Single particle excitation

(in spherical nuclei)

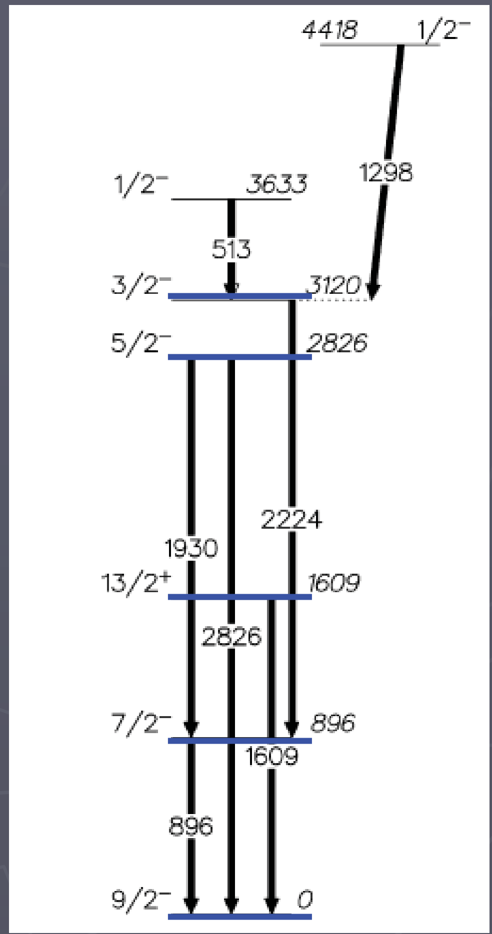
^{209}Bi (Z = 83, N = 126)
a spherical nucleus.

unpaired nucleons determine the spin and parity of a nuclear state.



Protons

Spherical shell model levels



M. Lipoglavsek et al, PLB 593 (2004) 61

Recent Trends in Nuclear Structure Studies:

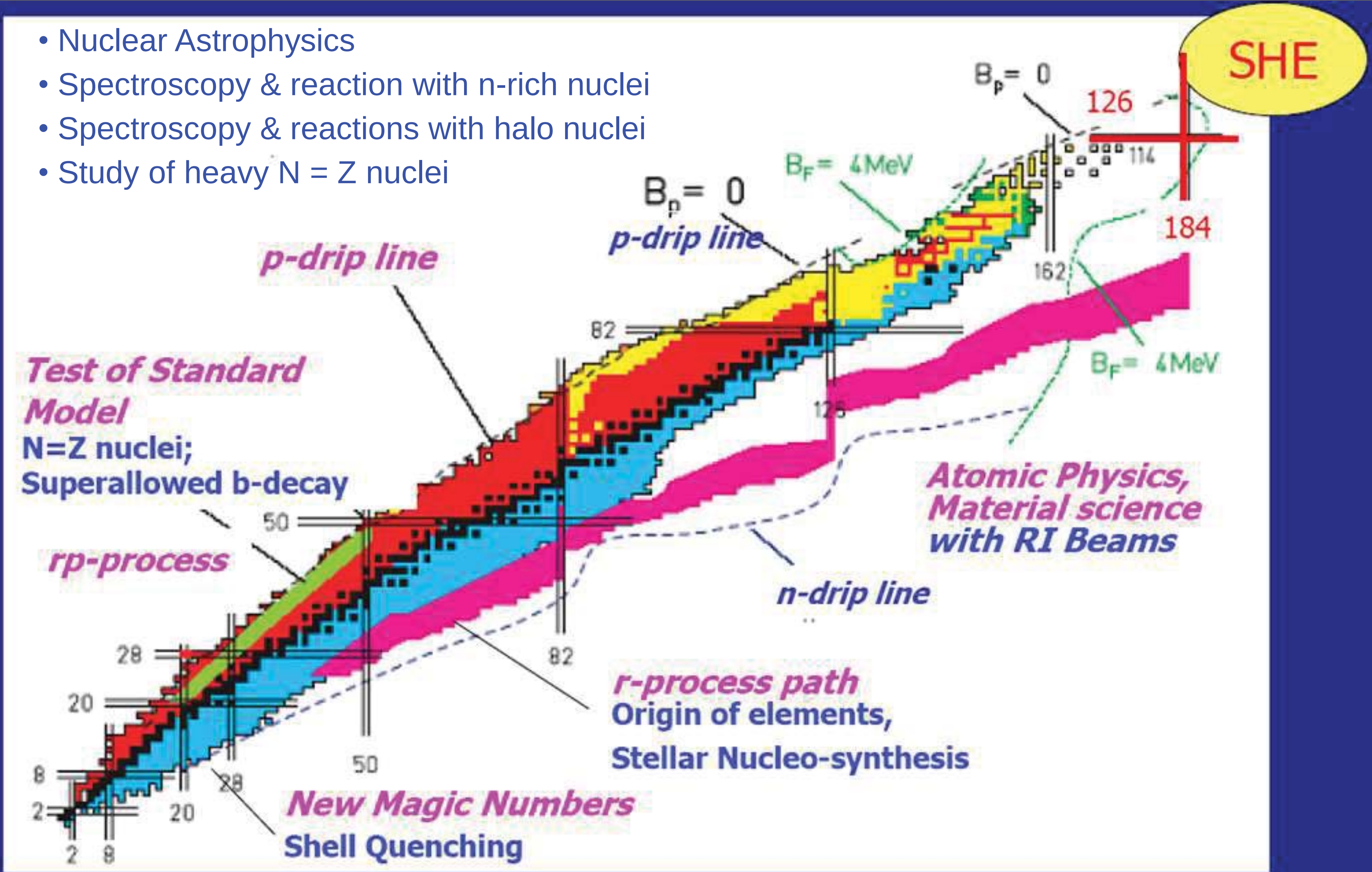
- limits of stability
- shell structure far from stability
- halo nuclei
- exotic radioactivities
- exotic excitations
- nuclear astrophysics
- facility upgrades

Many of these need Radioactive Ion (Rare Isotope) Beams

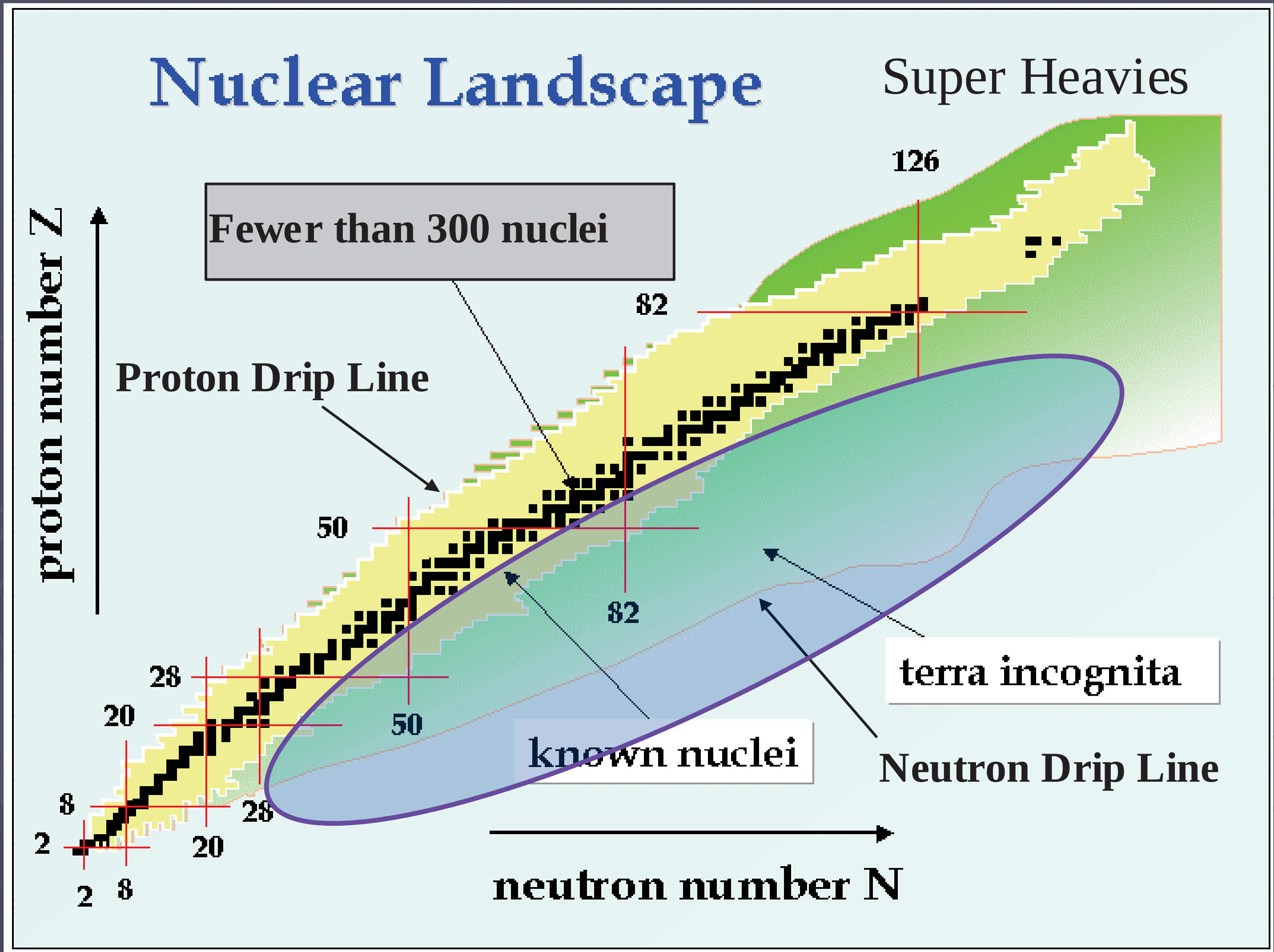
RIB

Physics with Radioactive Ion Beams (RIB)

- Nuclear Astrophysics
- Spectroscopy & reaction with n-rich nuclei
- Spectroscopy & reactions with halo nuclei
- Study of heavy N = Z nuclei



The future



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

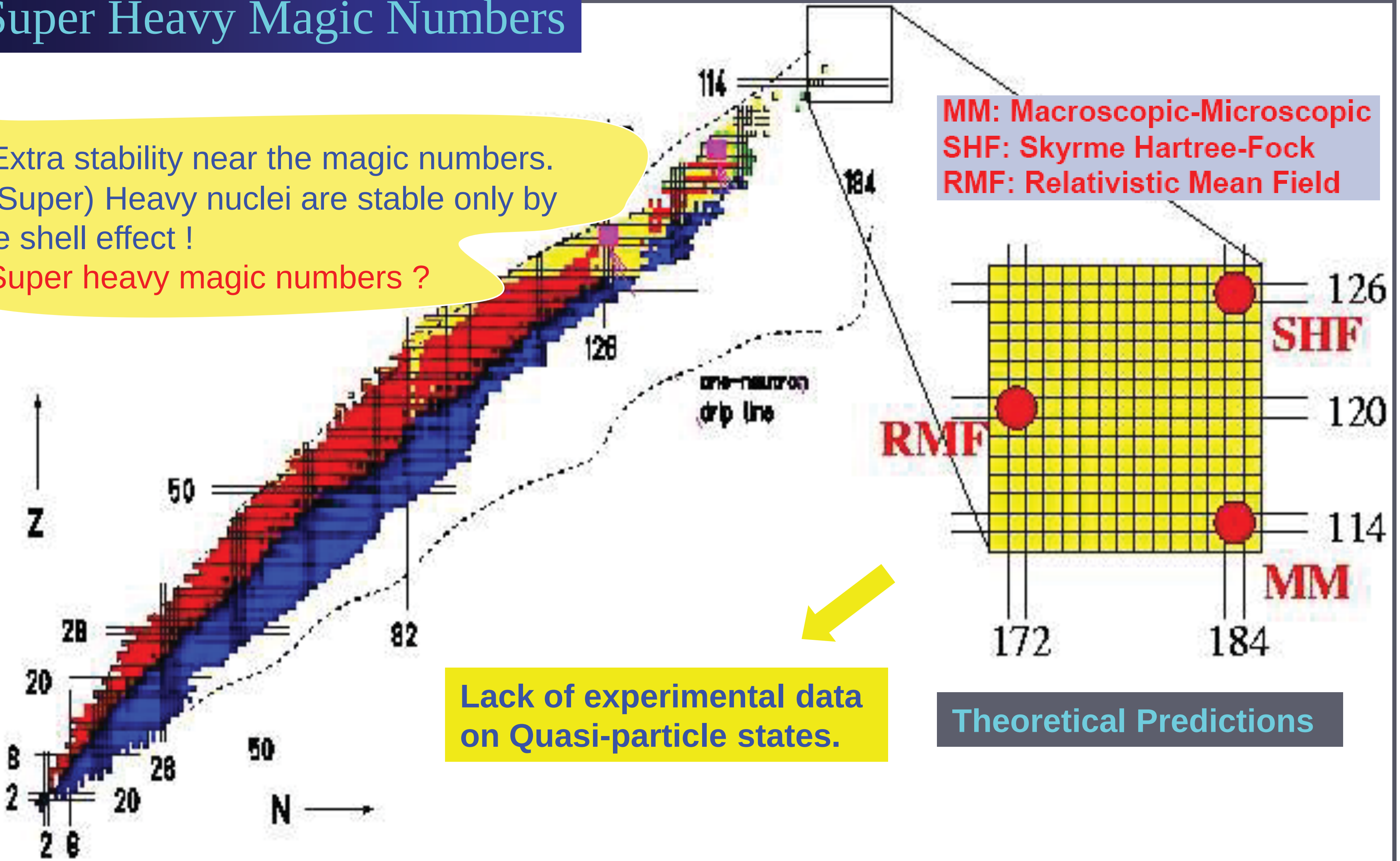
Some of the Interesting aspects

- Knowing the Limits
  - Drip lines and superheavies
  - P-rich and N-rich doubly magic nuclei e.g ^{100}Sn, ^{78}Ni, ^{132}Sn
- Change in shell structure in nuclei
  - Change (weakening) in the Spin-Orbit Interaction
  - Change in magic numbers
- Structural change in nuclei.
  - Shape transition in isotopic chain.
- Astrophysical importance
  - R-process path
  - Waiting point nuclei

Shell gaps beyond Z=82 and N=126

Super Heavy Magic Numbers

- Extra stability near the magic numbers.
- (Super) Heavy nuclei are stable only by the shell effect !
- Super heavy magic numbers ?



MM: Macroscopic-Microscopic
SHF: Skyrme Hartree-Fock
RMF: Relativistic Mean Field

Lack of experimental data on Quasi-particle states.

