In-beam gamma spectroscopy on unstable nuclei with fast radioactive ion beams

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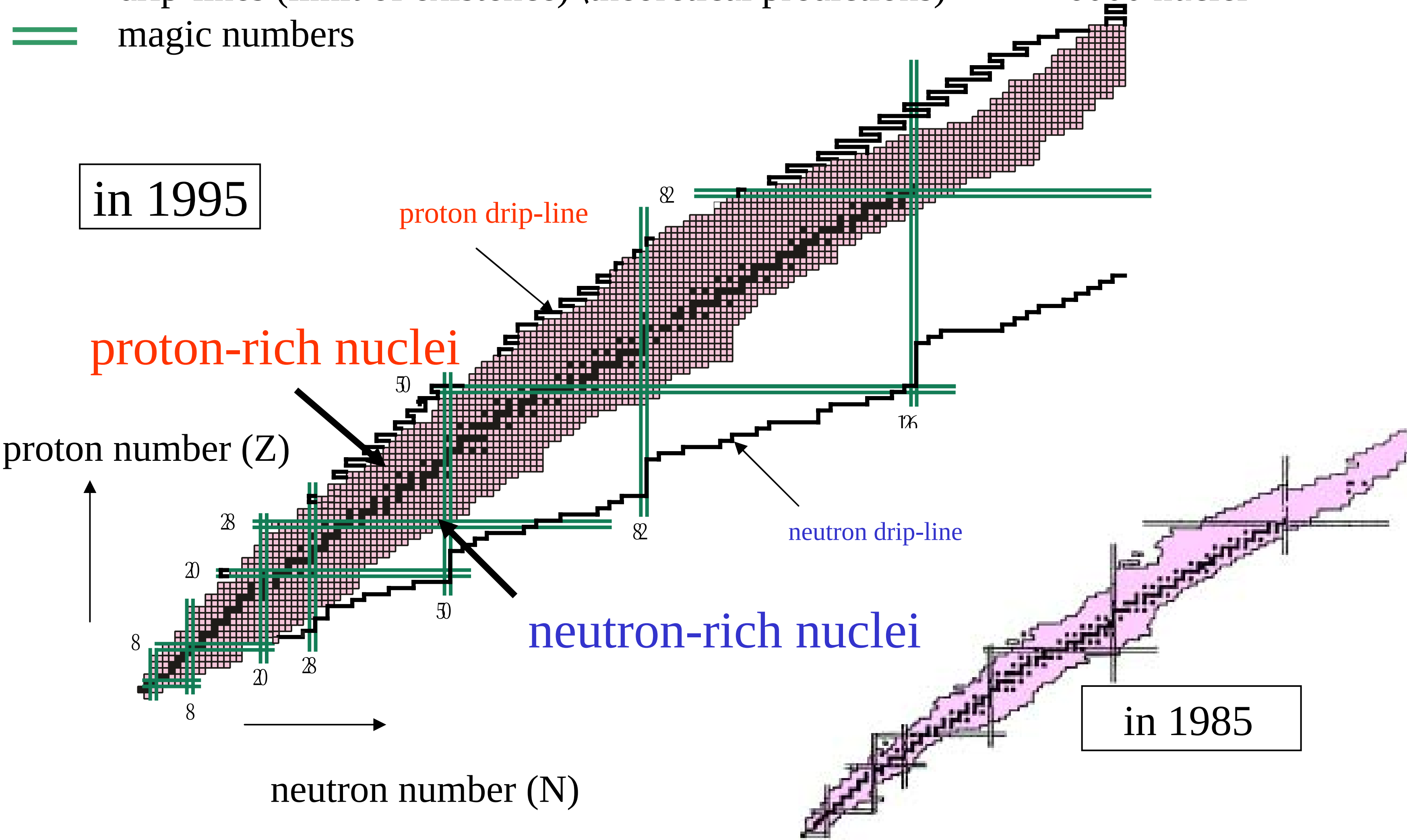
Exploration of the Limit of Existence

■	stable nuclei	~300 nuclei
□	unstable nuclei observed so far	~2700 nuclei
—	drip-lines (limit of existence) (theoretical predictions)	~6000 nuclei
=	magic numbers	



New frameworks for the new region of nuclear chart

from **stable nuclei** to **neutron-rich** nuclei

Nuclear Structure

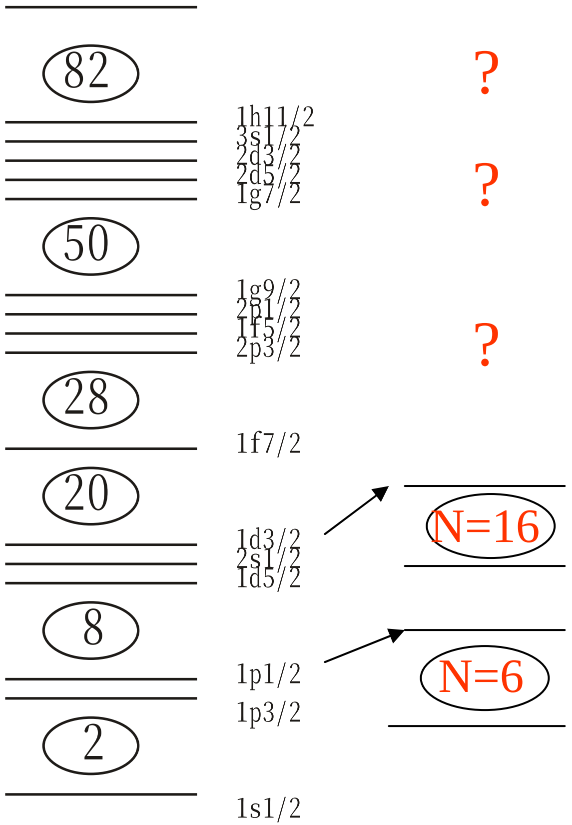
"magicity loss" N=8, 20, ...

"new magic numbers" N=6, 16, ...

large changes of shell structures

Stable Nuclei

Neutron-rich Nuclei



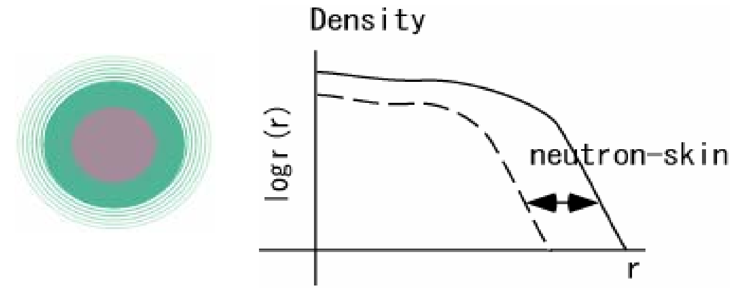
Nuclear Matter

isospin dependence of nuclear radii

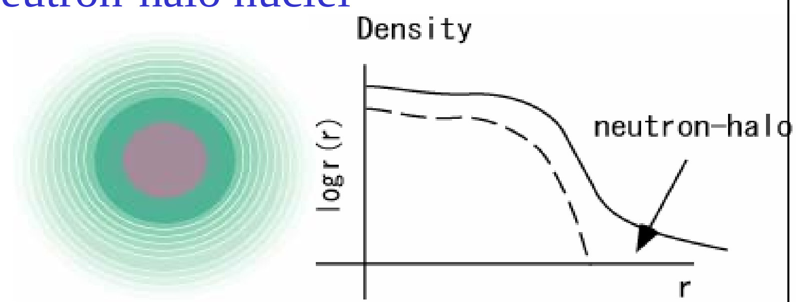
$r = r_0 \times A^{1/3}$ (r_0=1.2 fm) ?

new forms of nuclear matters

neutron-skin nuclei



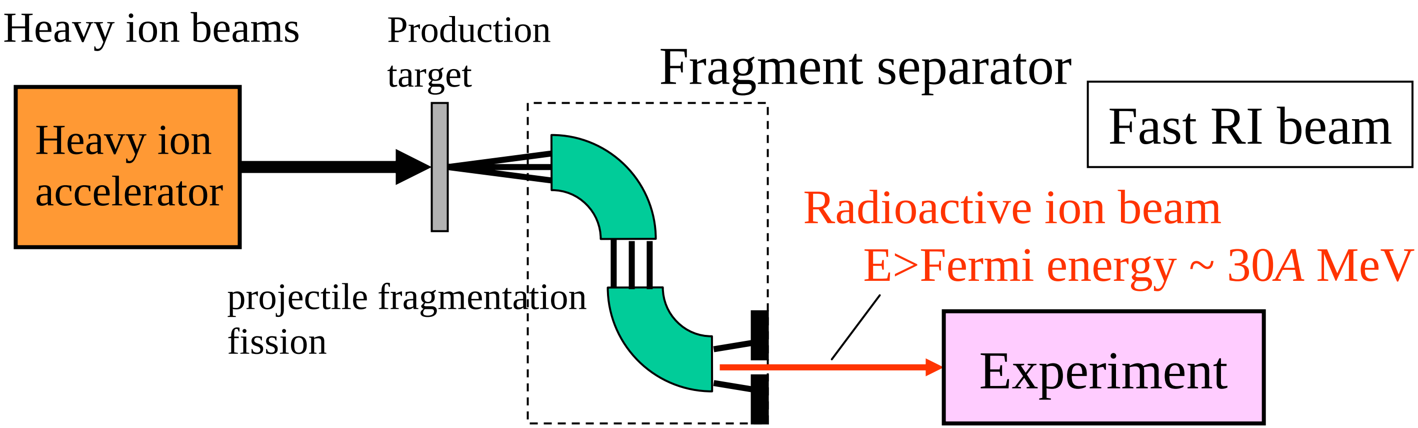
neutron-halo nuclei



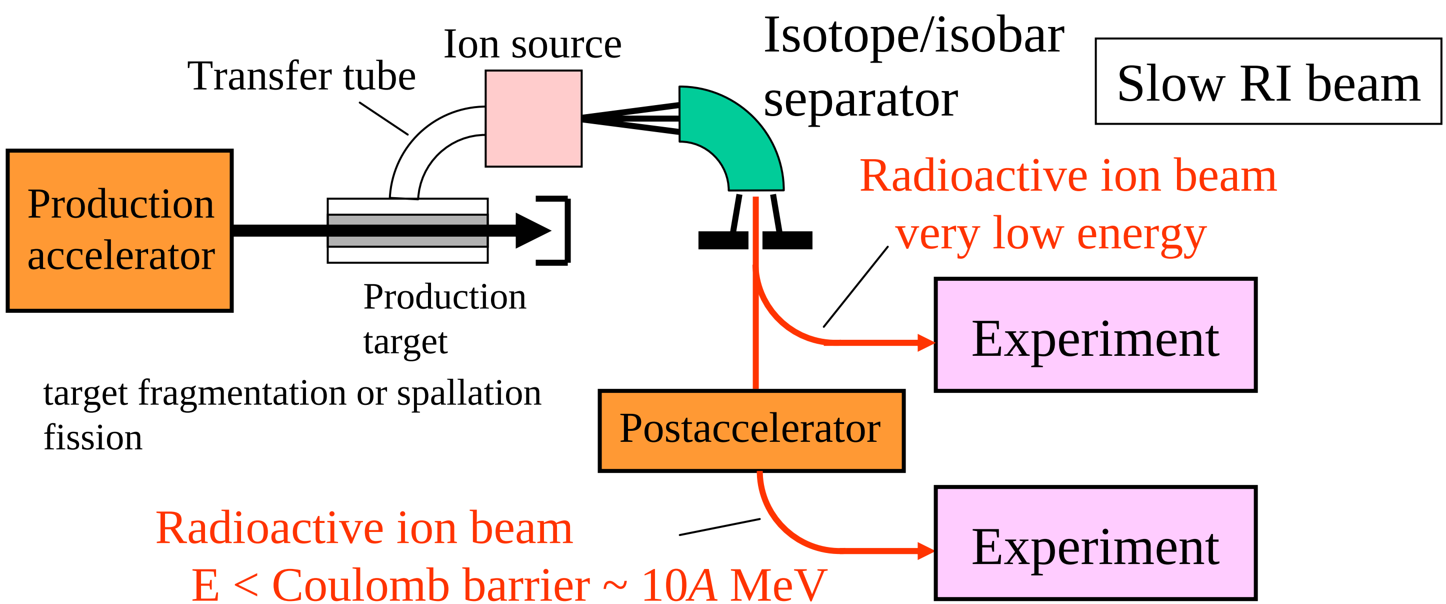
^{11}Be, ^{11}Li, ^{19}C...

In-flight and ISOL methods to produce radioactive ions

In-Flight Method

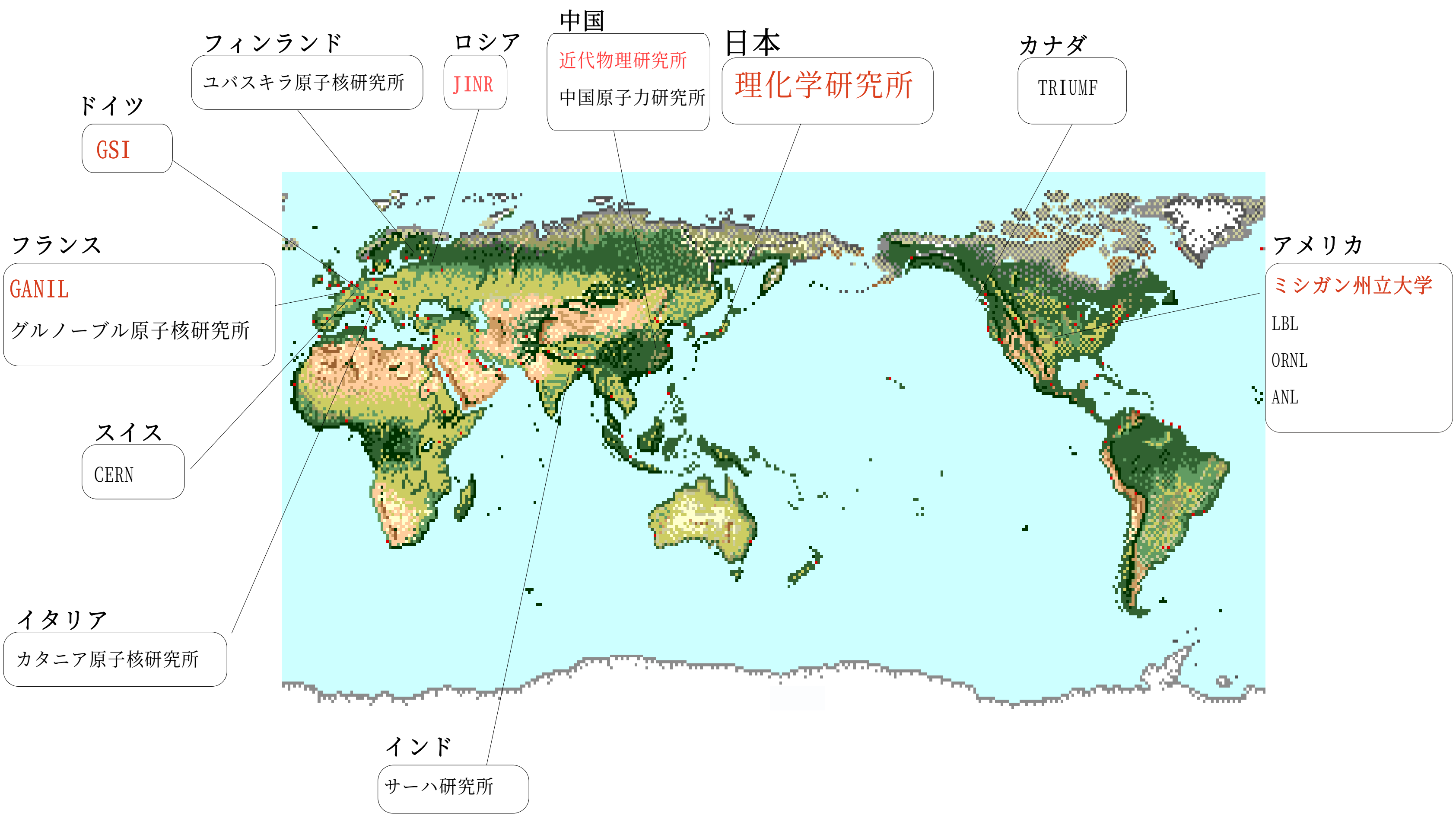


ISOL Method



不安定核研究を推進している研究所

赤色：入射核破砕反応による不安定核生成



RIKEN Facility

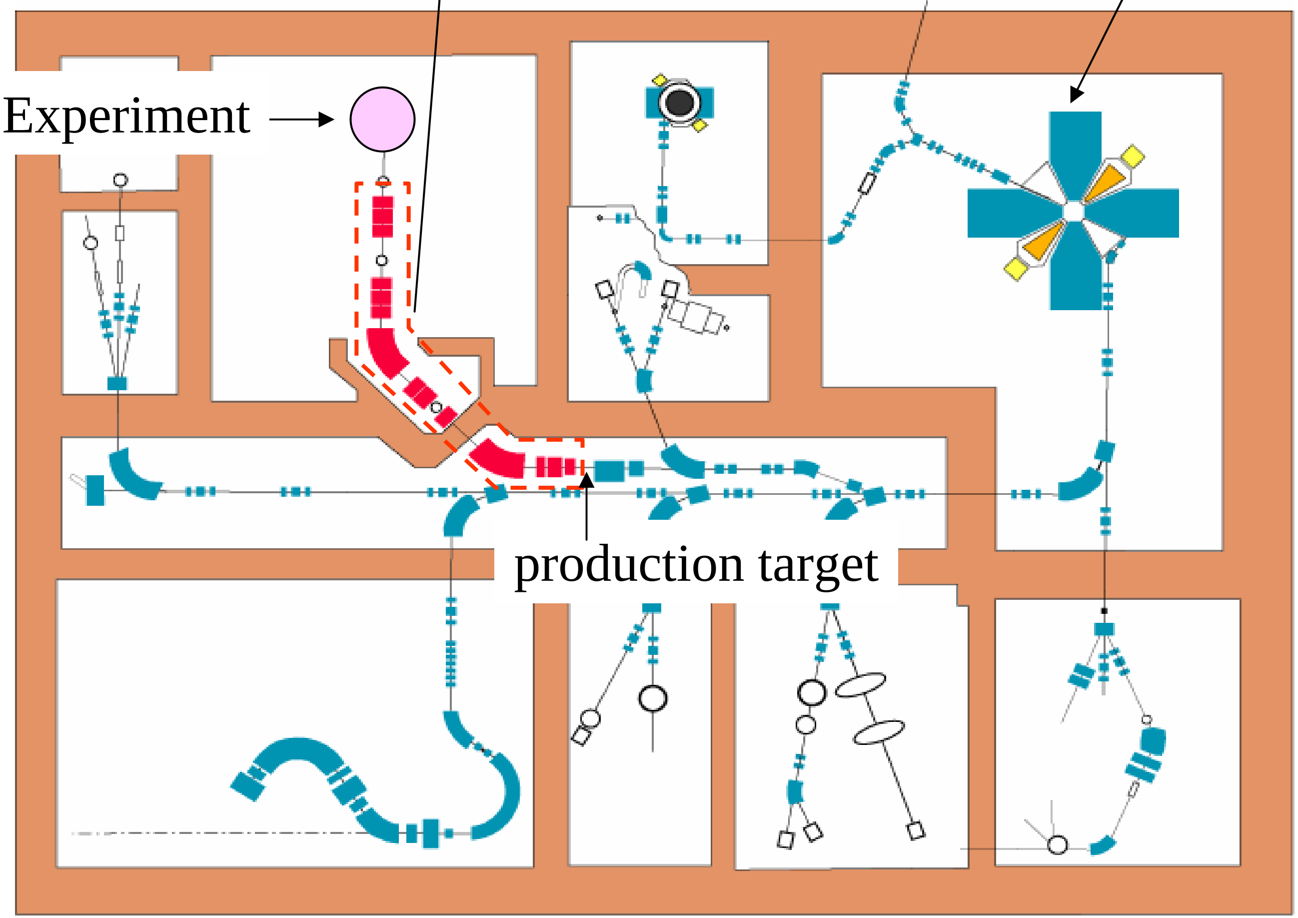
In-flight RI beam production

RIPS (Riken Projectile Fragment Separator)