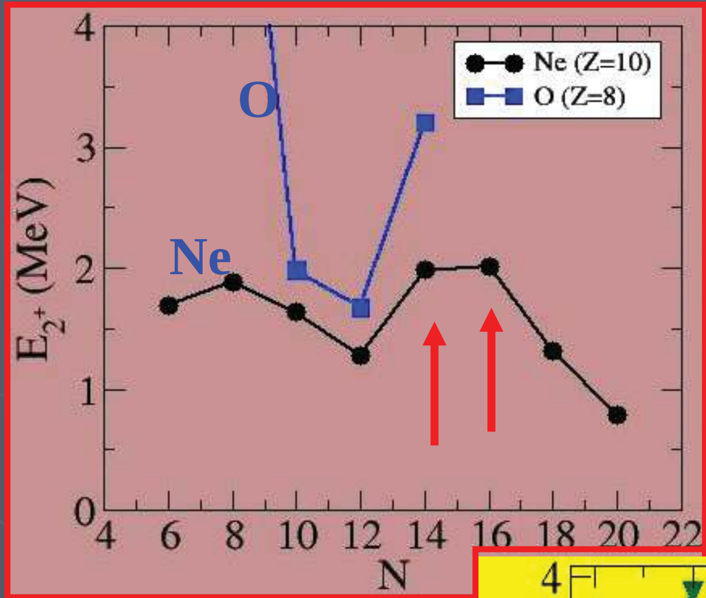
Theoretical Predictions

New Magic Numbers
Experimental Evidence

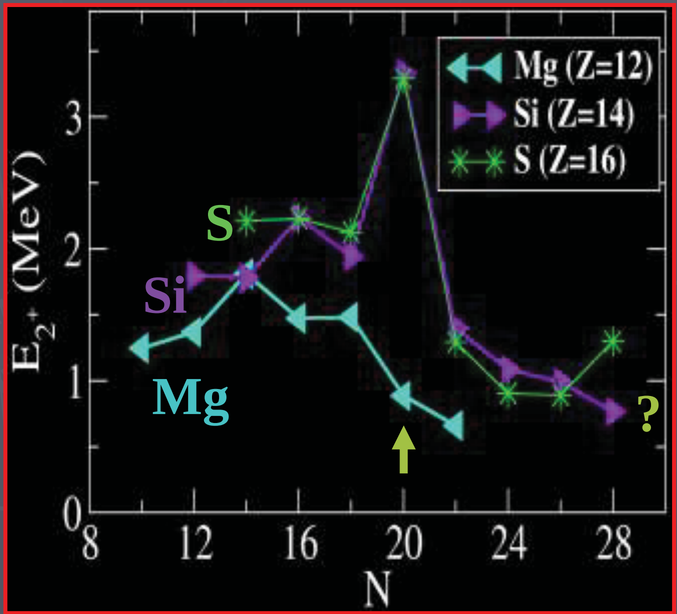
Excitation energy of 2^+ (E_{2+}) state in even-even nuclei is a measure of gap/ deformation

Large E_{2+} : Large gap in SPE (spherical)

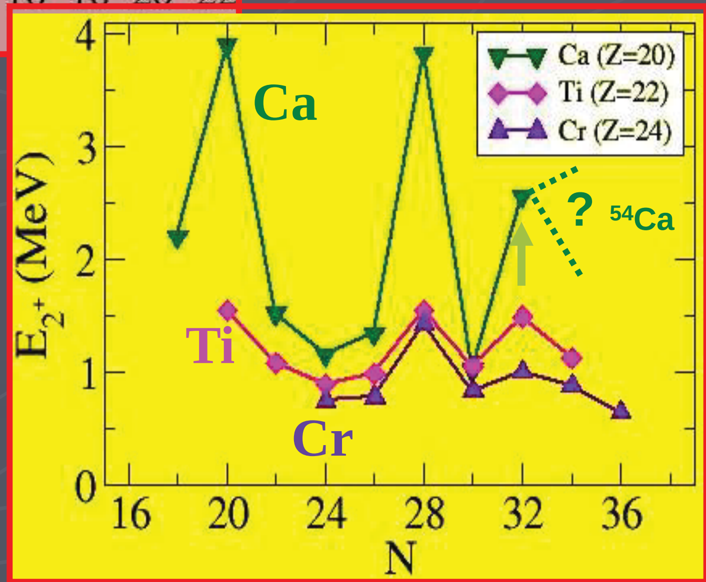
Small E_{2+} : Small gap in SPE (deformed)



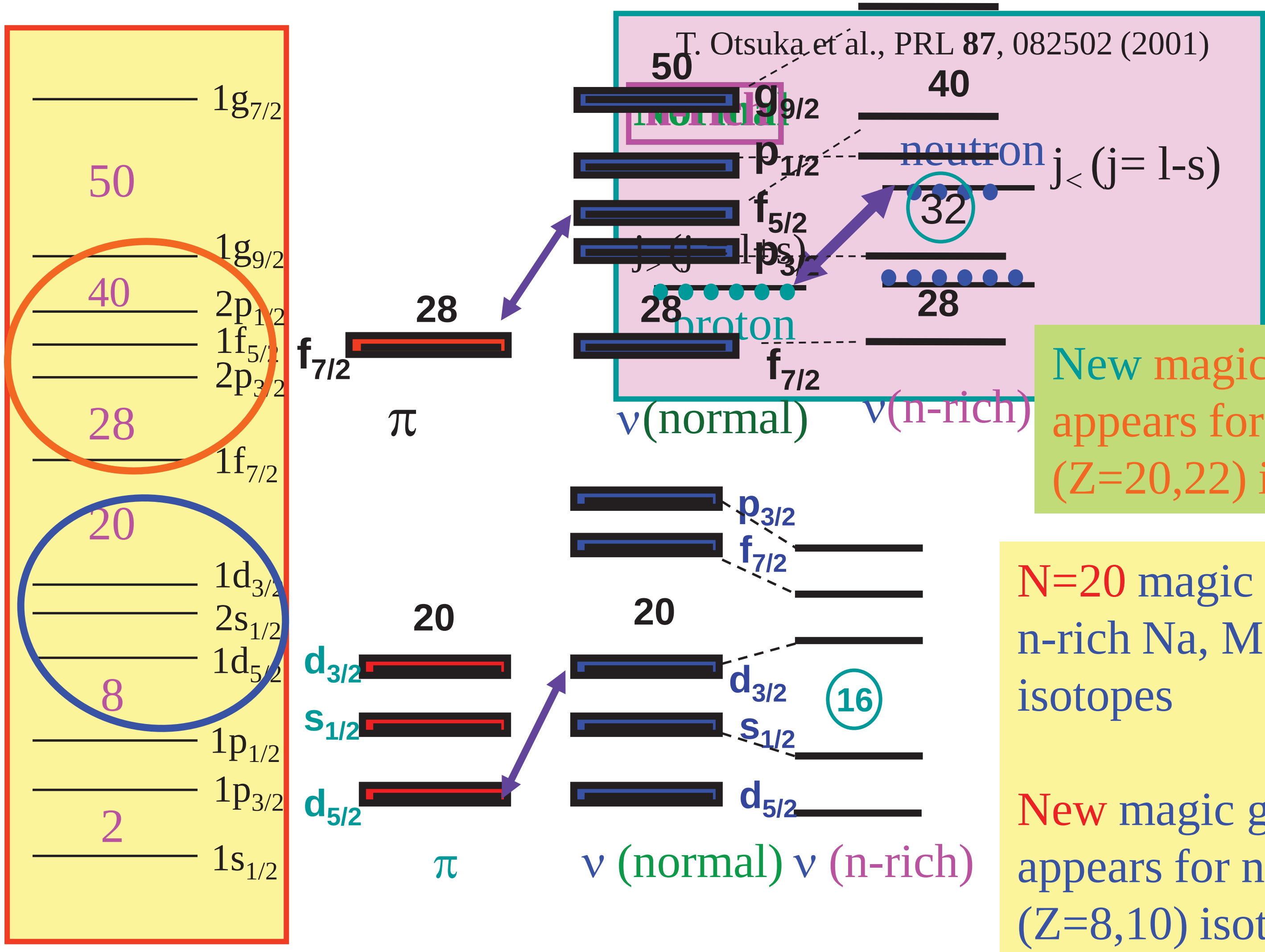
Evidence for new magic numbers at N = 14,16 & 32



Conventional magic number at N = 20 disappears



New Magic Numbers in light nuclei

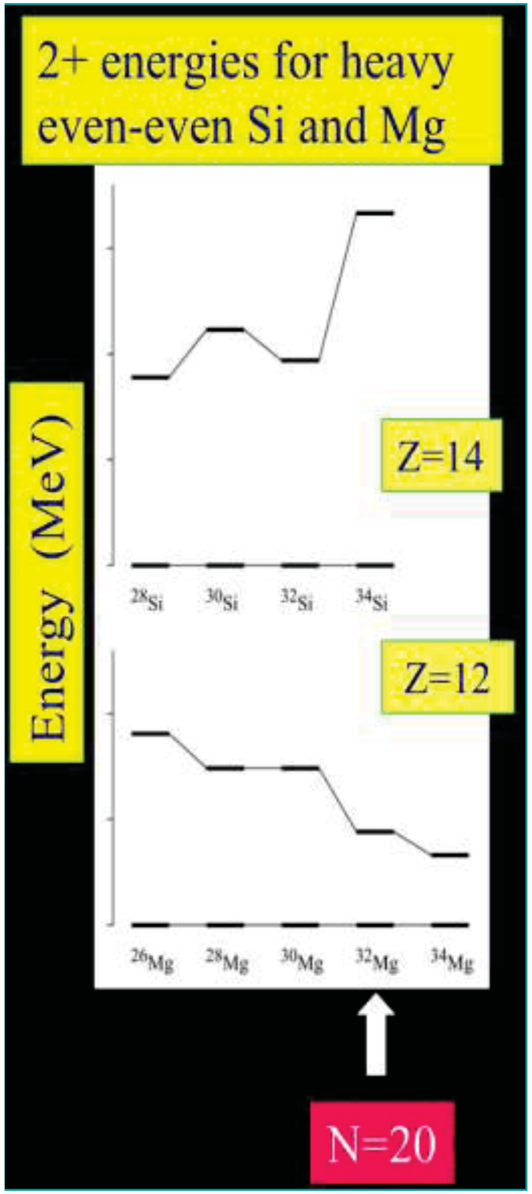


New magic gap at N=32 appears for n-rich Ca and Ti (Z=20,22) isotopes.

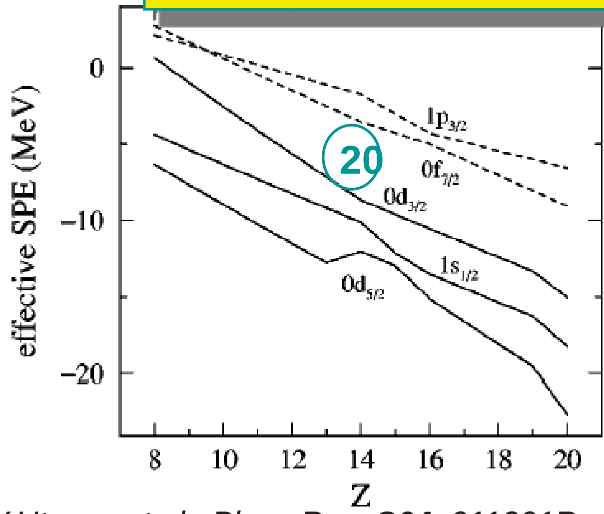
N=20 magic gap disappears for n-rich Na, Mg (Z=11,12,..) etc. isotopes

New magic gap at N=16 appears for n-rich Ne and O (Z=8,10) isotopes.

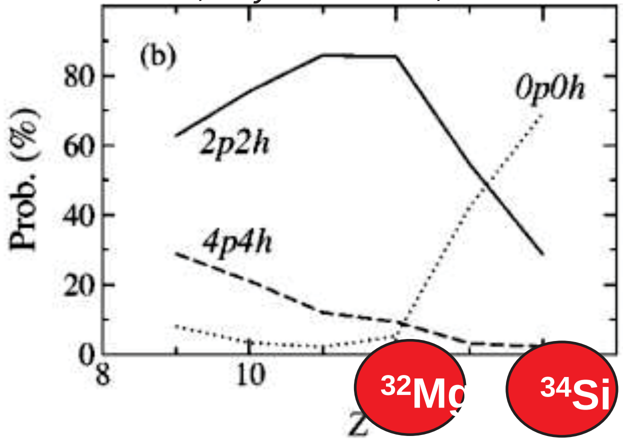
Island of Inversion



Effective single-particle Energies for N=20 isotones

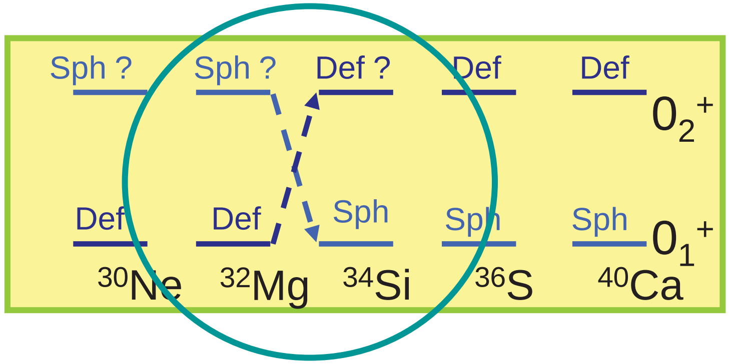


Y.Utsuno et al., Phys. Rev. ***C64****, 011301R*



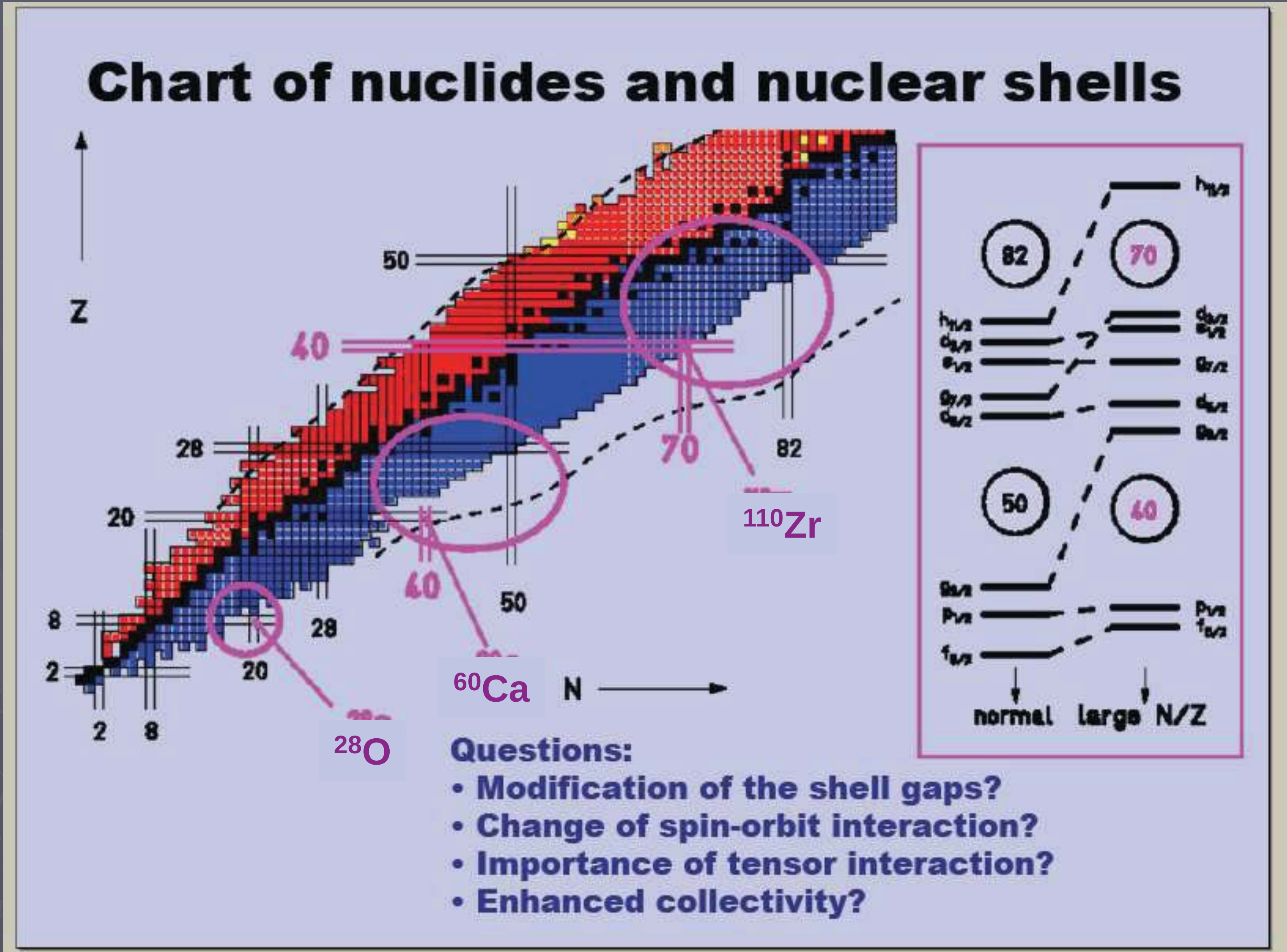
Probabilities of np-nh configurations for N=20 isotones

N=20 shell closure



- Mixing of configurations
  0p-0h, 2p-2h

For the heavier nuclei as well …



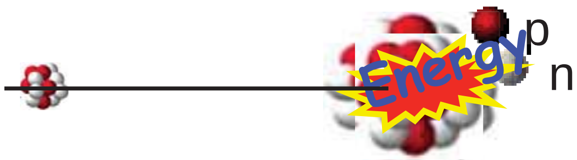
Ways to reach the neutron rich nuclei

- Deep Inelastic Collision
- Fission
  - Spontaneous fission: nuclei with large N - Z
  - Induced fission: nuclei with moderate N - Z
- Multi-fragmentation
- Fusion with RIB.

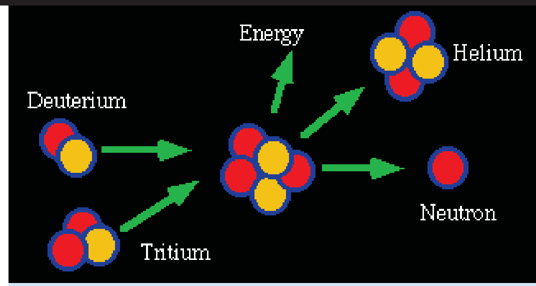
Nuclear Reactions

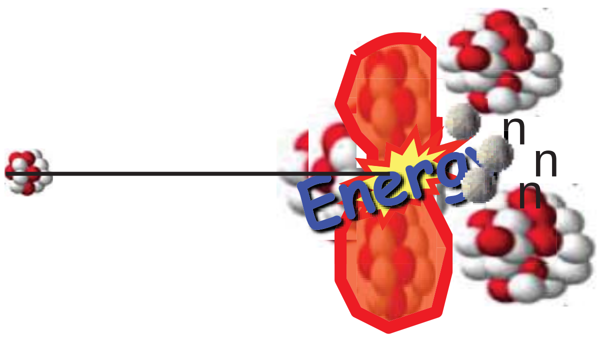
Elastic Scattering

Inelastic and Deep inelastic Scattering



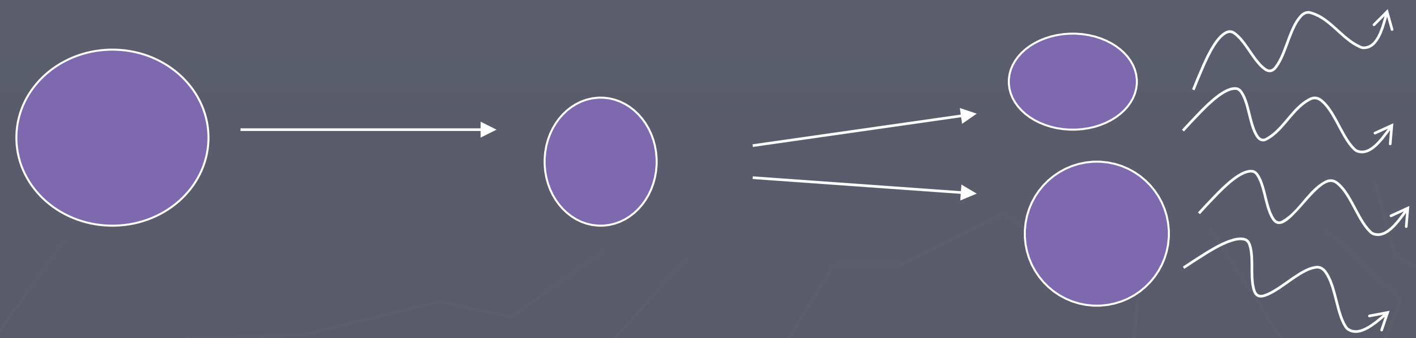
Fusion evaporation reaction





Fusion Fission reaction

Deep Inelastic reaction in Inverse Kinematics



Higher N/Z + Lower N/Z → Equilibration of N/Z

Formation of excited states of projectile like or target like nuclei

Forward focused and high velocity

Gamma rays are Doppler shifted

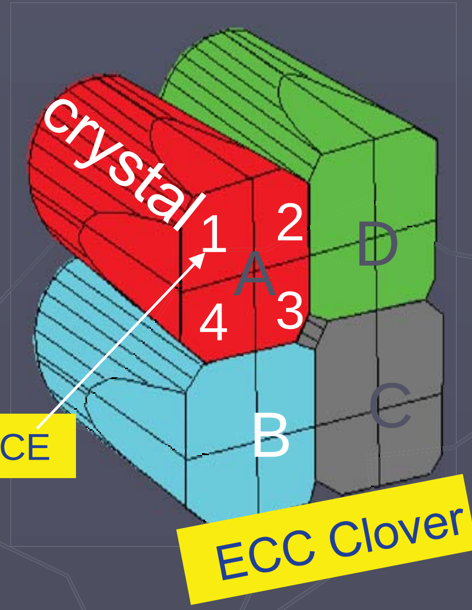
Identification of nuclei of interest

Spectrometer + Focal plane detection system

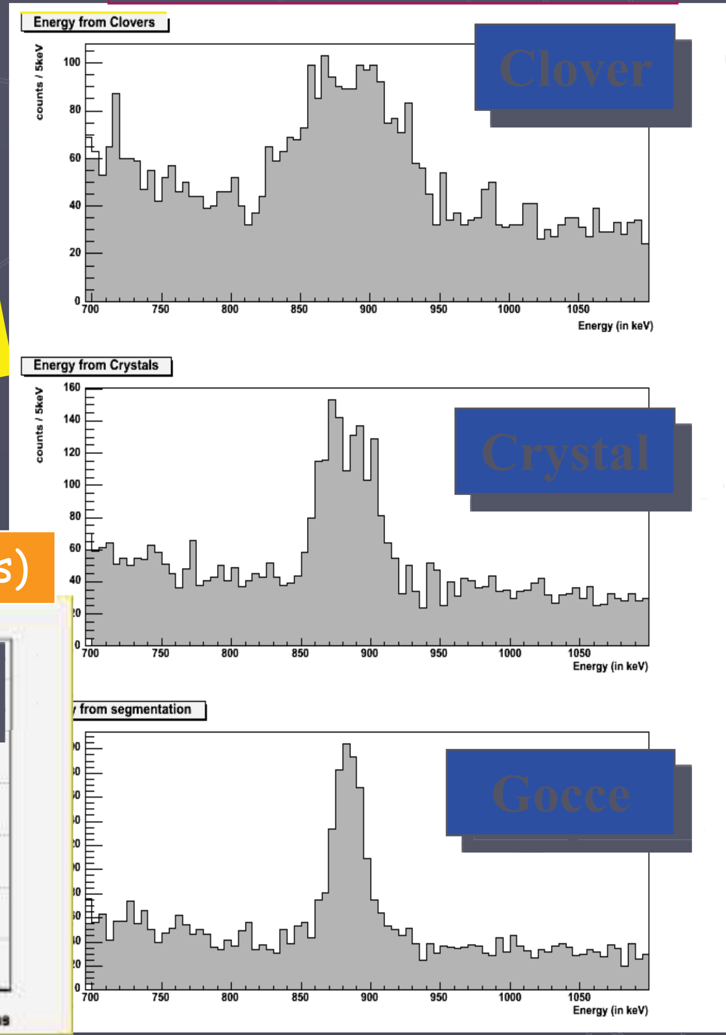
High efficiency gamma detector array with large granularity

VAMOS + EXOGAM at GANIL, France

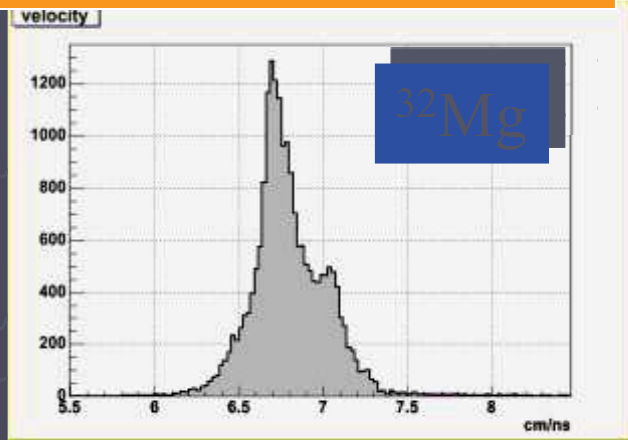
- Energy from crystal
- Angle from GOCCE
  - * Doppler correction
  - *Angular distribution



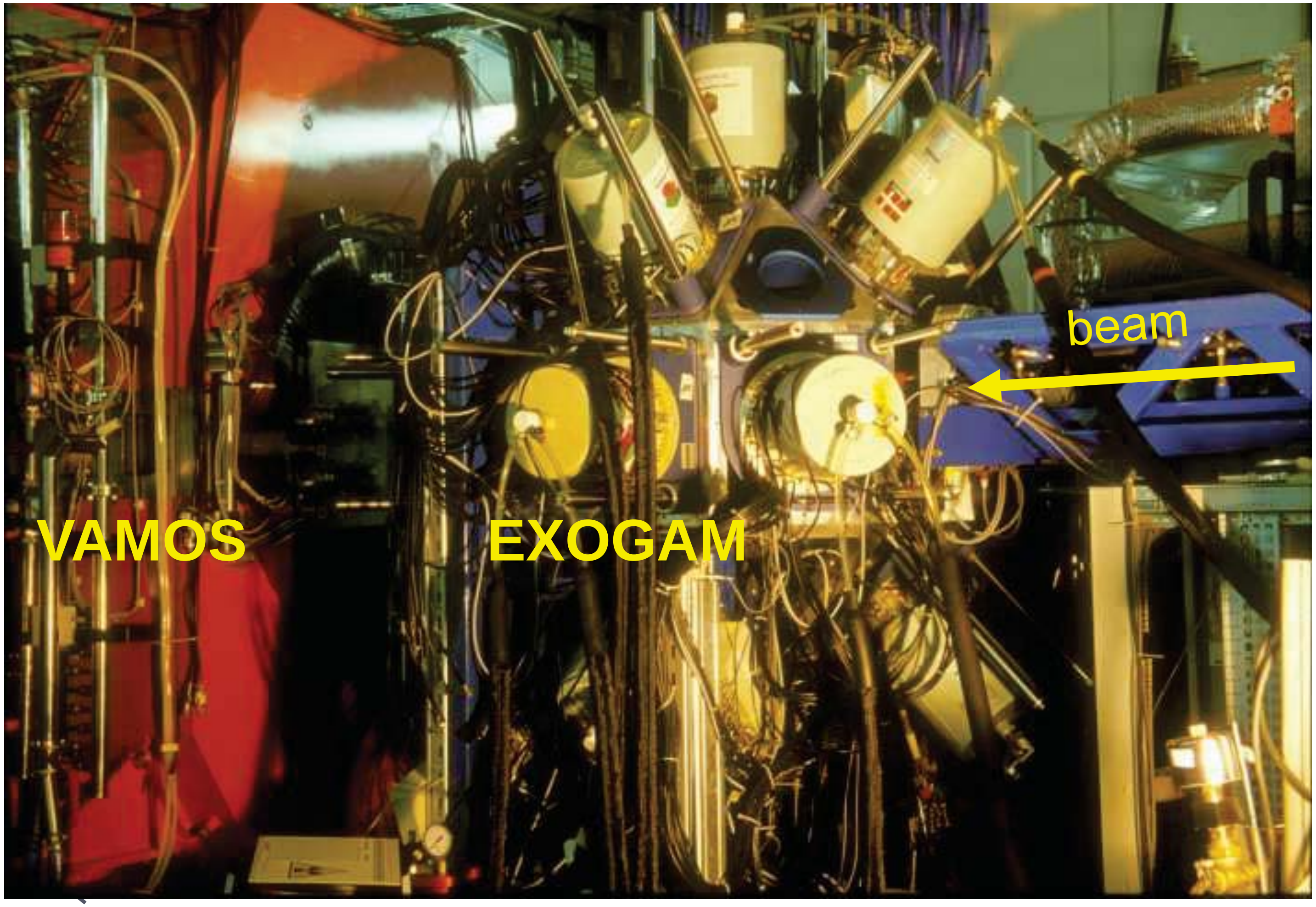
Doppler correction for 885 keV γ-ray in ^{32}Mg