RIKEN Ring Cyclotron

RI beam E/A~30-90 MeV

Primary beam E/A~64-135 Me

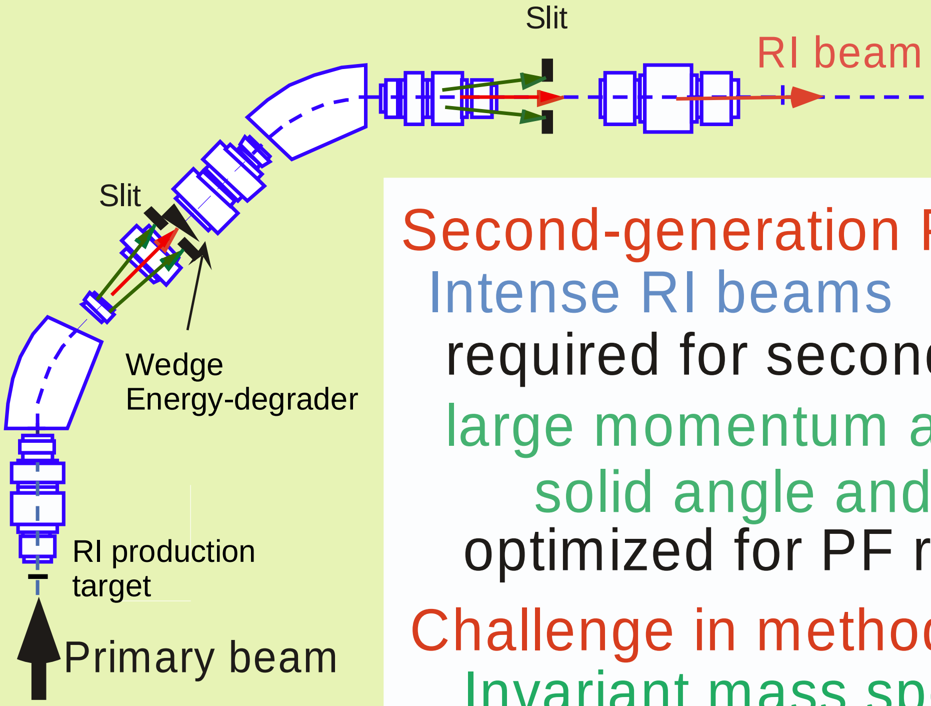


Progress of Research Opportunities with RI Beams

Construction of a dedicated facility for RI beam production
via the projectile fragmentation

RIPS (RIKEN Projectile-fragment Separator)

T.Kubo et al. NIMB70, 309(92)



Second-generation PF separator

Intense RI beams
required for secondary nuclear reactions

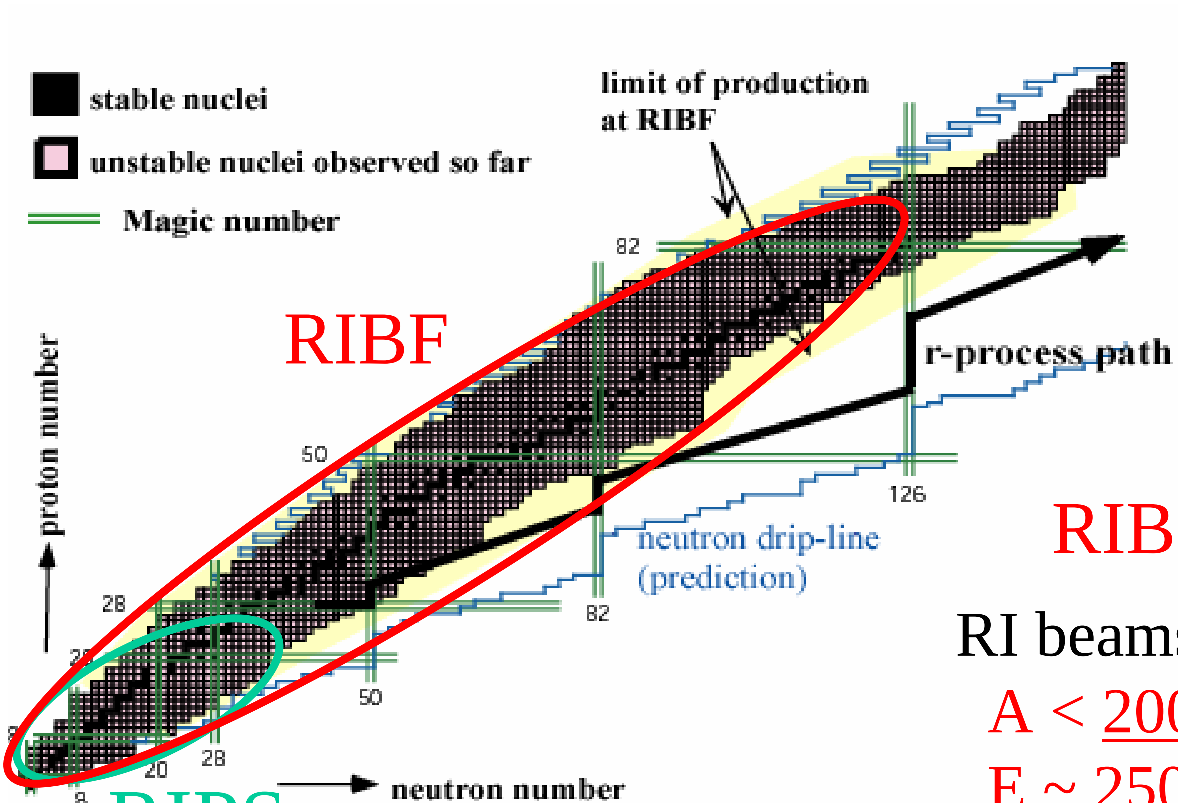
large momentum acceptance,
solid angle and high magnetic rigidity
optimized for PF reaction

Challenge in methodology

Invariant mass spectroscopy
for particle unbound states
Intermediate energy Coulomb excitation
for B(E2)
etc...

RIBF

RI Beam Factory : the 3rd generation facility



RIBF

RI beams

A < 200

E ~ 250A MeV

RIPS

present facility

RI beams

A < 50

E ~ 50A MeV

Investigation on Nuclear Structure via In-beam γ Spectroscopy

- "Magicity Loss" and Collective Motion -

Present Facility RIPS

→ 1. Magicity loss at N~20

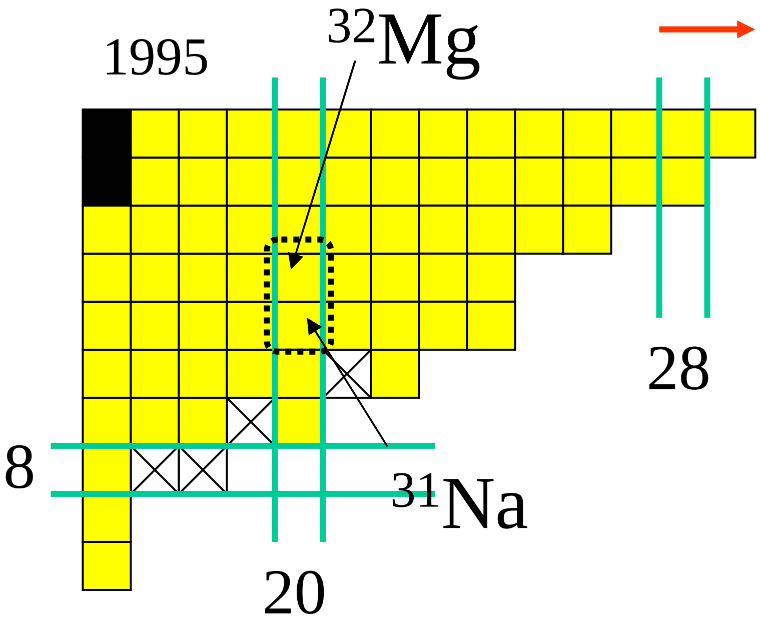
2. ^{16}C

The New Facility RIBF

3. Future

Magicity Loss at N~20

Island-of-Inversion region Z~11 and N~20



upto 1995

Stability

Extra-enhancement of
binding energies around ^{31}Na
mass measurement at CERN-ISOLDE,
LANL-TOFI and GANIL-SPEG

Low lying excited states E(2^+)

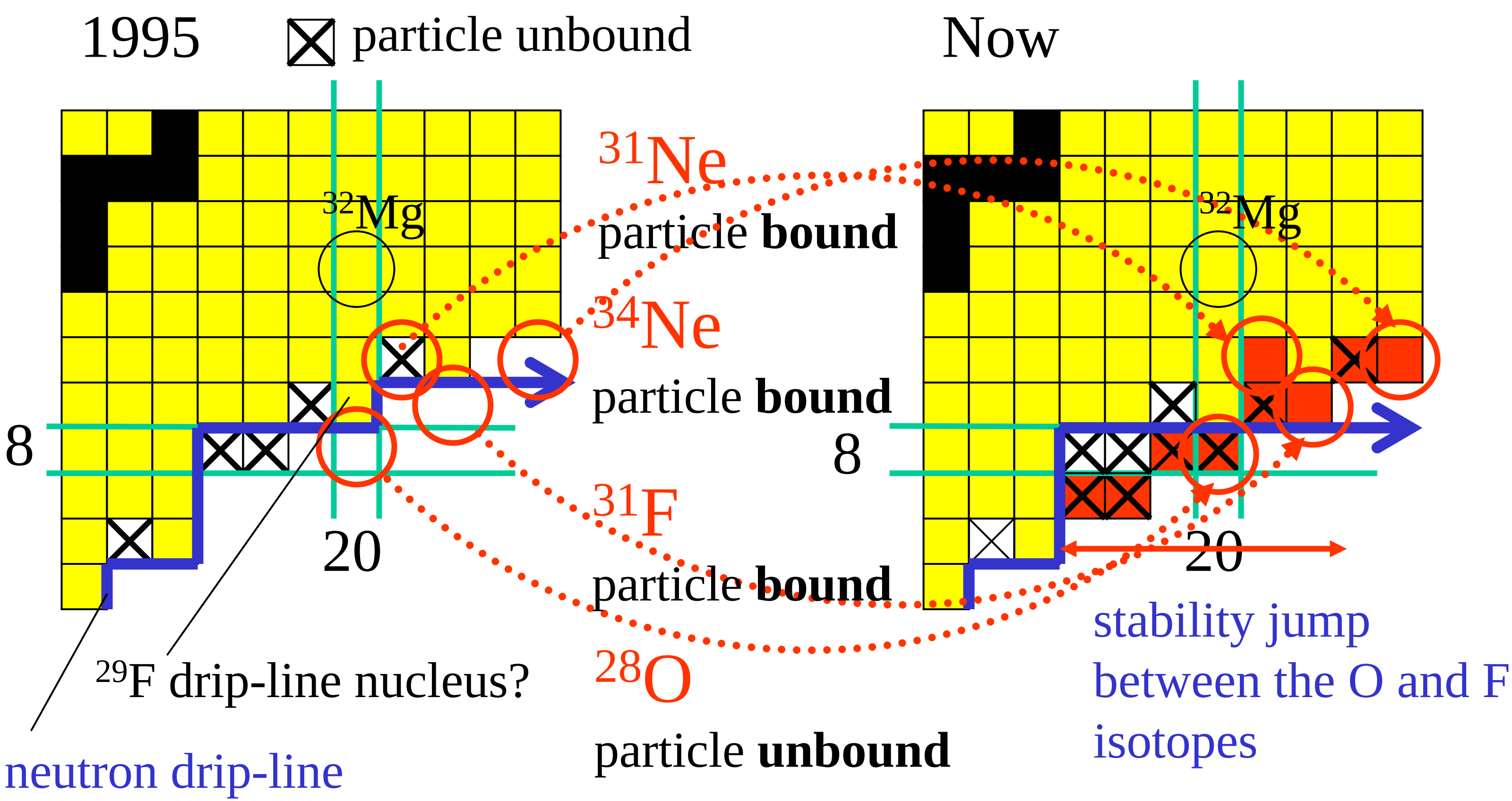
Anomalous energy of E(2^+) of ^{32}Mg
β-γ-spectroscopy at CERN-ISOLDE

B(E2)

Large B(E2) ^{32}Mg
In-beam γ-spectroscopy at RIKEN
Coulomb excitation at intermediate energies

Stability Enhancement in the neutron-rich F and Ne isotopes

Search for new neutron-rich nuclei at RIKEN-RIPS from 1996 to 2002

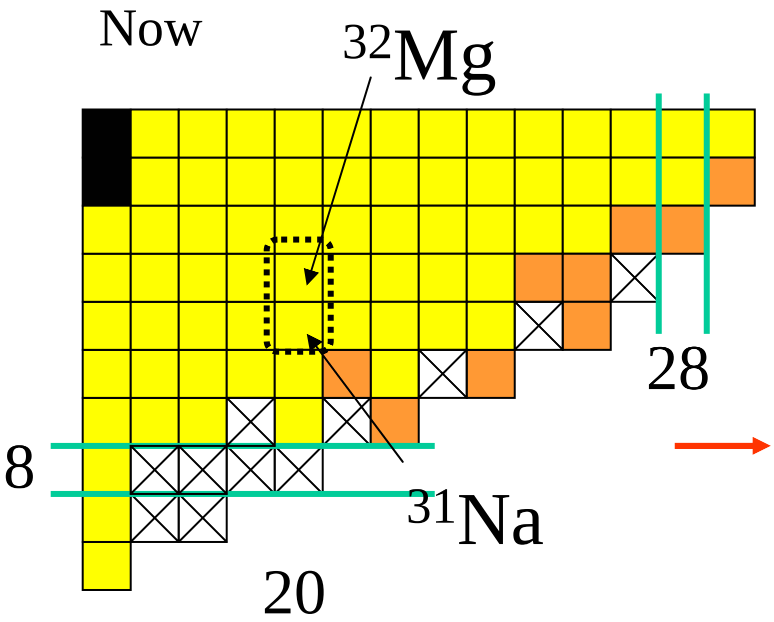


^{31}Ne, ^{37}Mg — H.Sakurai et al., Phys. Rev. C 54, R2802 (1996)

^{31}F, ^{28}O, ... — H.Sakurai et al., Phys. Lett. B 448, 180 (1999)

^{34}Ne, ^{37}Na, ^{43}Si, ... — M.Notani et al., Phys. Lett. B 542, 49 (2002)

Island-of-Inversion region
Z~11 and N~20



Stability

Extra-enhancement of
binding energies around ^{31}Na
mass measurement
particle stability ^{31,34}Ne, ^{31}F...

Low lying excited states E(2$^+$)

Anomalous energy of E(2$^+$) of ^{32}Mg
β-γ-spectroscopy at CERN-ISOLDE

B(E2)

Large B(E2) ^{32}Mg
In-beam γ-spectroscopy at RIKEN
Coulomb excitation at intermediate energies

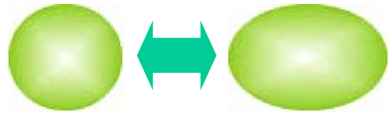
Nuclear Collective Motion

closed shell ↔ open shell

at magic number

spherical nuclei

surface vibration



deformed nuclei

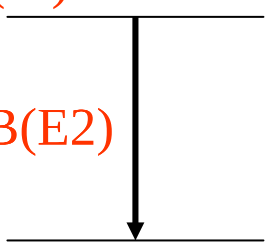
$|\beta| \sim 0$ ← Quadrupole deformation parameter β → $|\beta|$ large

degree of collectivity

Quantum Liquid Drop Model

Even-Even Nuclei

$E(2^+)$



2^+

B(E2)

0^+

ground state

Energy of the first excited state

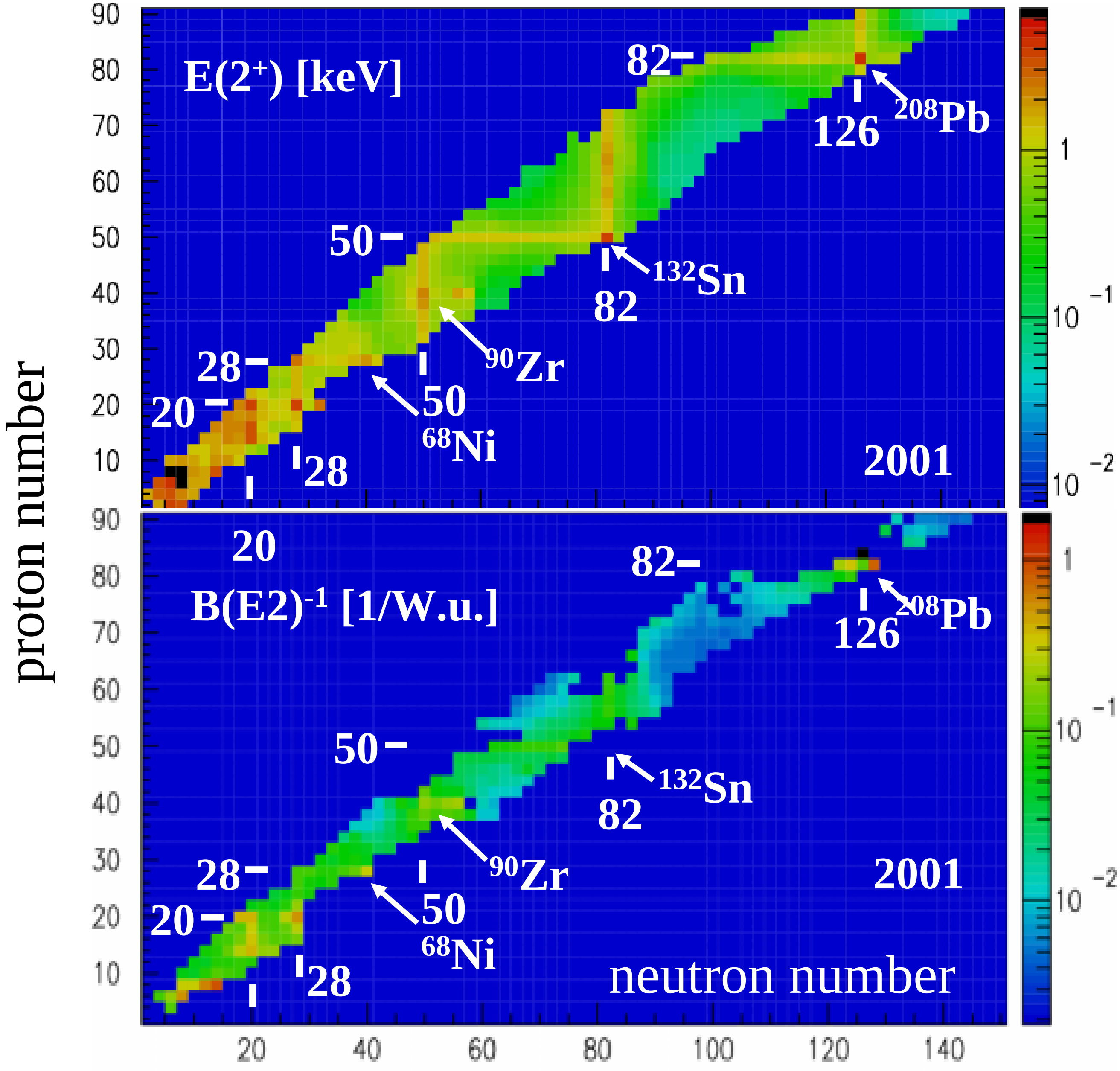
$E(2^+) \propto 1/\beta^2$

E2 transition probability between 2^+ and 0^+

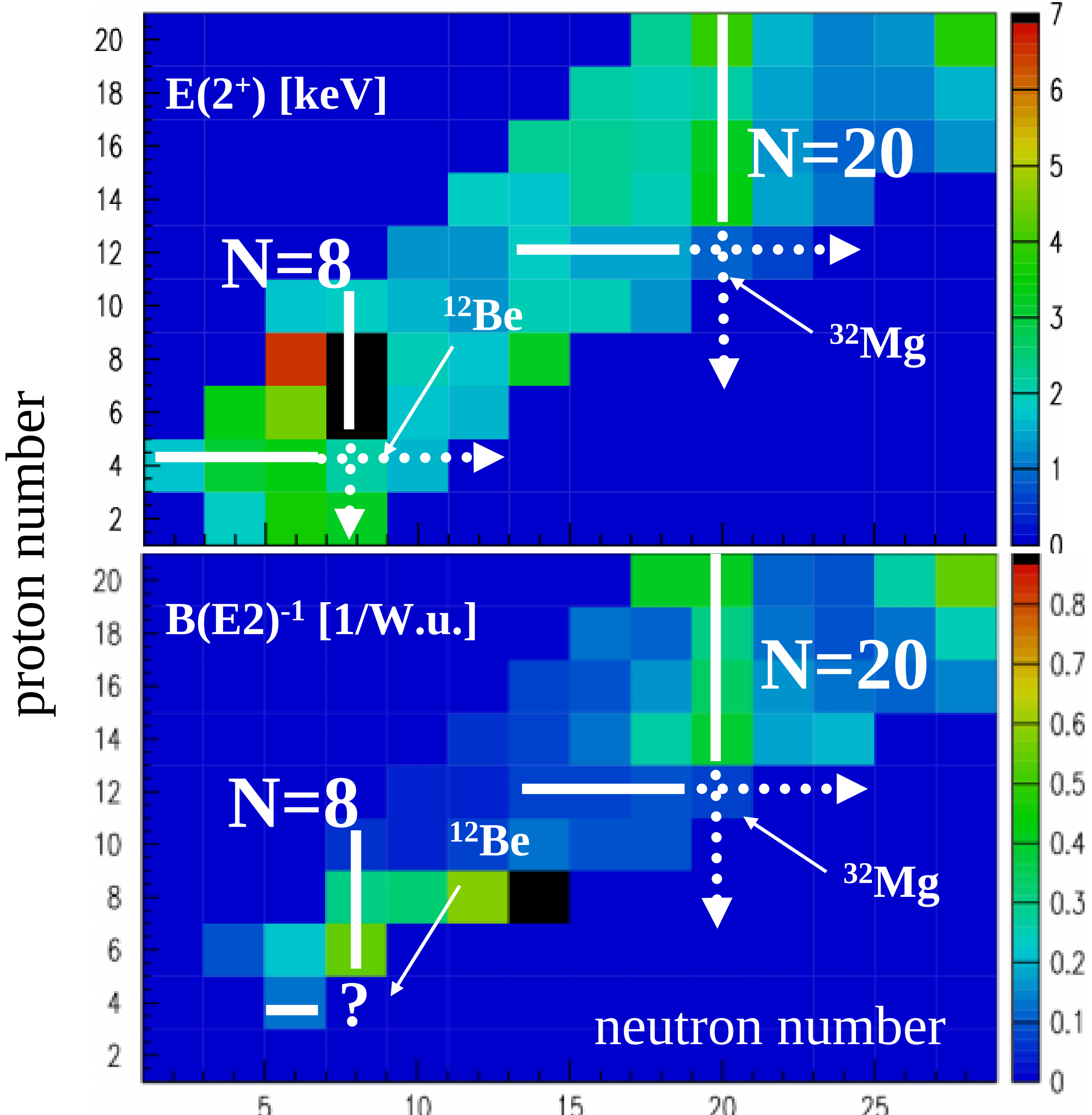
$B(E2) \propto \beta^2$

$E(2^+) \propto B(E2)^{-1}$

Magic number, E(2+) and B(E2)