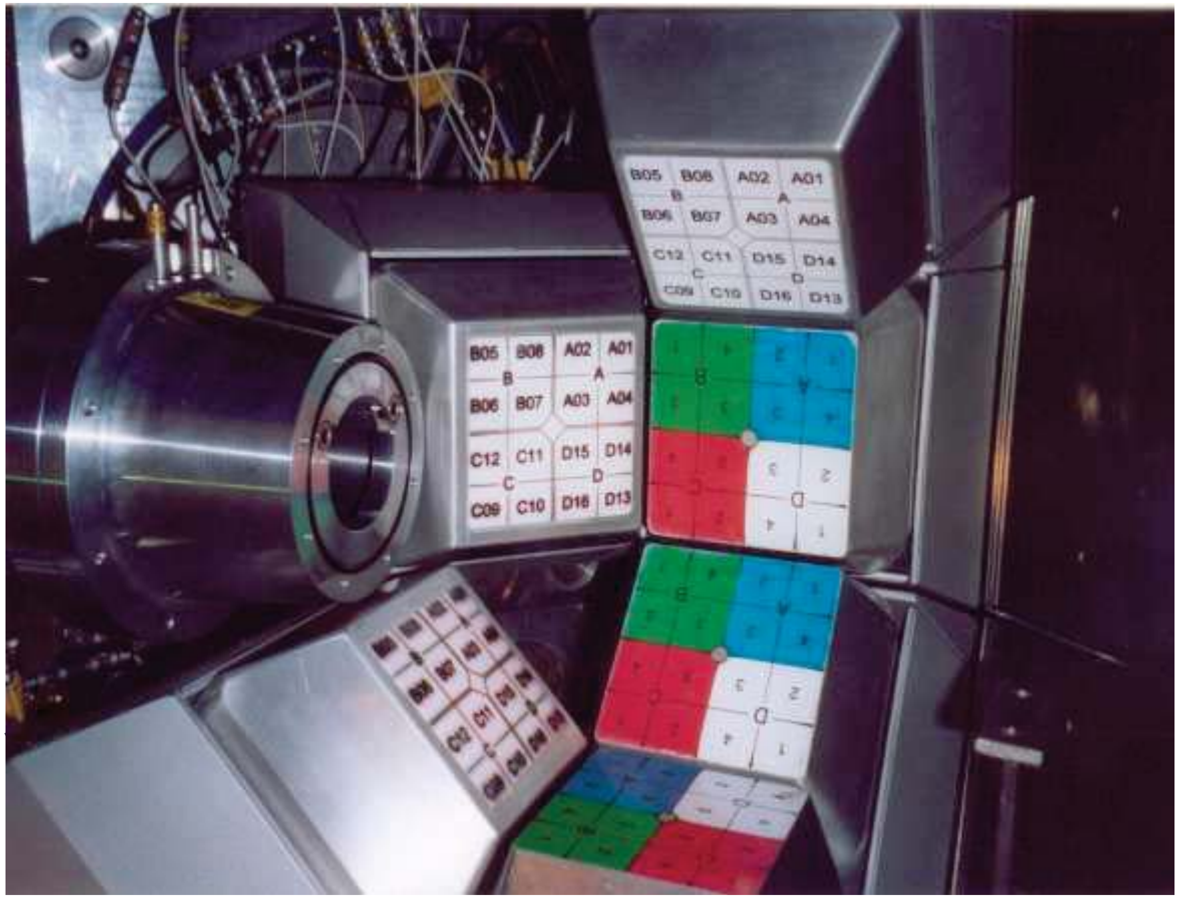
➲ Recoil velocity (v ~ 6.8 cm/ns)



VAMOS + EXOGAM at GANIL, France



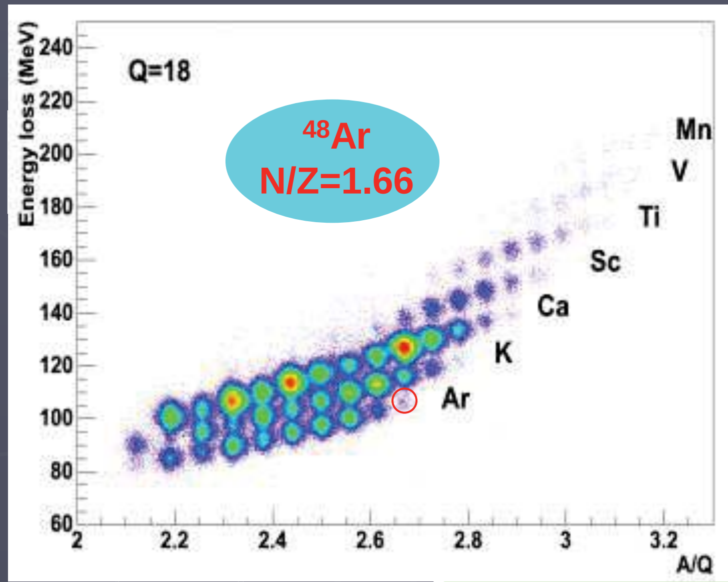
VAMOS + EXOGAM at GANIL, France



Deep inelastic reaction in inverse kinematics @GANIL

^{238}U @ 5.5 MeV/u
(N/Z=1.58)
~ 12% above barrier

^{48}Ca (1 mg/cm^2)
(N/Z=1.4)



High v/c (~ 14%) of fragments

Accurate Doppler correction is must !!

Determination of Angle event by event

Velocity of fragment (VAMOS Reconstruction)

and segments of EXOGAM Clover

Identification

M/q ~ Bρ x TOF

M ~ E x TOF^2

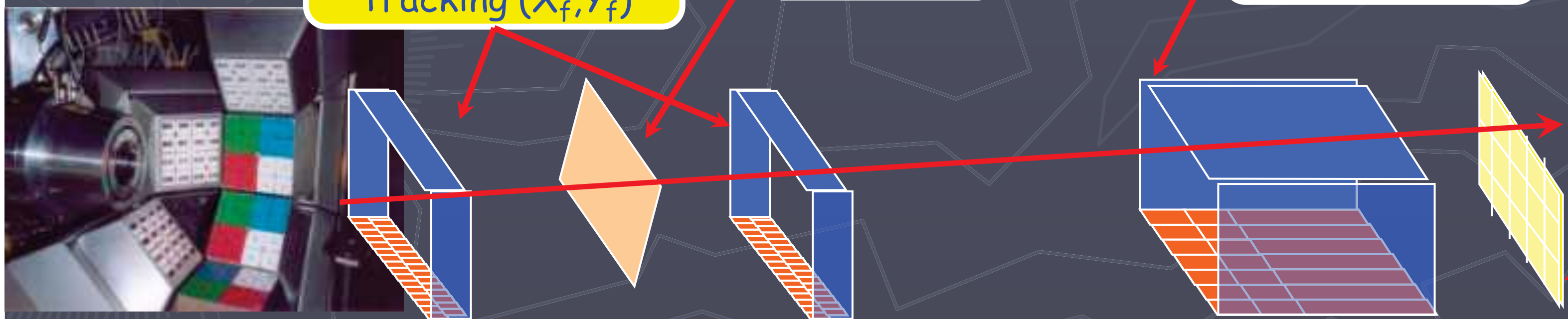
Z ~ E x ΔE

Drift Chamber
Tracking (X_f,Y_f)

SED (TOF)

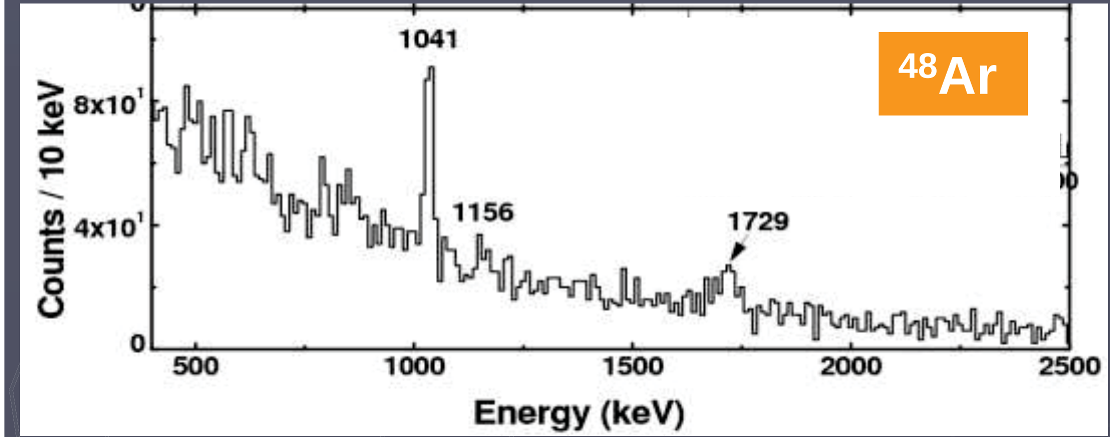
IC
Energy loss (ΔE)

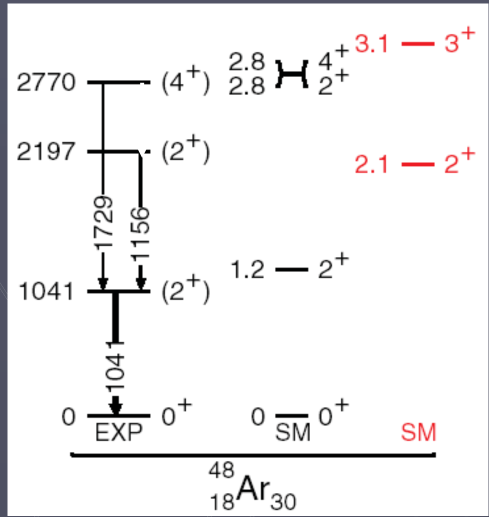
Silicon Wall
7 x 3 (500 μm)
(E)



Spectroscopy of n-rich fp shell nuclei

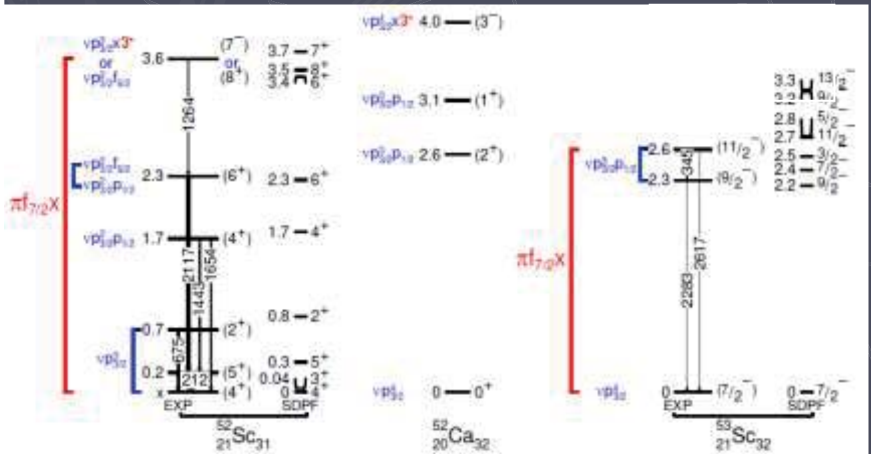
S. Bhattacharyya et al., PRL 101, 032501 (2008)





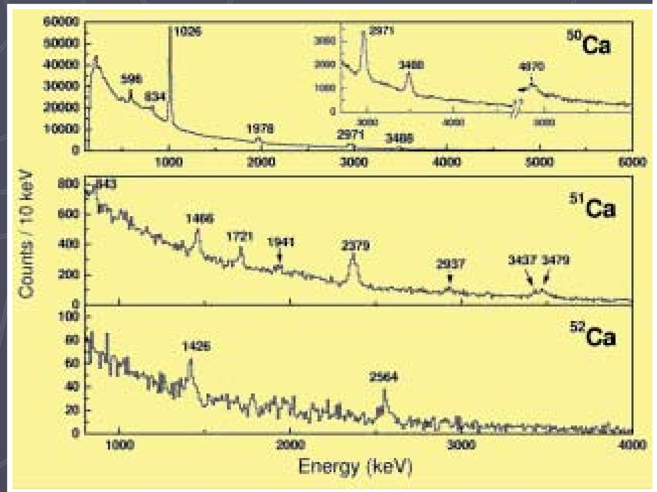
$^{48}_{18}Ar_{30}$ low lying γ-band: Deviation from axial symmetry β=0.25, γ=40°

On the magicity at N = 32, 34



$^{50-52}_{20}Ca_{30-32}$

$^{52,53}_{21}Sc_{31,32}$



S. Bhattacharyya et al., PRC 79, 014313 (2009)

M. Rejmund et al., PRC 76, 021304(R) (2007)

Spectroscopy of n-rich fp shell nuclei

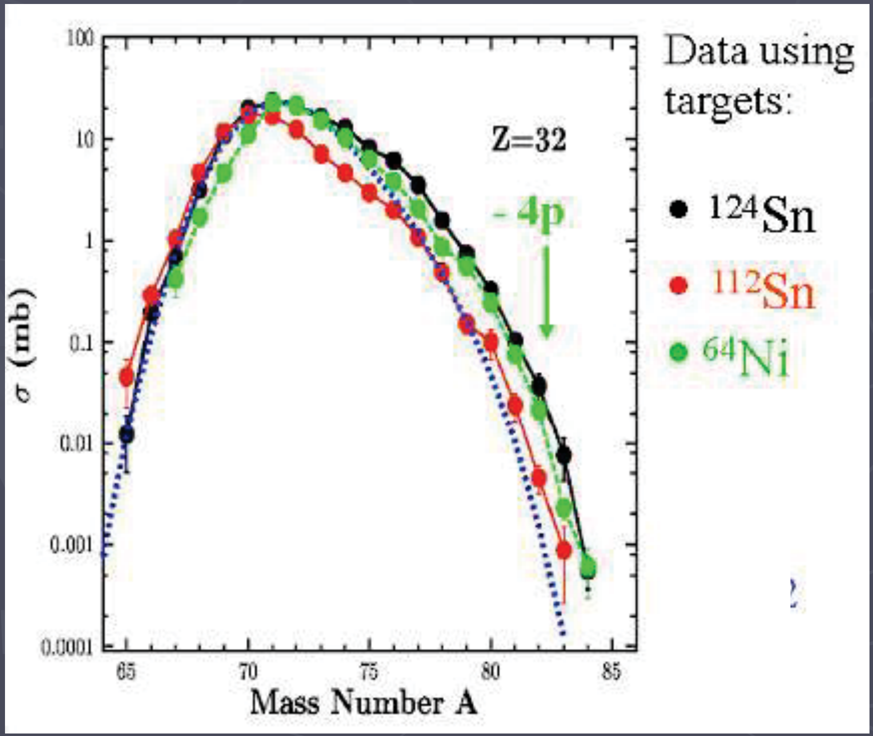
Z \ N	24		26		28		30		32		34		36		38		N
Z	48Cr	49Cr	50Cr	51Cr	52Cr	53Cr	54Cr	55Cr	56Cr	57Cr	58Cr	59Cr	60Cr	61Cr	62Cr	63Cr	64Cr
	47V	48V	49V	50V	51V	52V	53V	54V	55V	56V	57V	58V	59V	60V	61V	62V	63V
22	46Ti	47Ti	48Ti	49Ti	50Ti	51Ti	52Ti	53Ti	54Ti	55Ti	56Ti	57Ti	58Ti	59Ti	60Ti	61Ti	62Ti
	45Sc	46Sc	47Sc	48Sc	49Sc	50Sc	^{51}Sc	^{52}Sc	^{53}Sc	54Sc	55Sc	56Sc	57Sc	58Sc	59Sc	60Sc	61Sc
20	44Ca	45Ca	46Ca	47Ca	48Ca	49Ca	^{50}Ca	^{51}Ca	^{52}Ca	53Ca	54Ca	55Ca	56Ca	57Ca	58Ca		
	43K	44K	45K	46K	47K	48K	^{49}K	^{50}K	51K	52K	53K	54K	55K	56K			
18	42Ar	43Ar	44Ar	45Ar	46Ar	^{47}Ar	^{48}Ar	49Ar	50Ar	51Ar	52Ar	53Ar					
	41Cl	42Cl	43Cl	44Cl	45Cl	46Cl	47Cl	48Cl	49Cl	50Cl	51Cl						
16	40S	41S	42S	43S	44S	45S	46S	47S	48S	49S							