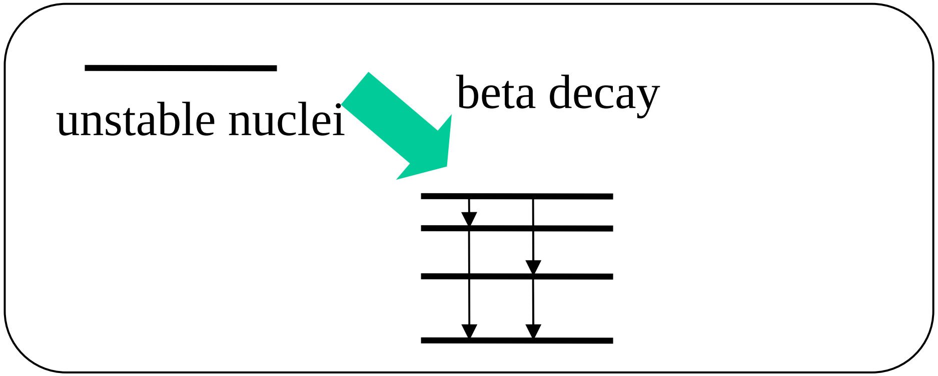


Magicity loss at N=8 and 20



γ-ray spectroscopy on nuclei
for particle-bound states

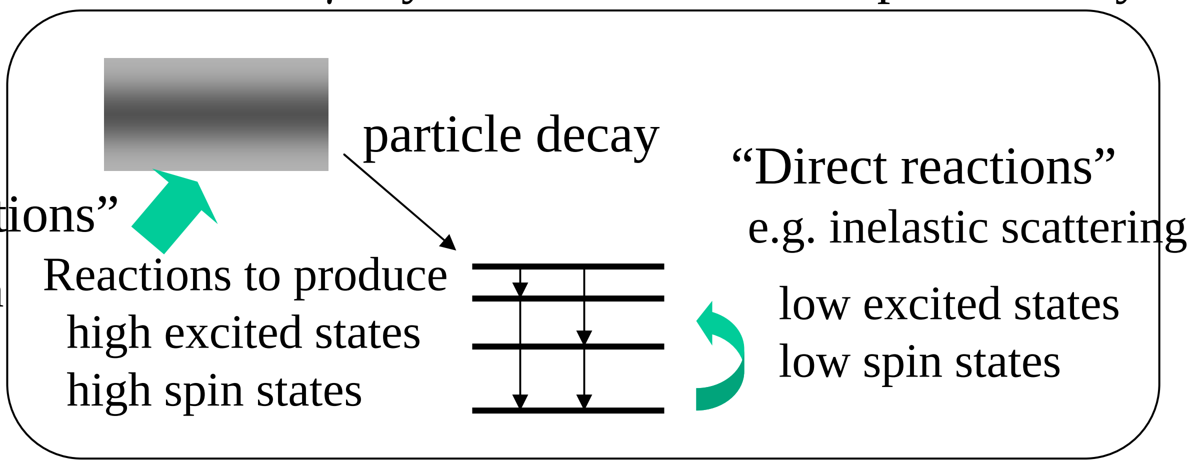
β–γ spectroscopy to observe de-excitation γ-rays in beta decay process



in-beam γ spectroscopy
to observe de-exitation γ-rays from excited states produced by reactions

"Hot reactions"

e.g. fusion



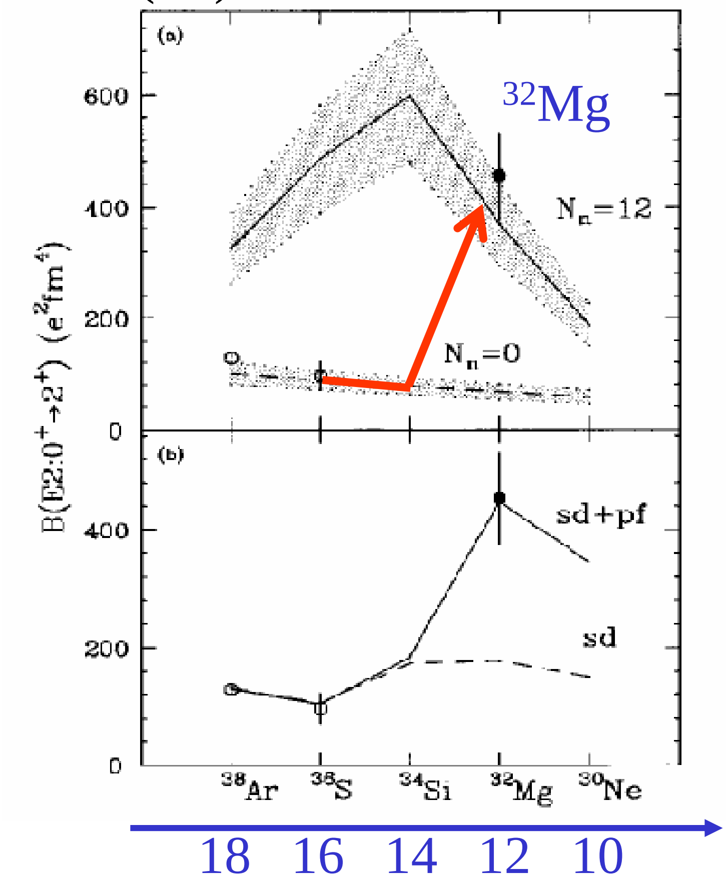
isomer spectroscopy
delayed coincidence measurements through isomeric states....

Large B(E2) observed for ^{32}Mg

The dawn of in-beam γ spectroscopy with fast RI beams

T.Motobayashi, et al., PLB 346, 9 (1995)

B(E2) for the N=20 isotones



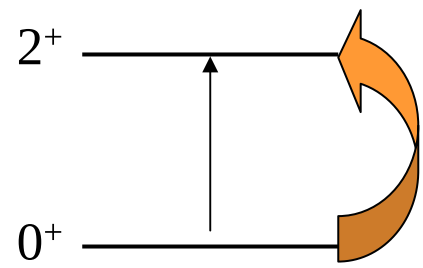
Intermediate energy Coulomb excitation

E ~ 50*A* MeV >> Coulomb barrier ~ 5*A* MeV

inelastic scattering on heavy target such as Pb

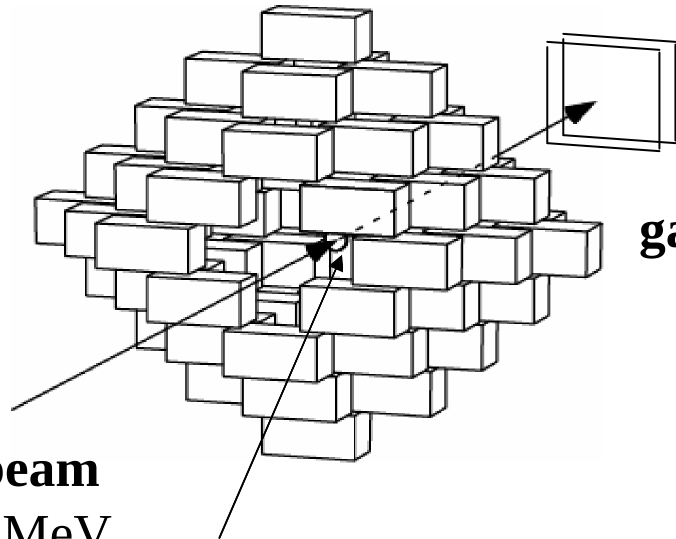
E2 excitation: Coulomb dominant if Z>10

fast interaction -> single step excitation



$\sigma \propto B(E2)$

Experimental setup for in-beam gamma spectroscopy with fast RI beams



RI beam

50 A MeV

target

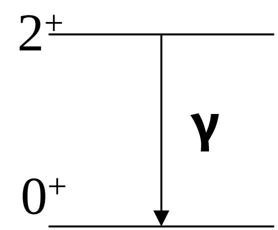
Charged particle detectors

particle identification for ejectiles

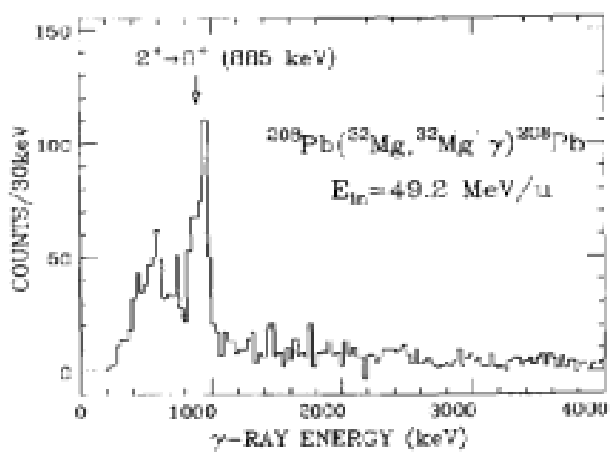
gamma-ray detector array

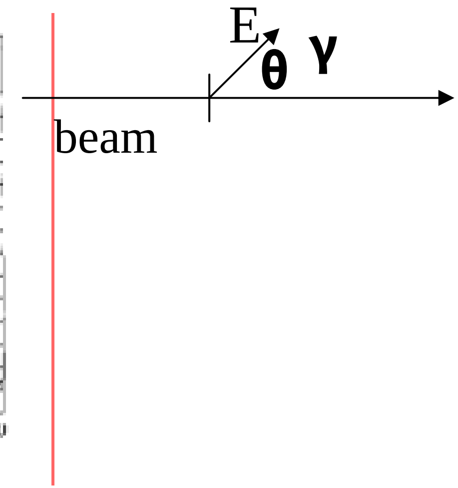
observation of de-excited γ rays

γ-ray energy and emission angle for Doppler correction



NaI detector





Doppler-shift corrected spectrum

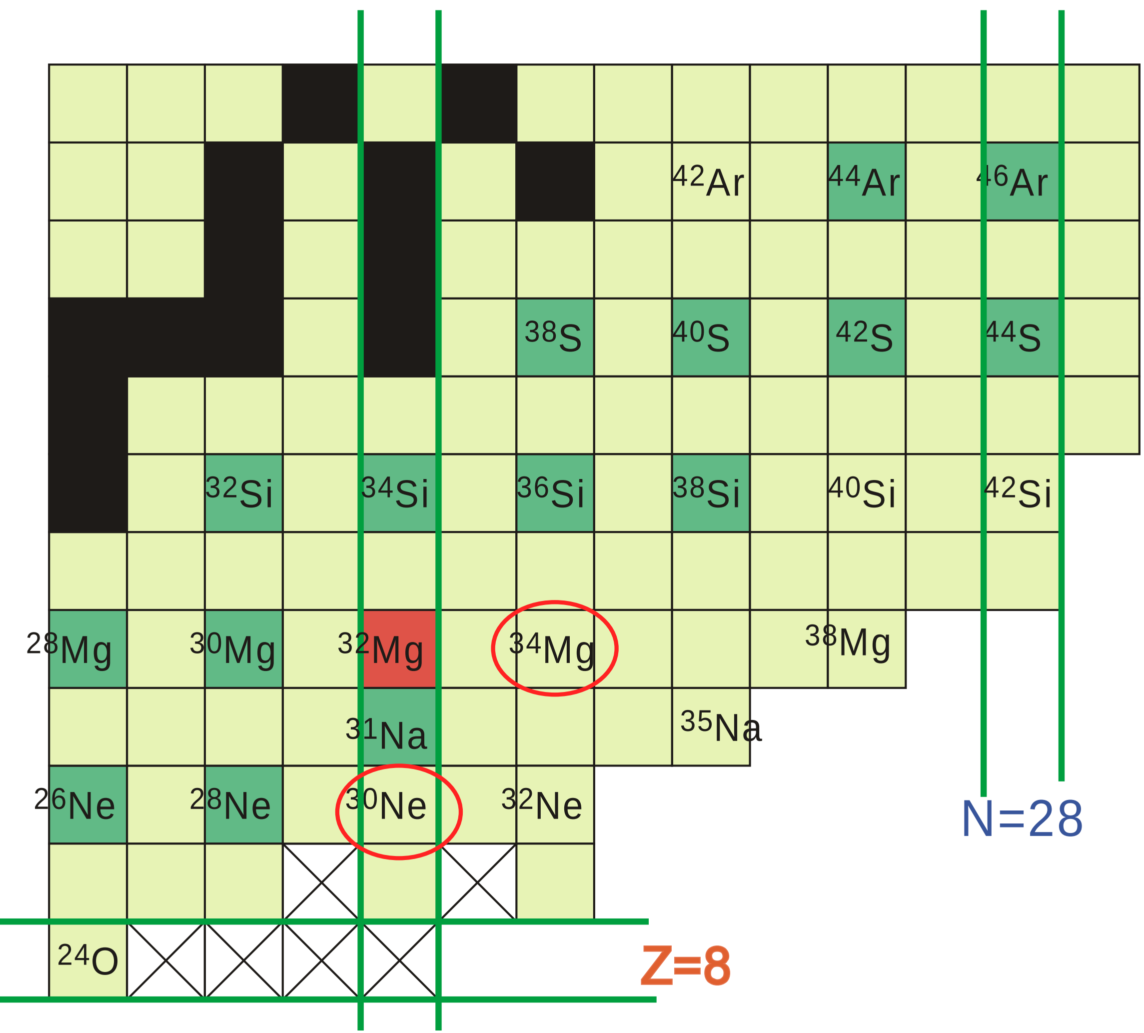
inverse reaction

high energy beam -> thick target

kinematical focusing -> high efficiency

B(E2) and E(2^+) measurements via the Coulomb excitation

From 1995 to 1999



RIKEN

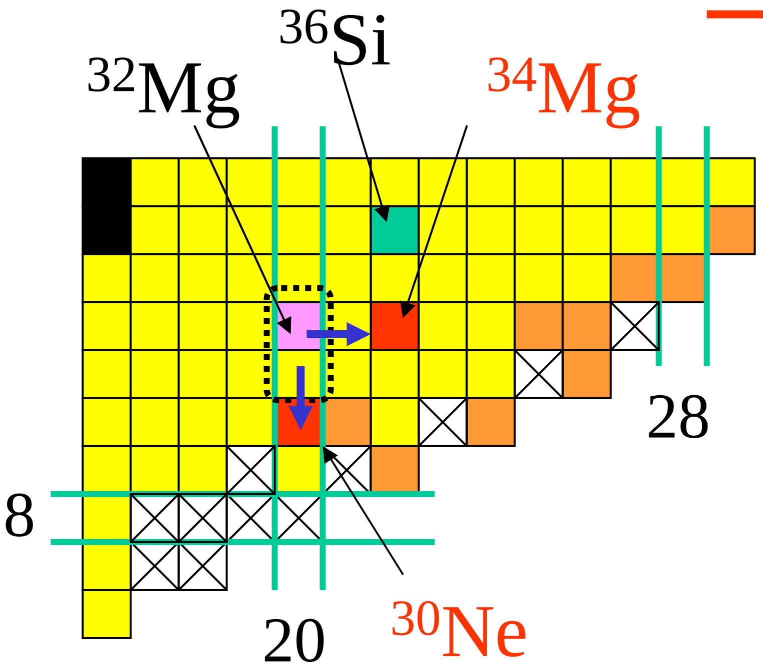
Motobayashi et al.
Phys.Lett. B346, 9 (95)

MSU

Glasmacher's group
Phy.Rev.Lett. 77, 3967(96)
Phys.Lett. B395, 163(97)
Phy.Rev.Lett. 80, 2081(98)
Phys.Lett. B461, 322(99)

Further investigation for the island-of-inversion region

How is the region extended ? lower Z and larger N



^{32}Mg **E(2$^+$)** **ISOLDE**
B(E2) **RIKEN**
E(4$^+$)/E(2$^+$) **GANIL**

^{34}Mg E(2$^+$), B(E2)

Coulomb excitation

^{34}Mg beam + Pb target

intensity ~3/sec

^{30}Ne E(2$^+$)

proton inelastic-scattering

^{30}Ne beam+ hydrogen target

intensity ~0.3/sec

^{34}Mg E(2$^+$), E(4$^+$) for E(4$^+$)/E(2$^+$)

RI beam fragmentation method

projectile fragmentation reaction

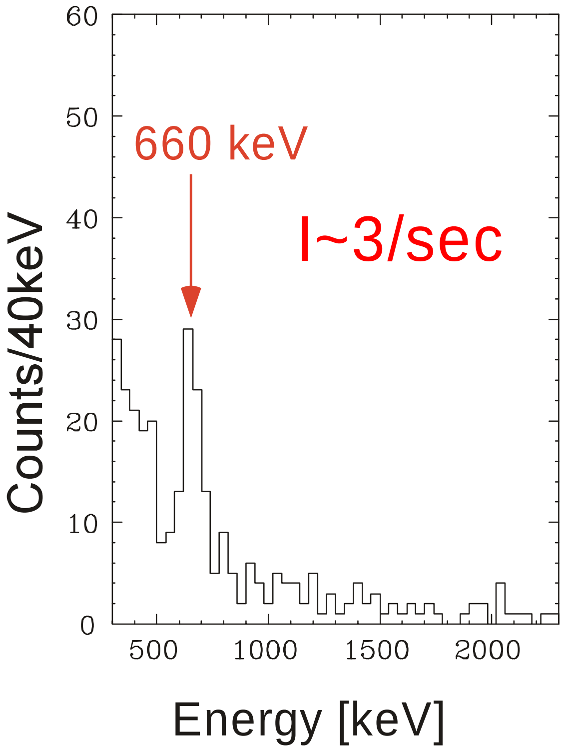
^{36}Si beam + Be target

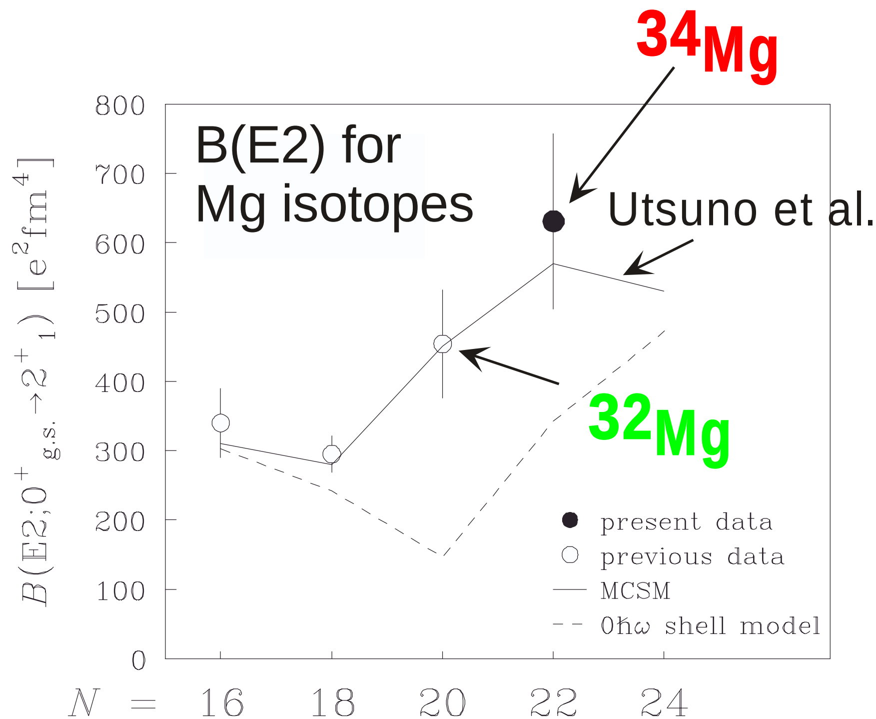
intensity ~10^4/sec

Gamma-ray spectroscopy of ^{34}Mg via the Coulomb excitation

Iwasaki et al., Phys.Lett. B 522, 227(2001)