DIC around Fermi energy : MARS and BIGSOL @ TAMU

Study of projectile fragment distributions from peripheral to mid-peripheral collisions
@ 15-25 MeV/ nucleon:

enhanced production of neutron-rich nuclei

^{86}Kr(25MeV/u) + ^{64}Ni, ^{124}Sn,^{112}Sn

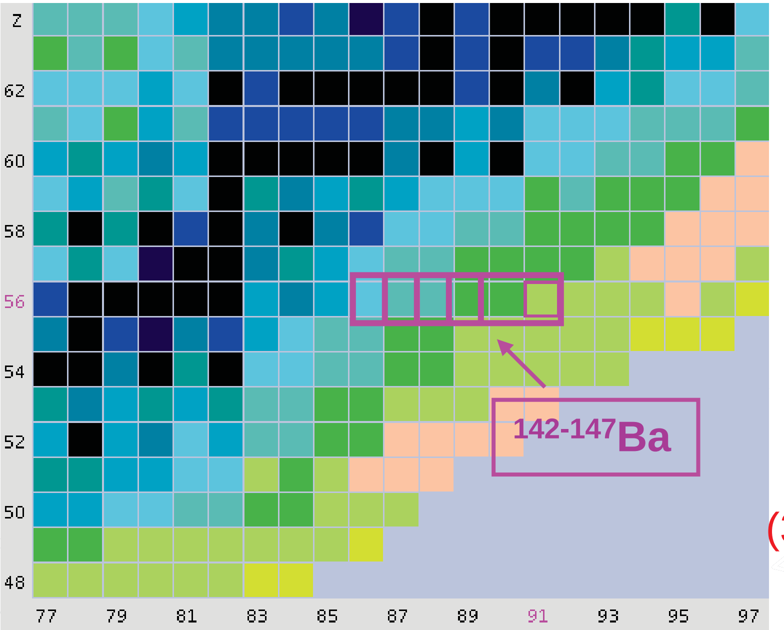


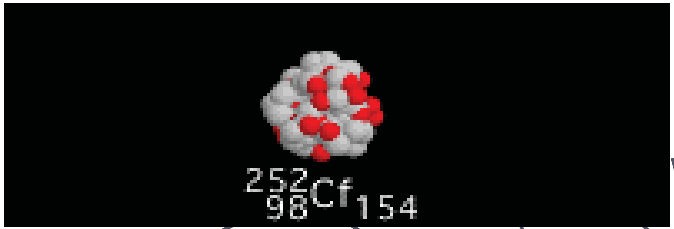
G.A Souliotis et al., PLB 543 163 (2002), PRL 91 022701 (2003)

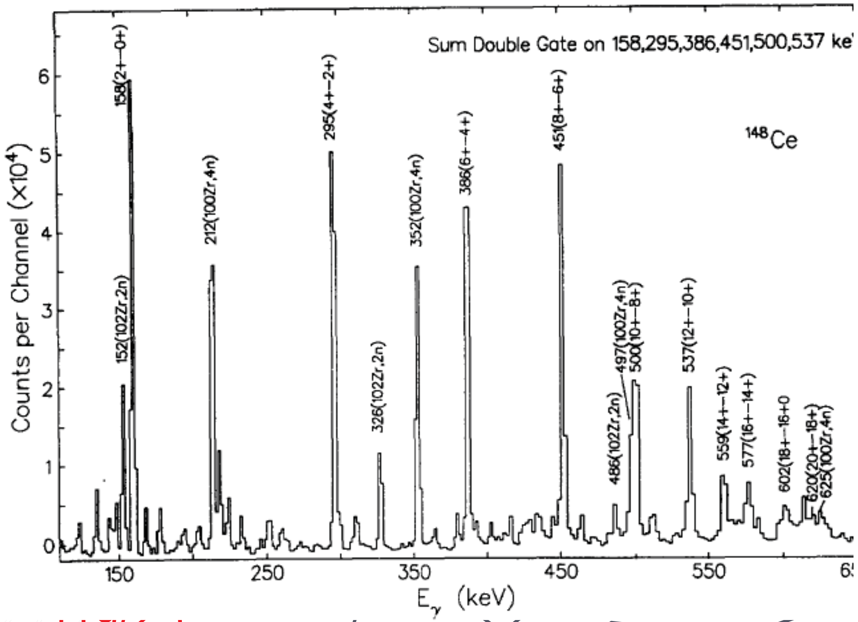
Ways to reach the neutron rich nuclei

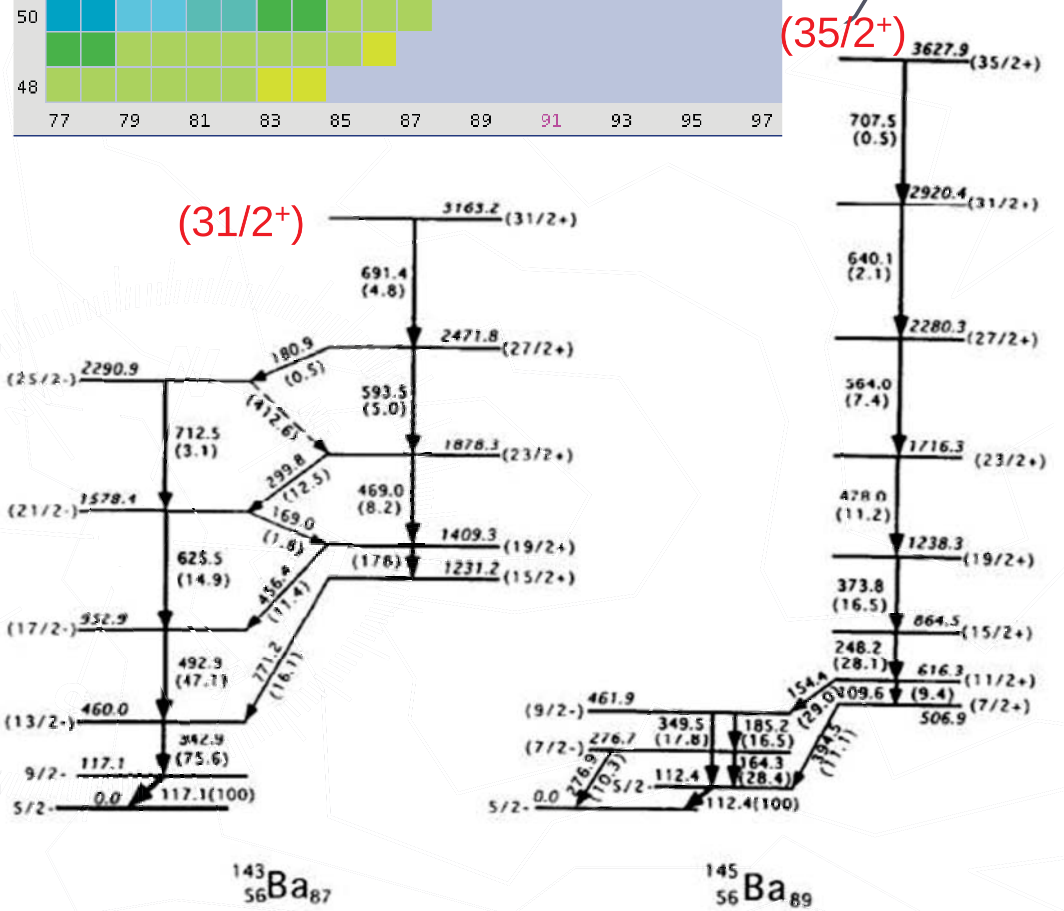
- Deep Inelastic Collision
- Fission
  - Spontaneous fission: nuclei with large N - Z
  - Induced fission: nuclei with moderate N - Z
- Multi-fragmentation
- Fusion with RIB.

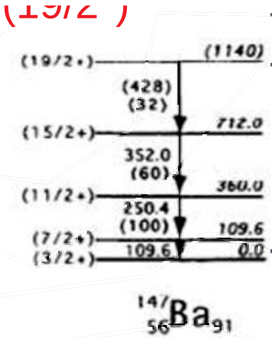
Spontaneous Fission



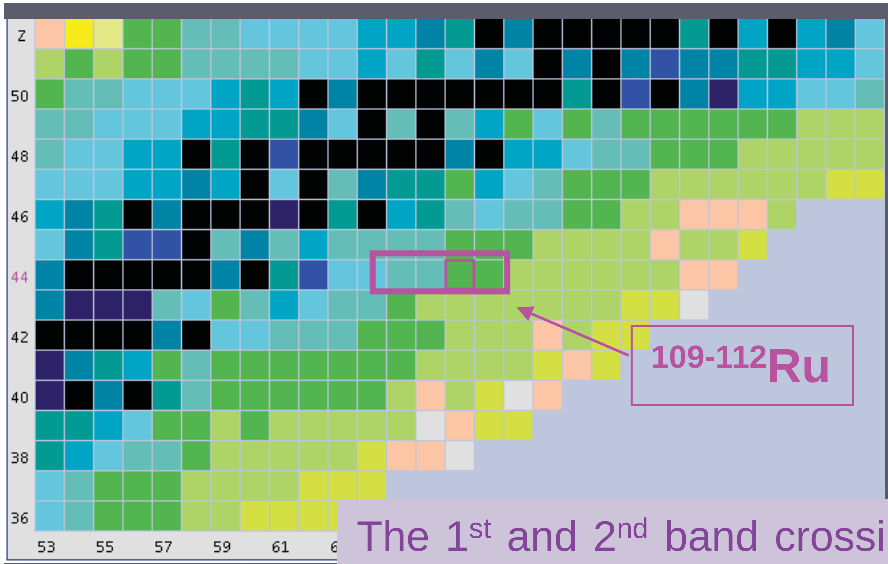






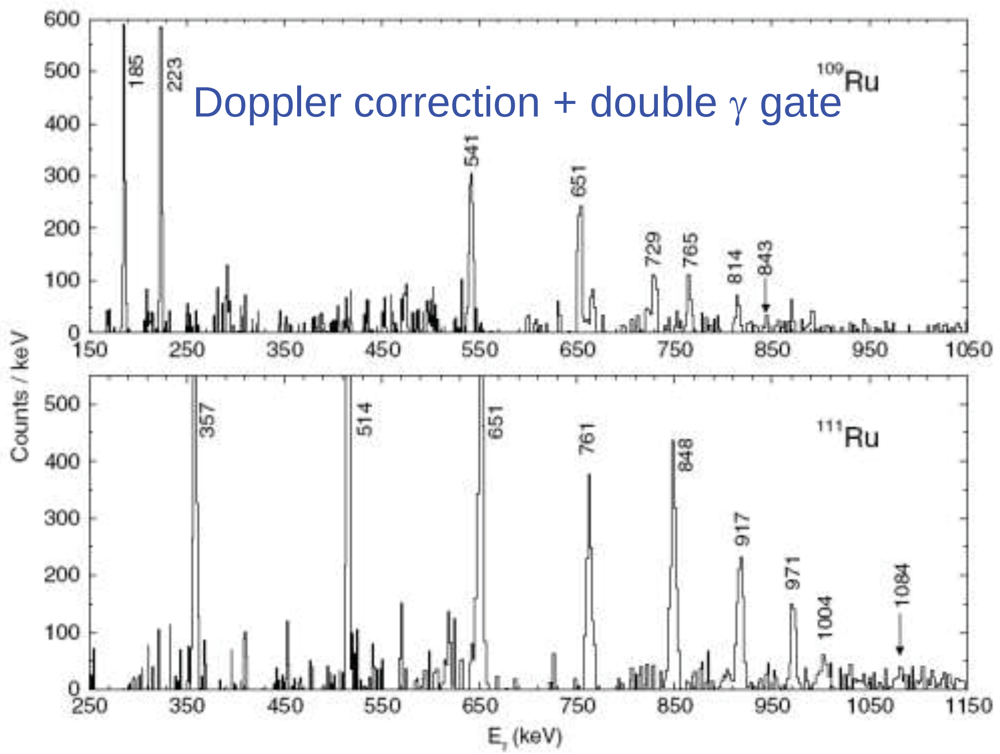


Observed angular mom. up to ~ 16ħ

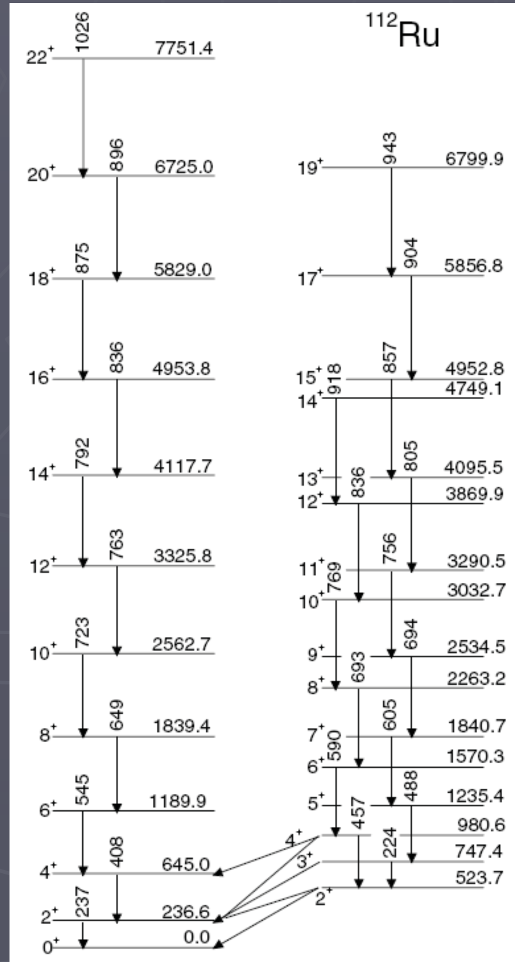


- $^{238}U(\alpha,f)$:
- thin target (~ 0.3 mg/cm^2), E_{baem} = 30 MeV
- Gammasphere + CHICO
- Detection: both fragments + γ–γ–γ
- ToF+θ → A & v of both fragments.
- Doppler correction

The 1st and 2nd band crossings $^{109-112}$Ru have been interpreted as triaxial shape change from prolate to oblate.