B(E2) of ^{34}Mg larger than that of ^{32}Mg





c.f. I ~ 300/sec for ^{32}Mg

E(2$^+$) = 890 keV

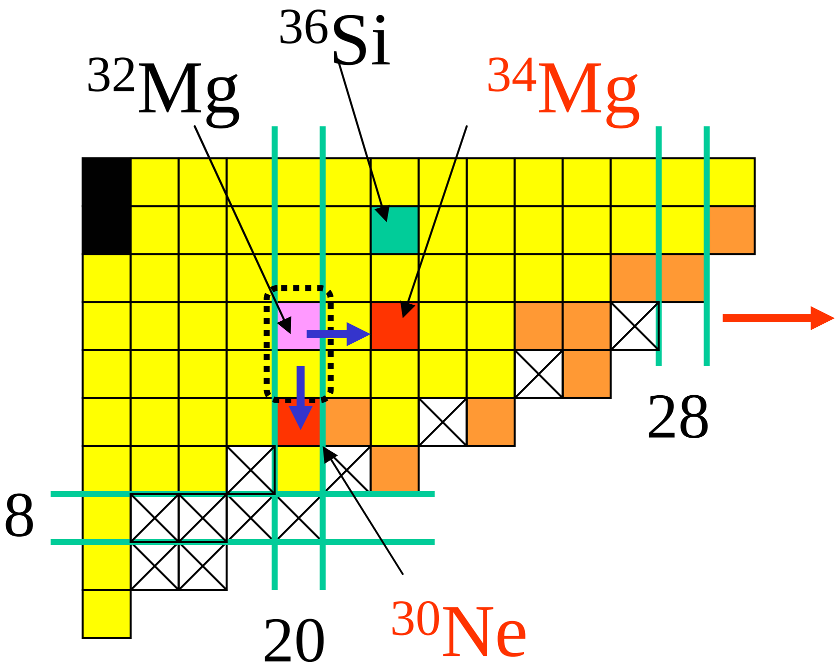
β_2 = 0.58(6)

B(E2) = 631±126 e^2fm^4

Utsuno et al.,
Phys. Rev. C 60(1999)054315

Further investigation for the island-of-inversion region

How is the region extended ? lower Z and larger N



^{34}Mg E(2$^+$), B(E2)

Coulomb excitation

^{34}Mg beam + Pb target

intensity ~3/sec

^{30}Ne E(2$^+$)

proton inelastic-scattering

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^{32}Mg	**E(2$^+$)**	**ISOLDE**
	B(E2)	**RIKEN**
	E(4$^+$)/E(2$^+$)	**GANIL**

E(2$^+$) measurement for ^{30}Ne via (p,p')

Yanagisawa et al., Phys. Lett. B566 ,84 (2003)

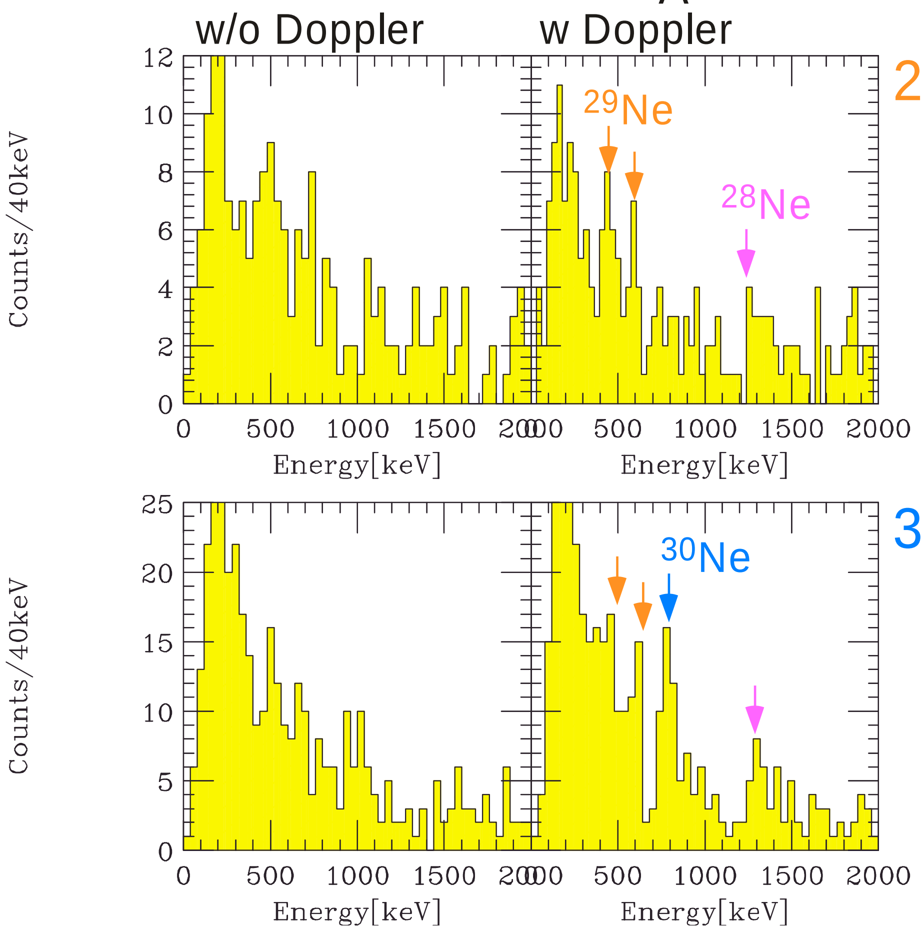
(p,p') liquid hydrogen target ~200mg/cm^2

Number of target nuclei

$$\frac{t[g/cm^2]}{A} \times N_a$$

hydrogen A = 1

Pb target A = 208



^{29}Ne beam

^{30}Ne beam I~0.3/sec

E(2$^+$) = 790 ±10 ±20 keV
stat. sys.

cf ^{32}Mg 890 keV

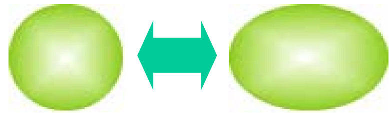
Nuclear Collective Motion

closed shell ⟷ open shell

at magic number

spherical nuclei

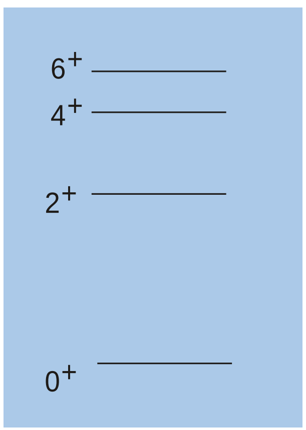
surface vibration

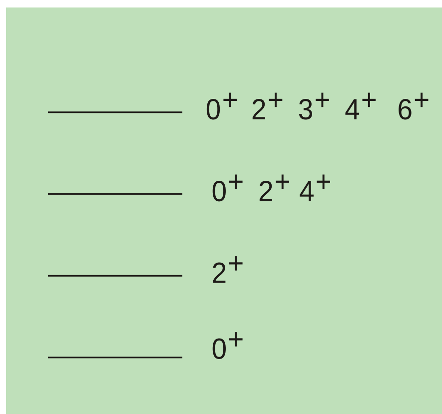


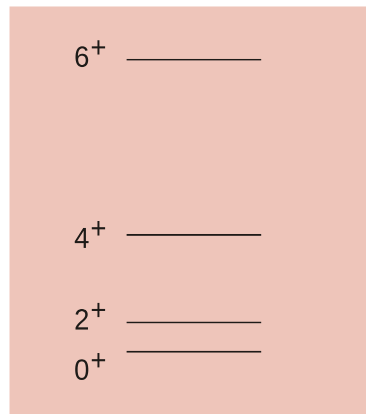
deformed nuclei

$|\beta|\sim 0$ ← Quadrupole deformation parameter β → $|\beta|$ large

degree of collectivity



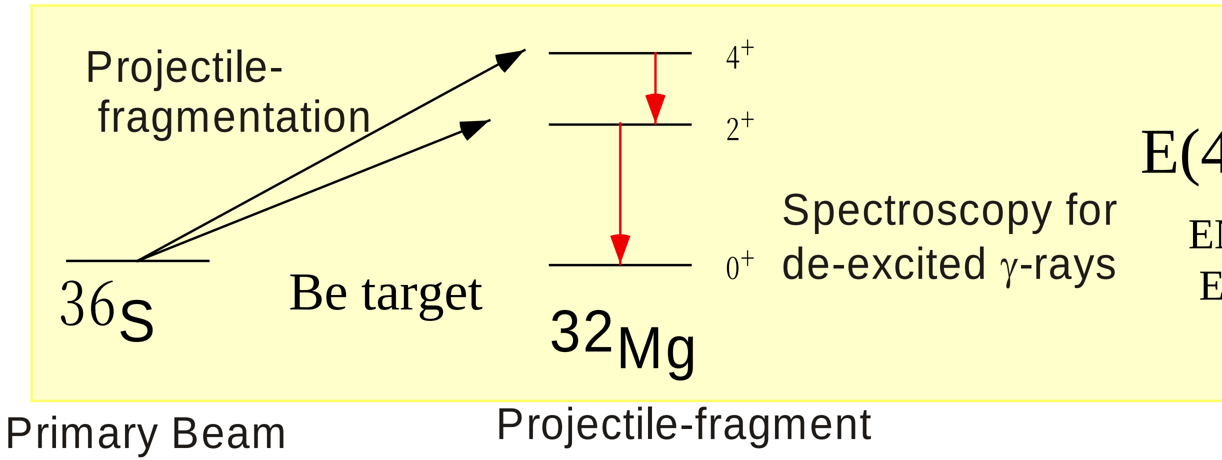




$E(4^+)/E(2^+)$ | ~ 1.8 | ~ 2.2 | ~ 3.3

In-beam γ-spectroscopy via projectile-fragmetation

^{32}Mg E(2^+) and E(4^+)?