C.Y. Wu et al.: PRC **73**, 034312 (2006)

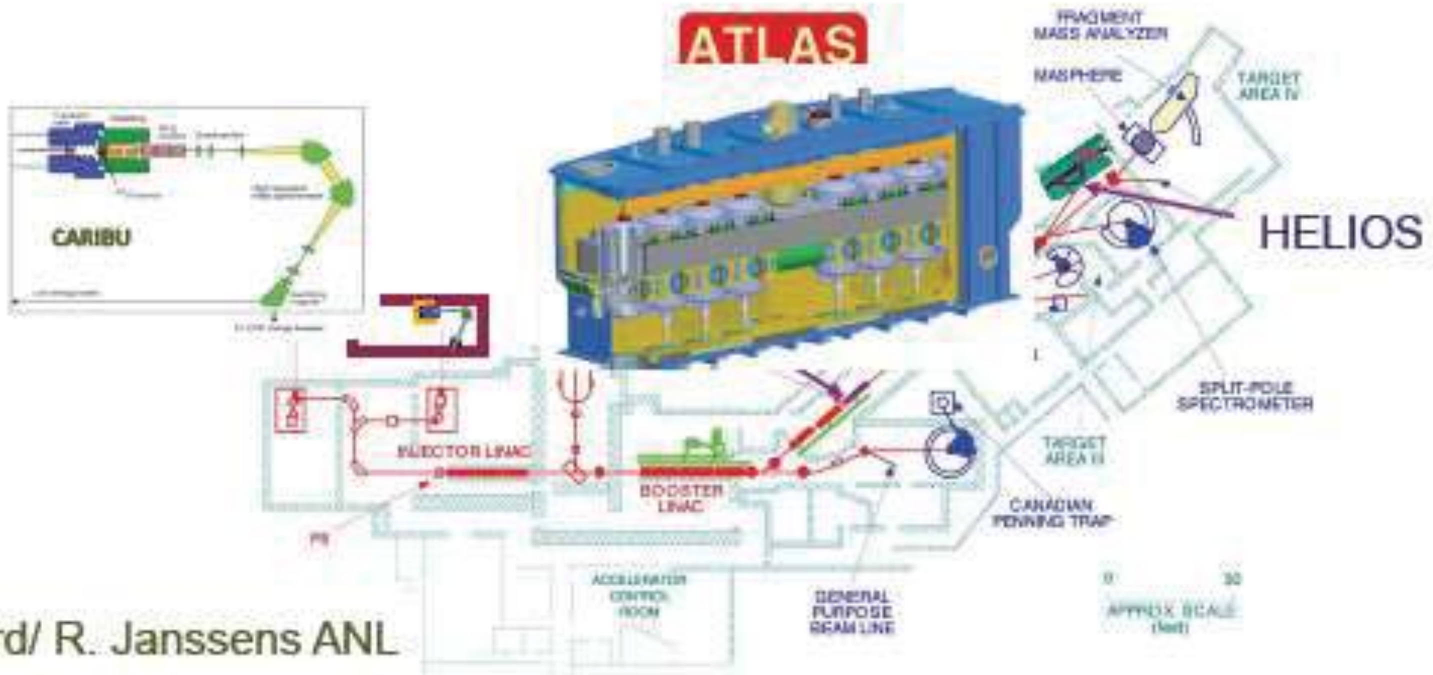


Production of RIB

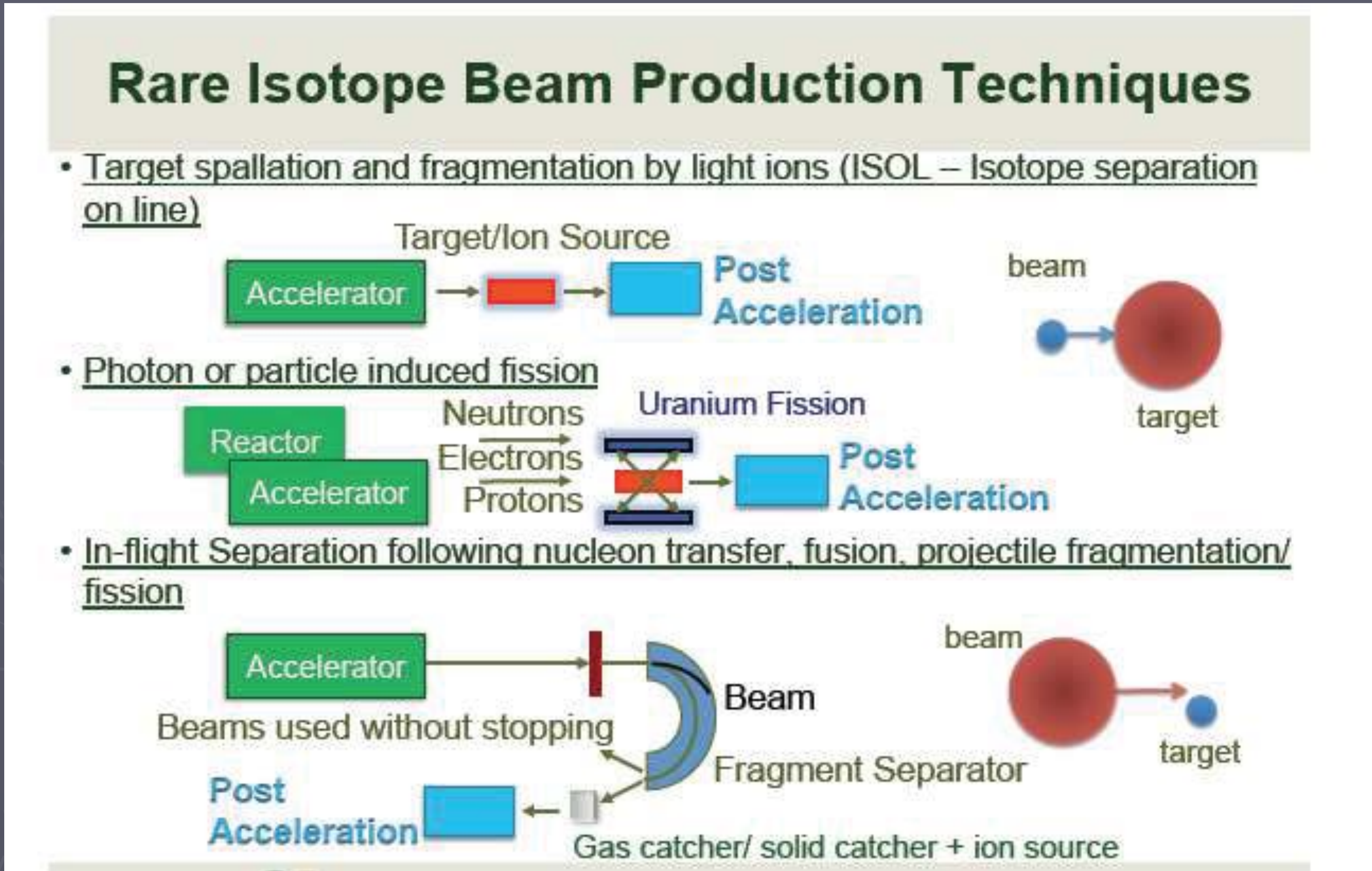
- Fission
  - Spontaneous fission: nuclei with large N - Z
  - Induced fission: nuclei with moderate N - Z
- Multi-fragmentation
- Spallation
- ...

Argonne National Laboratory: CARIBU & Energy Upgrade & HELIOS: Unique Synergy

- Fission products of ^{252}Cf spontaneous fission stopped in gas and accelerated
- CARIBU gives access to exotic beams not available elsewhere.
- Physics with beams from CARIBU (1 & 2 nucleon transfer reactions) needs the new energy regime opened by the Energy Upgrade (12 MeV/u) .
- Solenoid Spectrometer greatly expands the effectiveness of both the fission fragment beams and the existing in-flight RIB program at these higher energies.



G. Savard/ R. Janssens ANL



Courtesy: E. McCutchan

Production Mechanisms – High Energy

- Fragmentation (used at NSCL, GSI, RIKEN, GANIL, FRIB)
  - Projectile fragmentation of high energy (>50 MeV/A) heavy ions
  - Target fragmentation of a target with high energy massive ion. In the heavy ion reaction mechanism community this would include *intermediate mass and target fragments*.
- Spallation (ISOLDE, TRIUMF-ISAC, EURISOL, SPES, …)
  - Name comes from spalling or cracking-off of target pieces.
  - Major ISOL mechanisms, e.g. ^{11}Li made from spallation of Uranium.
- Fission (HRIBF, ARIEL, ISAC, JYFL, …)
  - There is a variety of ways to induce fission (photons, protons, neutrons (thermal, low, high energy)
  - The fissioning nuclei can be the target (HRIBF, ISAC) or the beam (GSI, NSCL, RIKEN, FAIR, FRIB).
- Coulomb Breakup (GSI) At beam velocities of > 200 MeV/u the equivalent photon flux is so high the GDR excitation cross section is many barns.
- Charge Exchange (GSI, NSCL, FRIB) a neutron or proton can change its charge with a proton or neutron; cross sections can be ≈mb at >100 MeV/u

Courtesy: E. McCutchan

Methods of Production of RIB

- Isotope separator Online (ISOL)

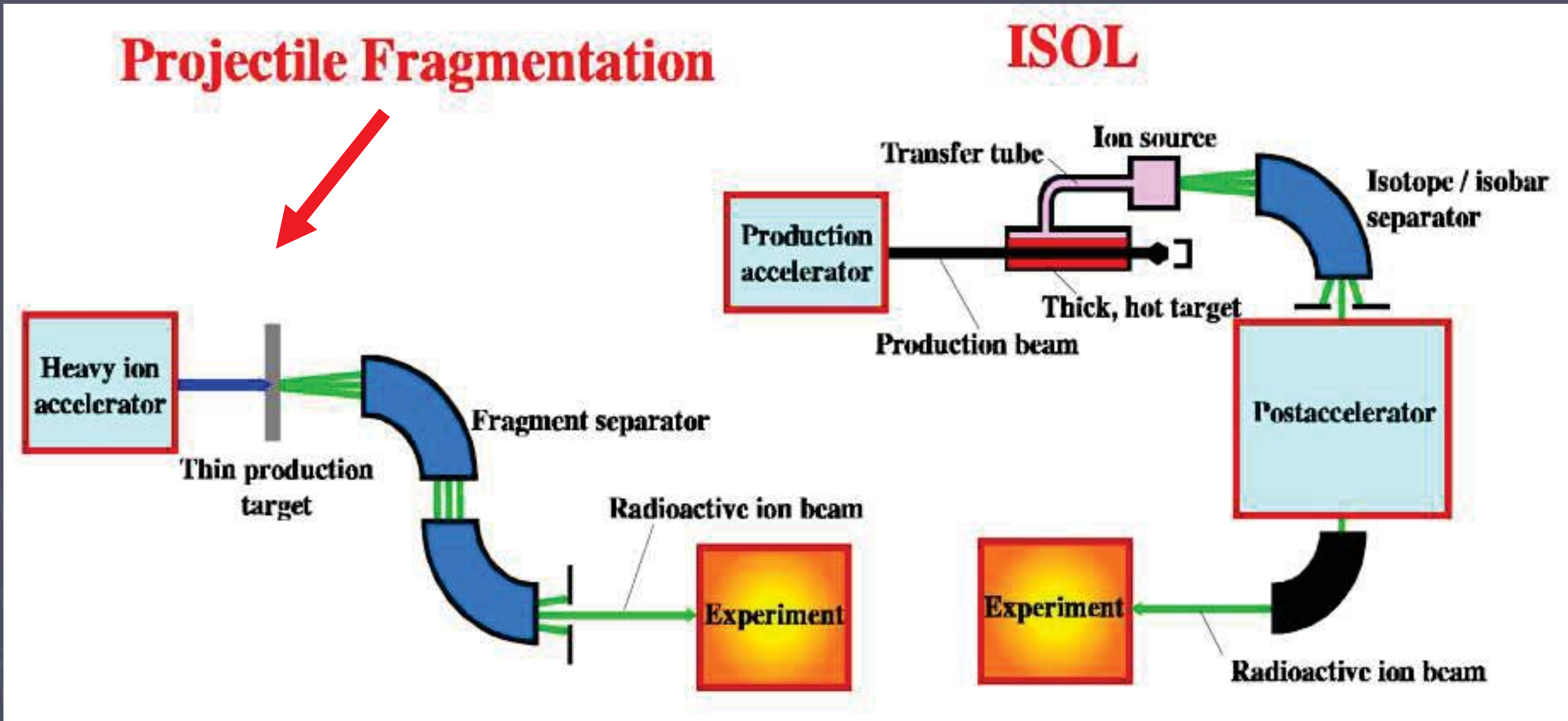
collision, stopped products

reaccelerated

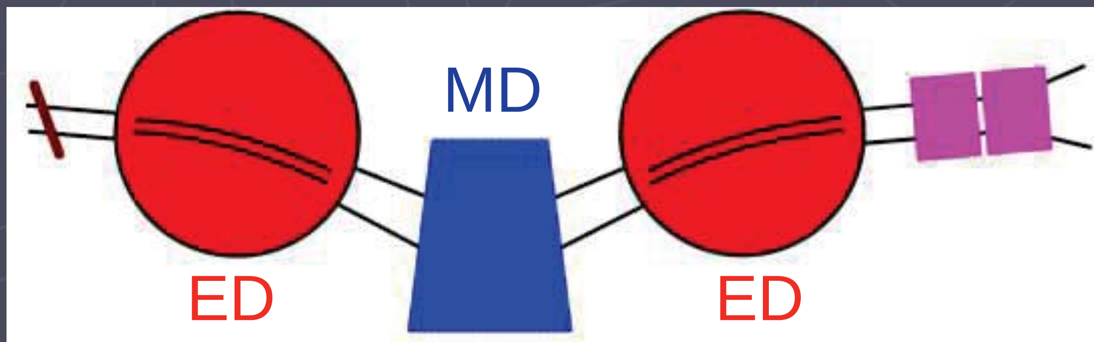
- In flight

high energy collision, fragments "fly" forward

Methods of Production of RIB



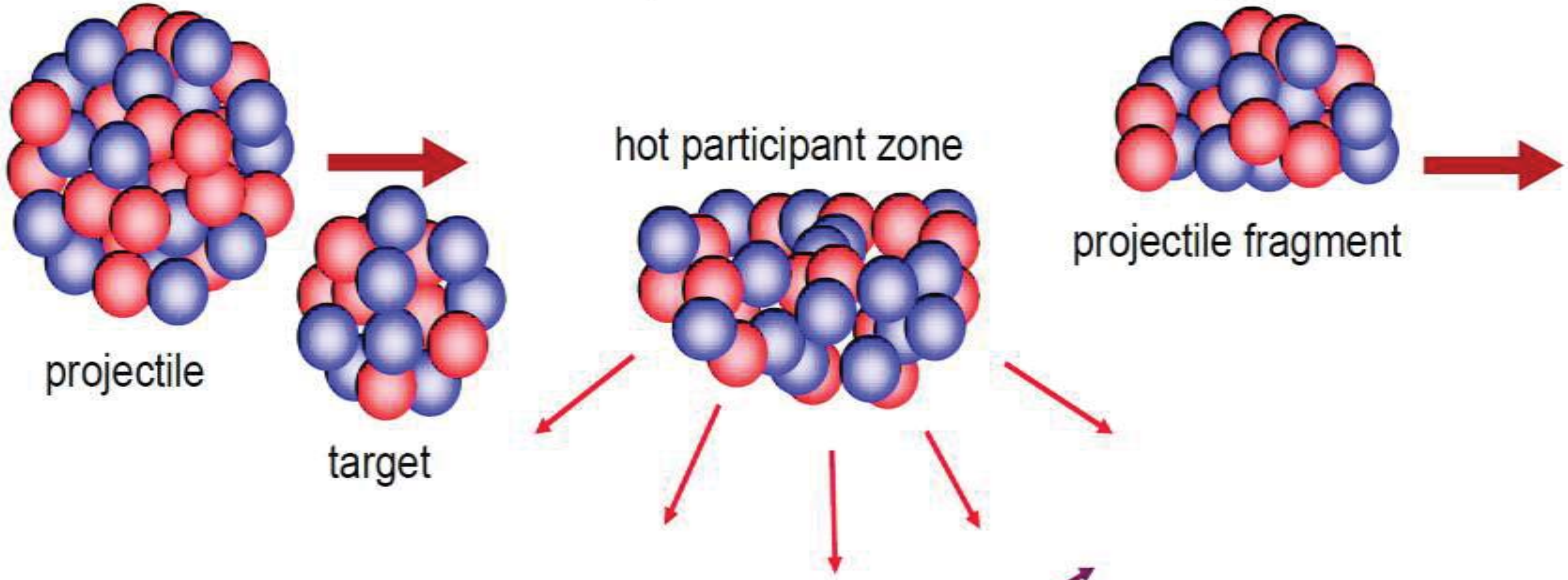
Recoil Separator



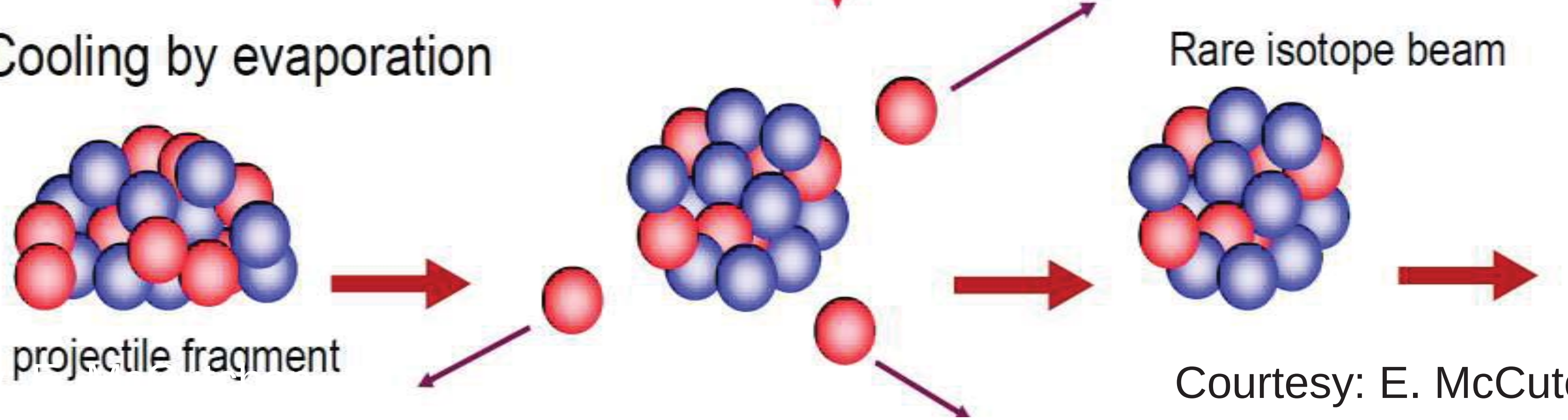
Production of Rare Isotopes in Flight

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

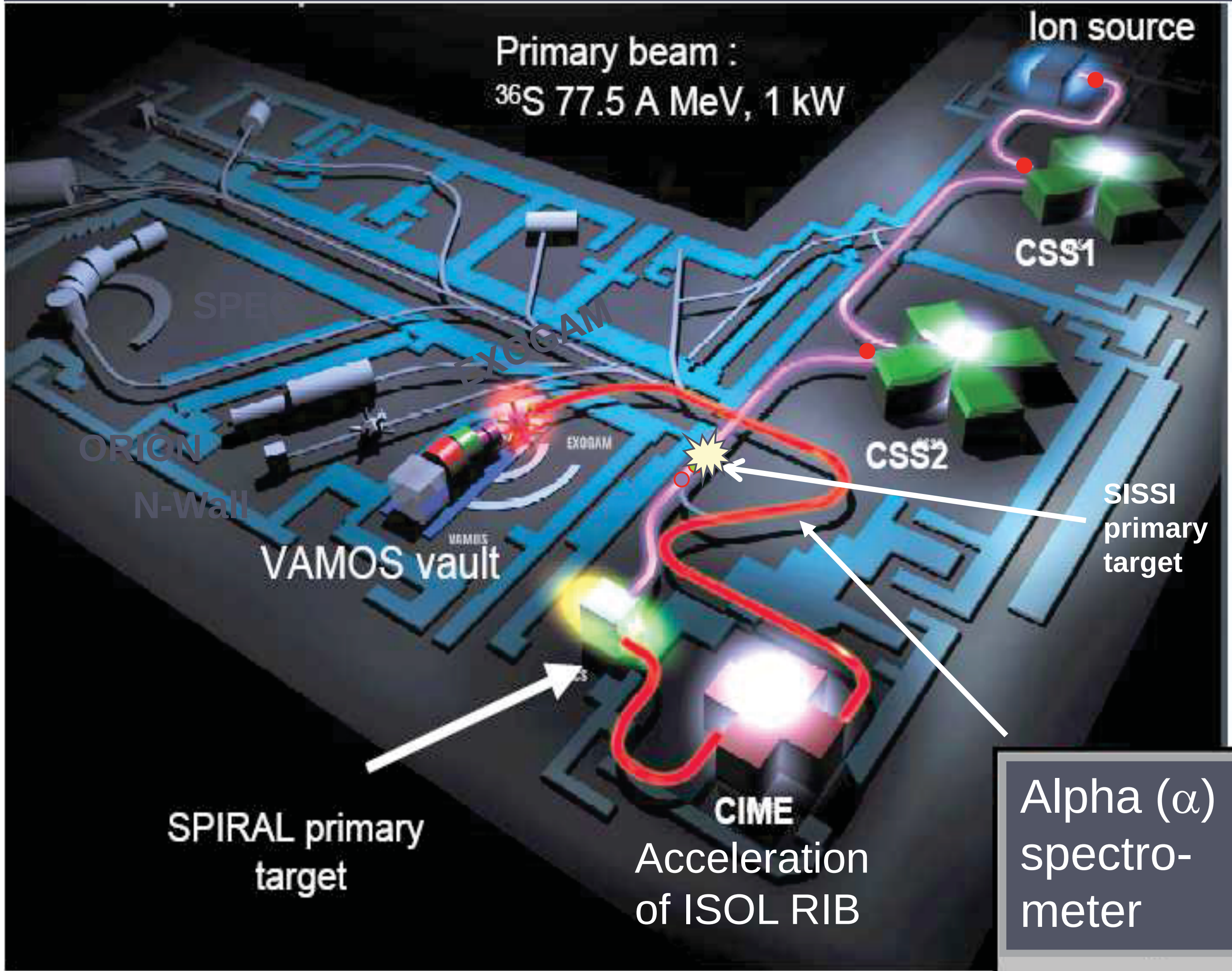


2. Cooling by evaporation



Courtesy: E. McCutchan

Example: RIB facilities at GANIL

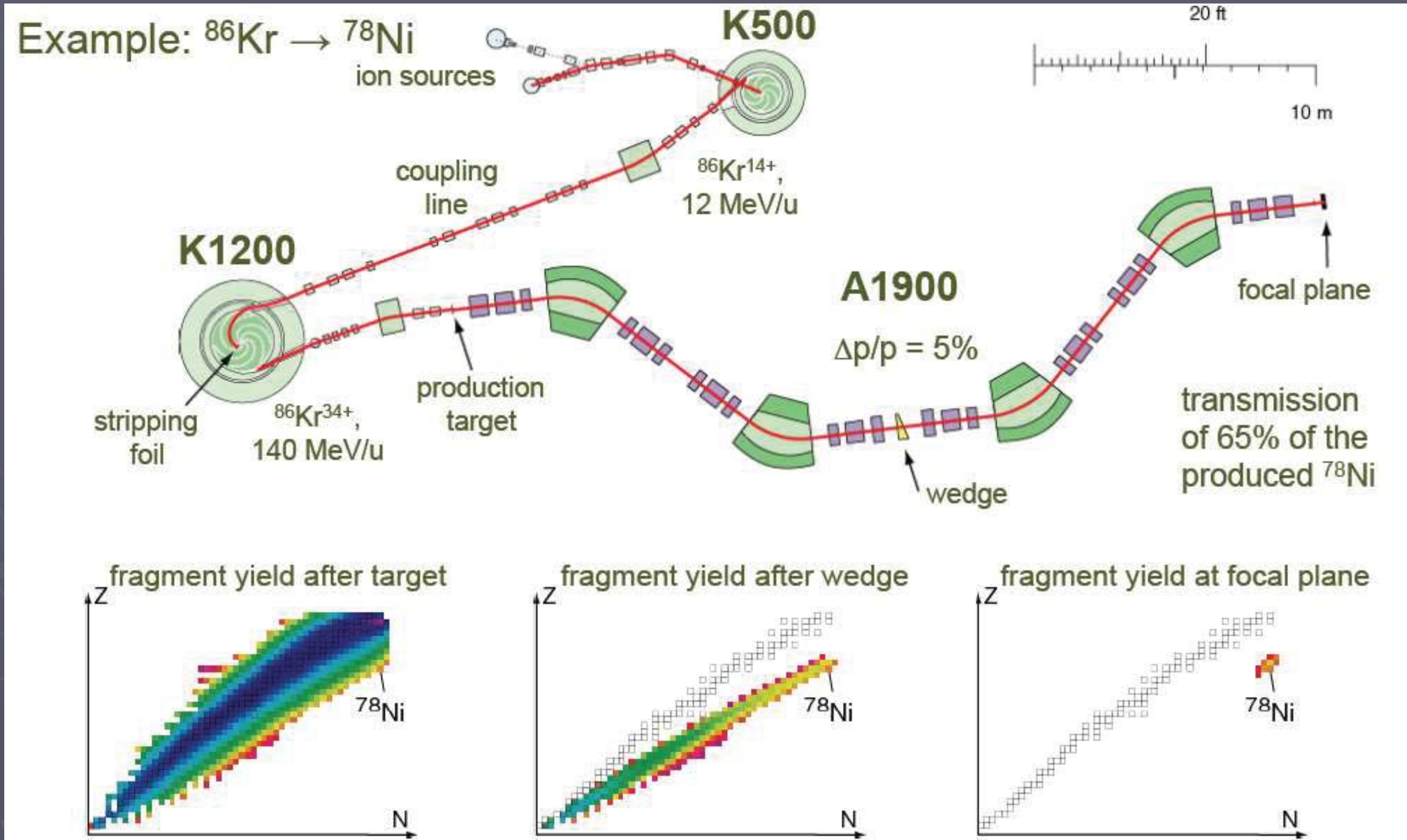


Alpha (α) spectro-meter

Fragmentation with SISSI primary target
- cocktail beam
- E > 25 MeV/A
- Intensity: ~ $10^4 - 10^7$ pps

ISOL type facility SPIRAL

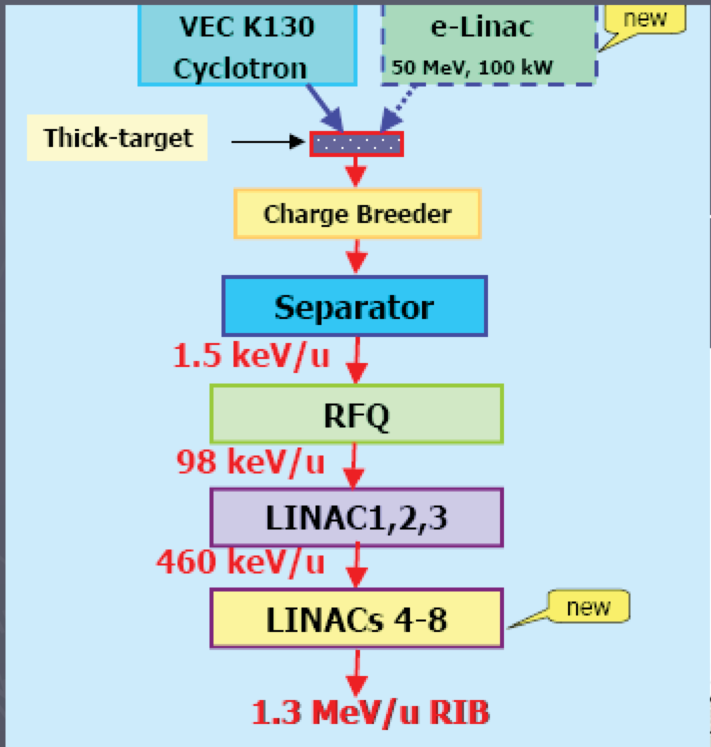
Example: In-Flight Production at NSCL



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

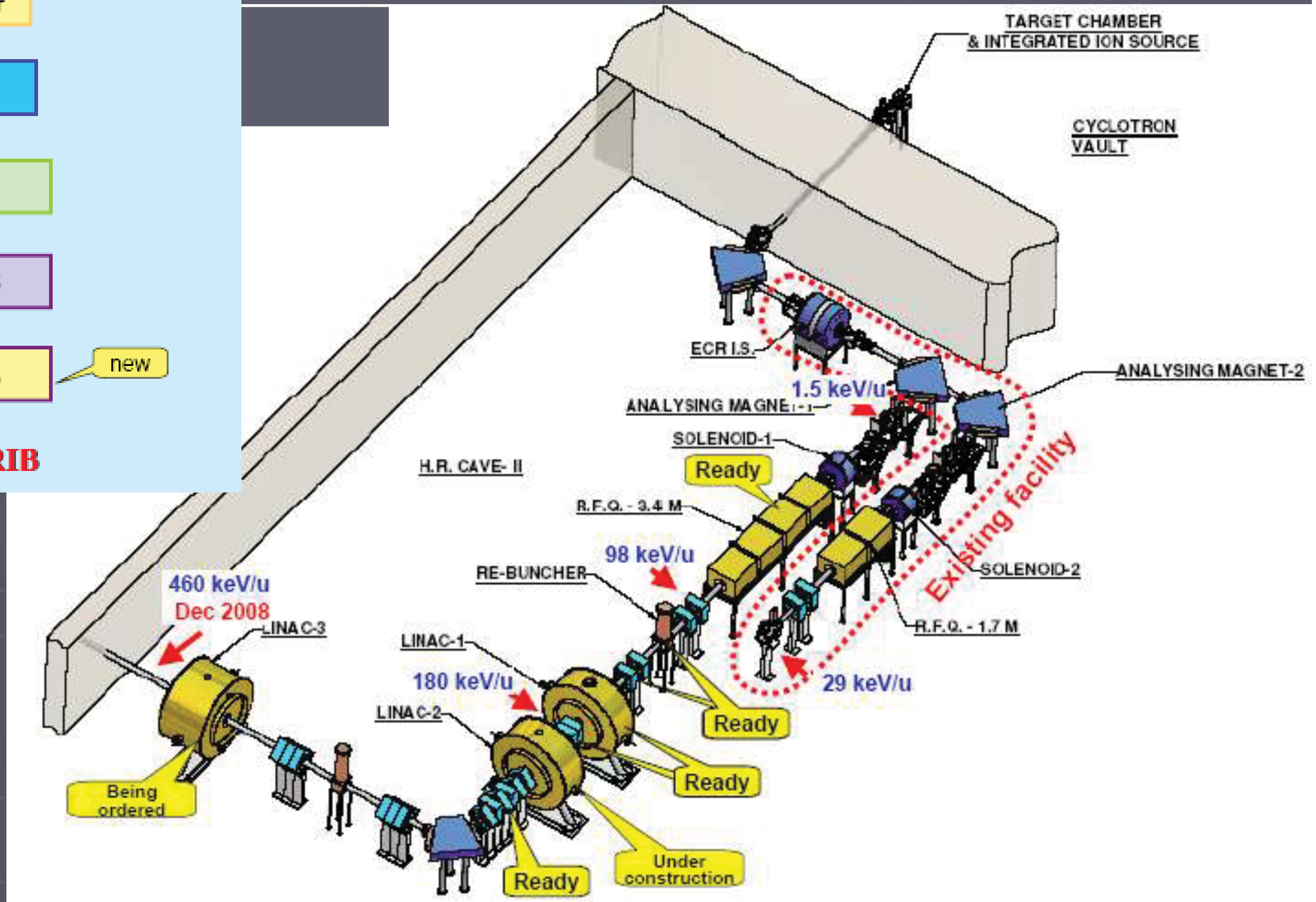
Courtesy: E. McCutchan

RIB Facility at VECC, Kolkata



ISOL Type with α as primary beam

RIB Facility Layout at VECC



Recently extracted beams

^{14}O, ^{41}Ar, $^{42,43}K$

Comparison of the two methods of RIB Production

ISOL Type:

- Low – medium energy
- Nuclei having larger half-life (~ ms and higher)
- pure beam

In Flight:

- Higher energy
- Nuclei having smaller half-life (~ μs)
- Cocktail beam

Experimental Challenges with RIB

- ***What Challenges:***
  - ⇩ Low Intensity (typically 4 to 7 orders of magnitude less than SIB's)
  - ⇩ Short Half-life
  - ⇩ Beam Contaminants
  - ⇩ High β and γ background : Beam is Radioactive !!
- ***How to cope with those:***
  - ⇧ Maximize detection efficiency: Active Target
  - ⇧ Beam identification on event-by-event basis: ΔE-E. ΔE-ToF
  - ⇧ Correlated events only: Coincidence measurements with charged particles, beam particles, recoils, recoil decays etc…
- ***Inverse kinematics and large velocity of recoiling Nucleus:***
  - ⇨ Kinematic focusing: Reaction products are forward peaked
  - ⇨ High velocity of recoils: Large Doppler shift of γ-rays.

Detection Requirement

✓ Beam identification:

- ΔE-E, ΔE-ToF measurements: IC, MCP

✓ Recoil Separation and Identification:

- Large Acceptance Spectrometer, Focal plane detector system (DC, IC, SeD, Si, CsI)

✓ Gamma Ray Detection:

- High efficiency, Good Doppler correction: Granular detectors: EXOGAM, AGATA, GRETA, INGA-II

✓ Correlated particle detection:

- p, α, n detection: Auxiliary detectors

Example: Excited states in Nuclei in the Island of Inversion
Experiment using cocktail beam at GANIL

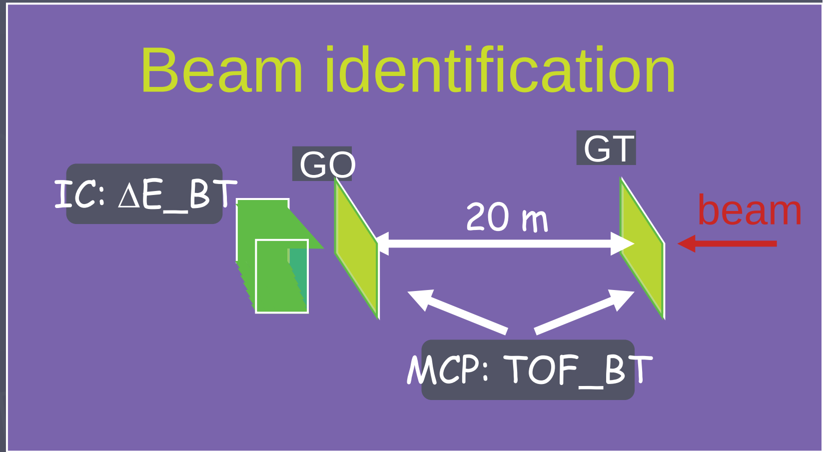
Production of RIB around ^{34}Si and ^{32}Mg: (Fragmentation technique)

Primary beam: ^{36}S (77 MeV/A)

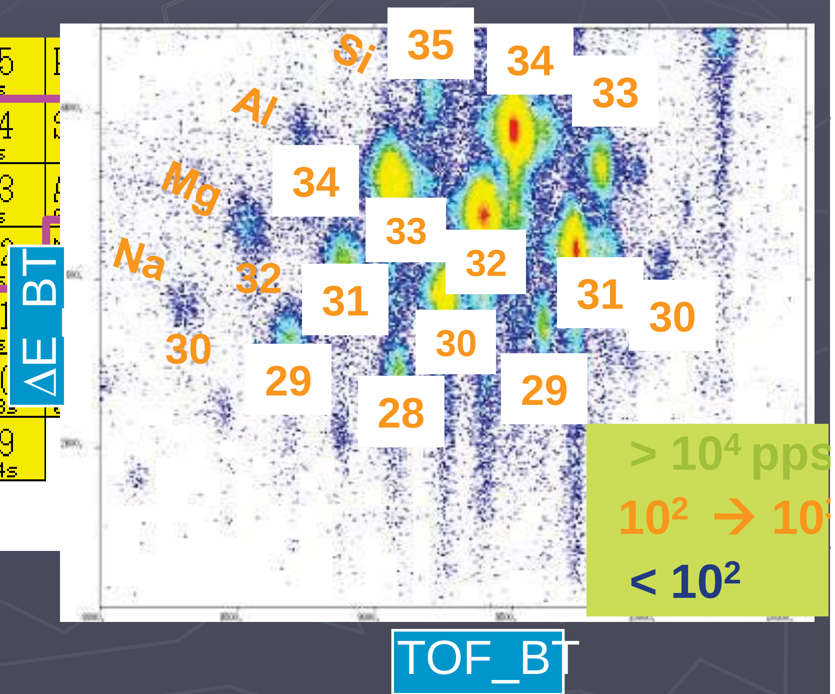
Primary Target: ~ 1gm/cm^2 Ta (SISSI)

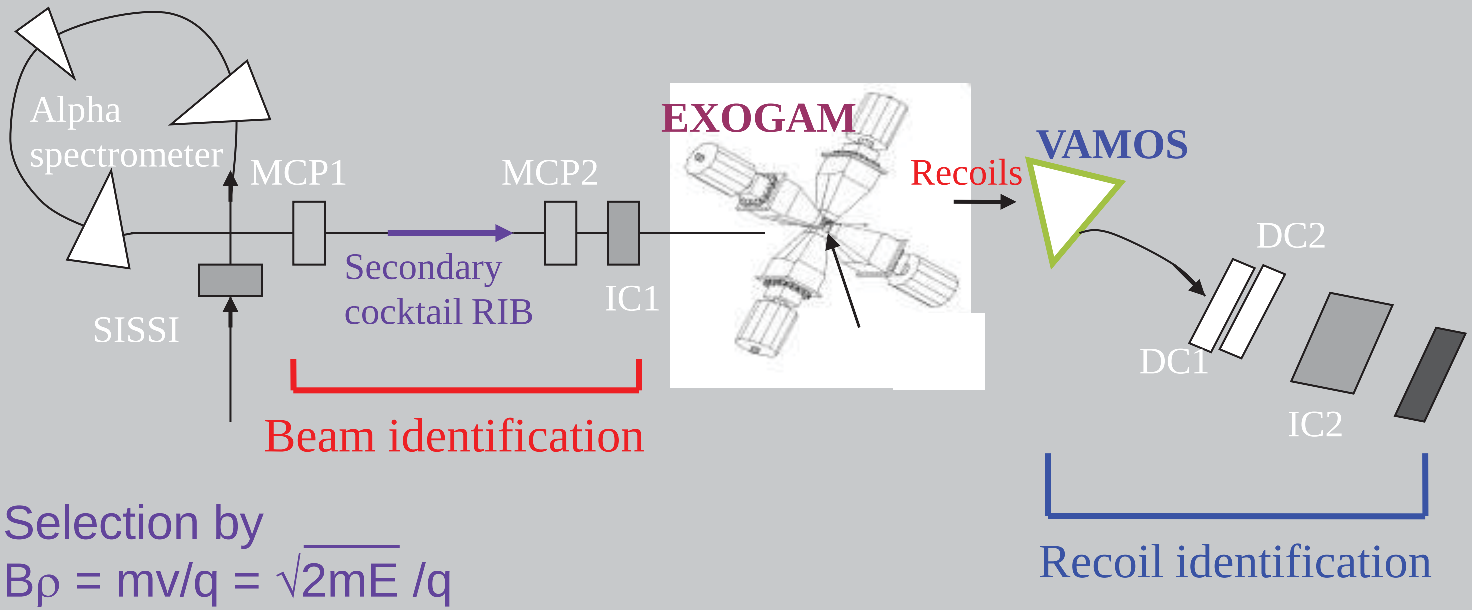
Selection: α- spectrometer

Energy: ~ 30 MeV/A



15	P 27 0.26s	P 28 0.2703s	P 29 4.14s	P 30 2.498m	P 31 100	P 32 14.26d	P 33 25.34d	P 34 12.43s	P 35 47.3s
14	Si 26 2.234s	Si 27 4.16s	Si 28 92.2297	Si 29 4.6832	Si 30 3.0872	Si 31 2.622h	Si 32 172y	Si 33 6.18s	Si 34 2.77s
13	Al 25 7.183s	Al 26 7.4e+05y	Al 27 100	Al 28 2.241m	Al 29 6.56m	Al 30 3.6s	Al 31 0.644s	Al 32 0.033s	Al 33 0.2s
12	Mg 24 78.99	Mg 25 10	Mg 26 11.01	Mg 27 9.458m	Mg 28 20.91h	Mg 29 1.3s	Mg 30 0.335s	Mg 31 0.23s	Mg 32 0.12s
11	Na 23 100	Na 24 14.96h	Na 25 59.1s	Na 26 1.072s	Na 27 0.301s	Na 28 0.0305s	Na 29 0.0449s	Na 30 0.048s	Na 31 0.017s
10	Ne 22 9.25	Ne 23 37.24s	Ne 24 3.38m	Ne 25 0.602s	Ne 26 0.23s	Ne 27 0.032s	Ne 28 0.019s	Ne 29 0.0156s	Ne 30 0.0058s
9	F 21 4.158s	F 22 4.23s	F 23 2.23s	F 24 0.34s	F 25 0.05s	F 26 0.0096s	F 27 0.0052s		F 29 0.0024s
8	O 20 13.51s	O 21 3.42s	O 22 2.25s	O 23 0.082s	O 24 0.065s		O 26 0.00568s		





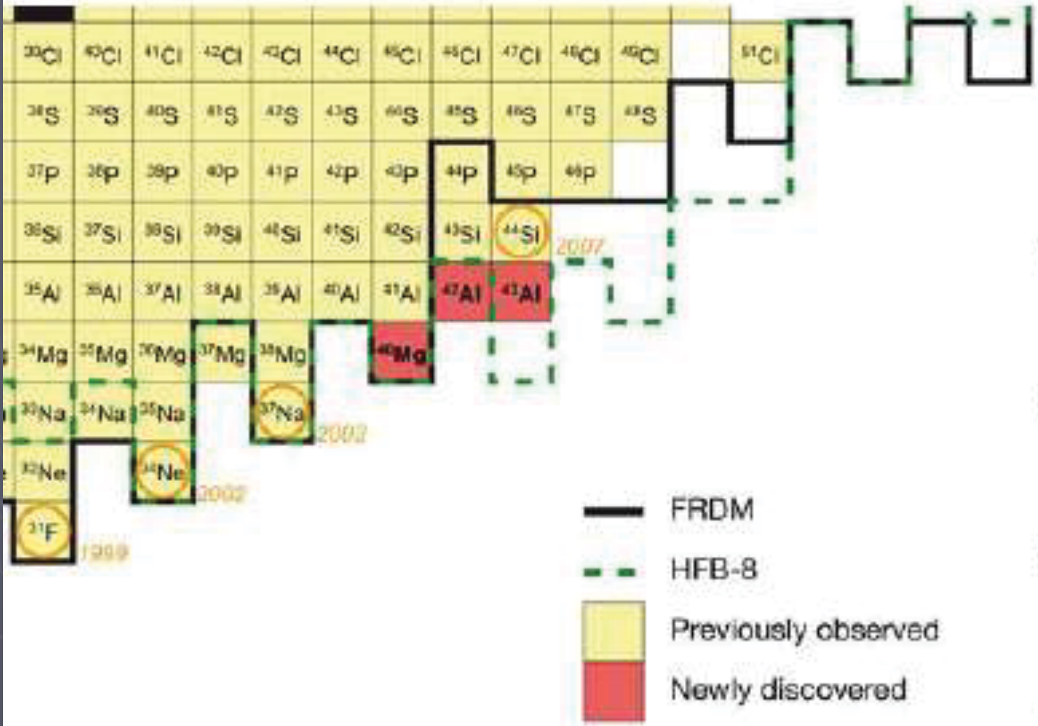
Selection by
$B\rho = mv/q = \sqrt{2mE}\,/q$

Population of excited states:
Target: CD_2 (30 mg/cm^2)
Mechanism: Reactions like
(d,d′), (d,^{3}He), (d,t) …etc.

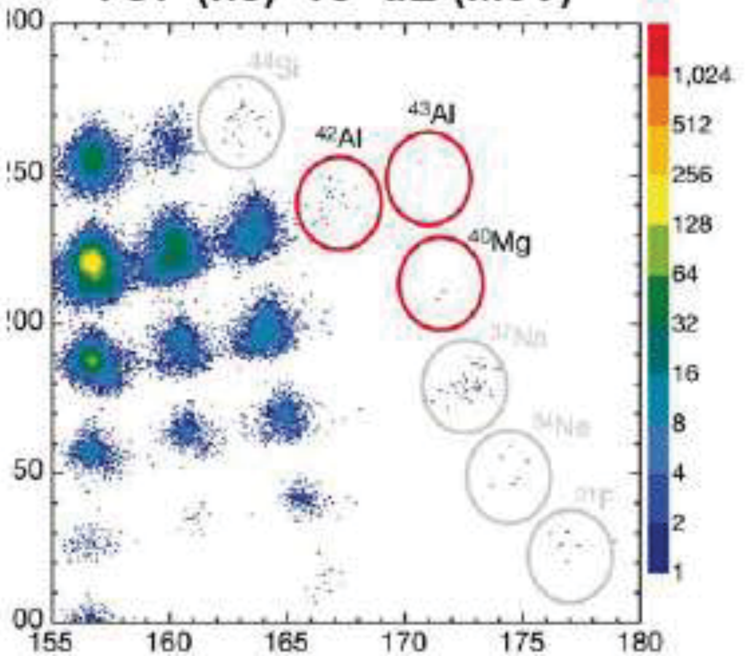
Discovery of ^{40}Mg and ^{42}Al @NSCL

In 2007, exotic neutron-rich nuclei (^{40}Mg and ^{42}Al) have been discovered at NSCL, in the ^{48}Ca + ^{9}Be reaction (≈10days beam time).

T.Baumann et al.,
Nature 449 (2007) 1022



Particle identification plot
TOF (ns) vs dE (MeV)



Upcoming facilities for High Intensity RIB

FAIR at GSI
http://www.fair-center.eu/

SPRIL-2 at GANIL
http://www.ganil-spiral2.eu/spiral2

FRIB at NSCL
http://www.frib.msu.edu/

End of lecture-1