E(4^+)/E(2^+) = 2.6

ENAM01
Eur.J.A. 15, 93(2002)

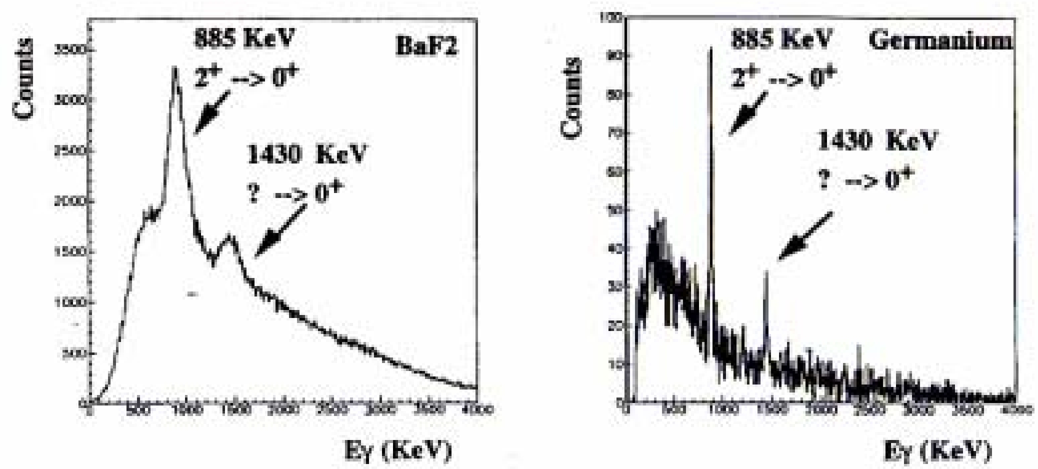


Fig. 4 : Gamma energy spectra of ^{32}Mg in the BaF_2 (left) and in the germanium (right)

XXXVII Int. Winter meeting
on Nuclear Physics
(Bormio, Italy, Jan. 99)

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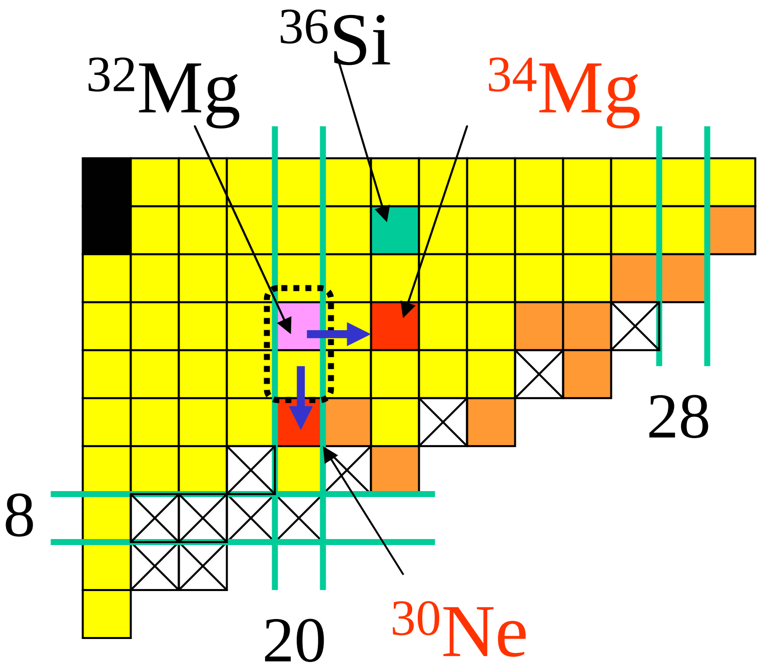

^{32}Mg E(2$^+$) ISOLDE
B(E2) RIKEN
E(4$^+$)/E(2$^+$) GANIL

^{34}Mg E(2$^+$), B(E2)

Coulomb excitation

^{34}Mg beam + Pb target
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^{30}Ne E(2$^+$)

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→ ^{34}Mg E(2$^+$), E(4$^+$) for E(4$^+$)/E(2$^+$)

RI beam fragmentation method

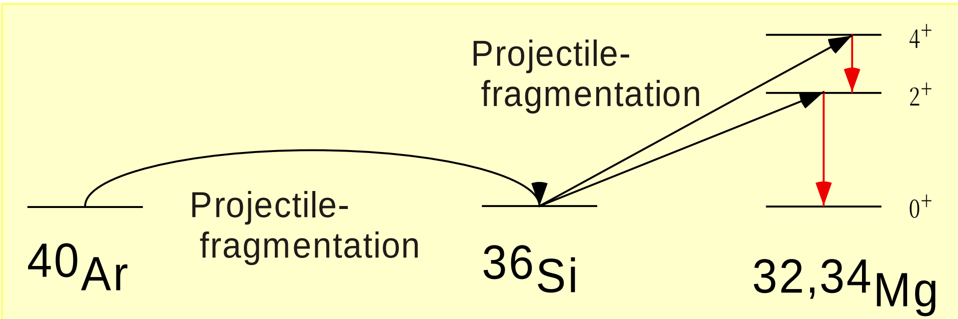
projectile fragmentation reaction

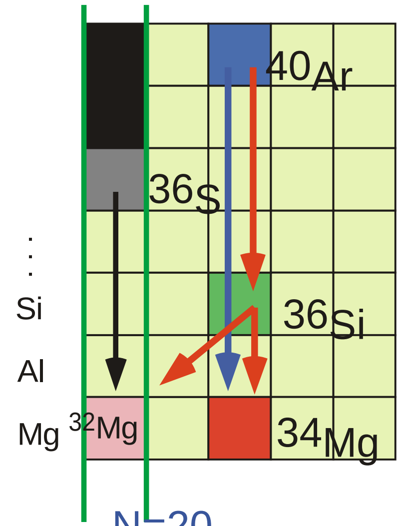
^{36}Si beam + Be target
intensity ~10^4/sec

RI beam fragmentation method

^{32,34}Mg E(2^+) and E(4^+)?

Two-steps RIKEN(99)





Primary Beam

2ndary-beam

one step

^{40}Ar -> ^{34}Mg

^{40}Ar primary beam

high intensity

But...

limit of Intensity and target thickness

to avoid accidental coincidence

two steps

^{40}Ar -> ^{36}Si

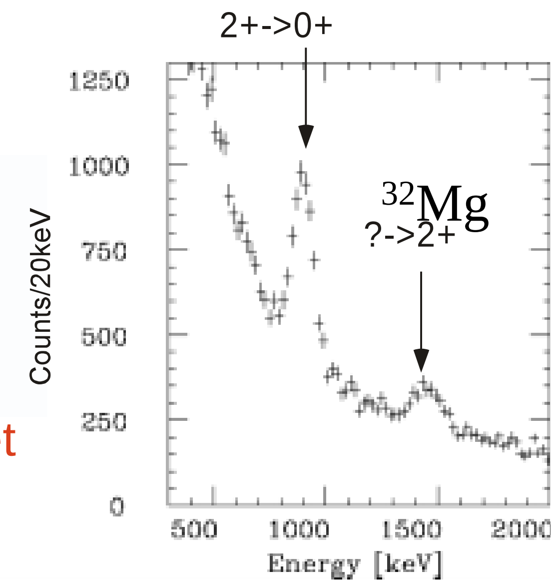
^{36}Si -> ^{34}Mg

^{36}Si RI beam

low intensity

So...

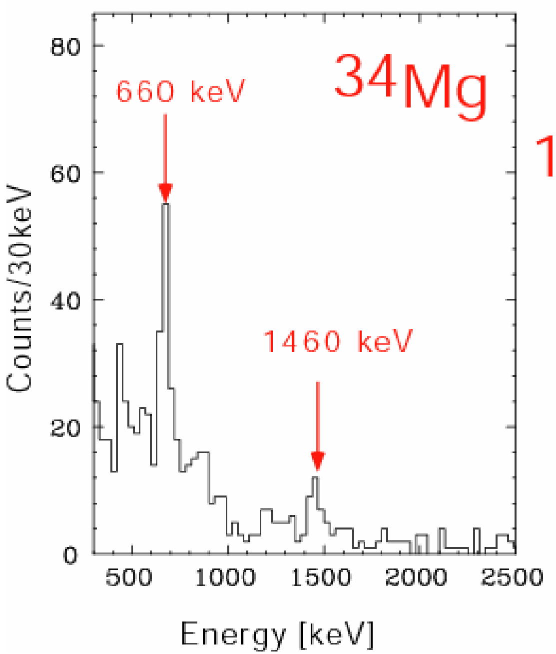
thick production target

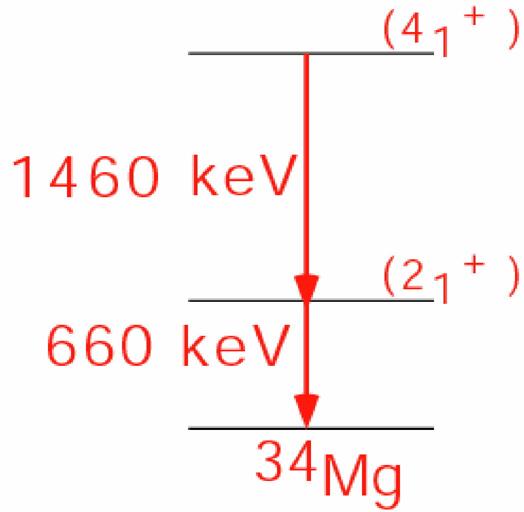


production cross sections o(1) nb o(0.1) mb

Spectroscopy on ^{34}Mg via RI beam fragmentation method

Yoneda et al., PLB499, 233(2001)





tentative Jp assignment

according to relative g-ray strength

^{18,20}O, ^{22,24,26}Ne

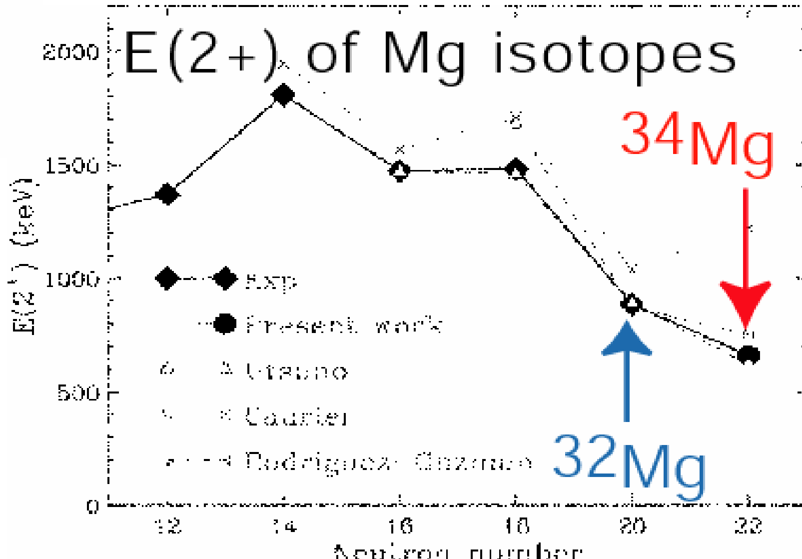
^{26,28}Mg

population of excited states along the Yrast line

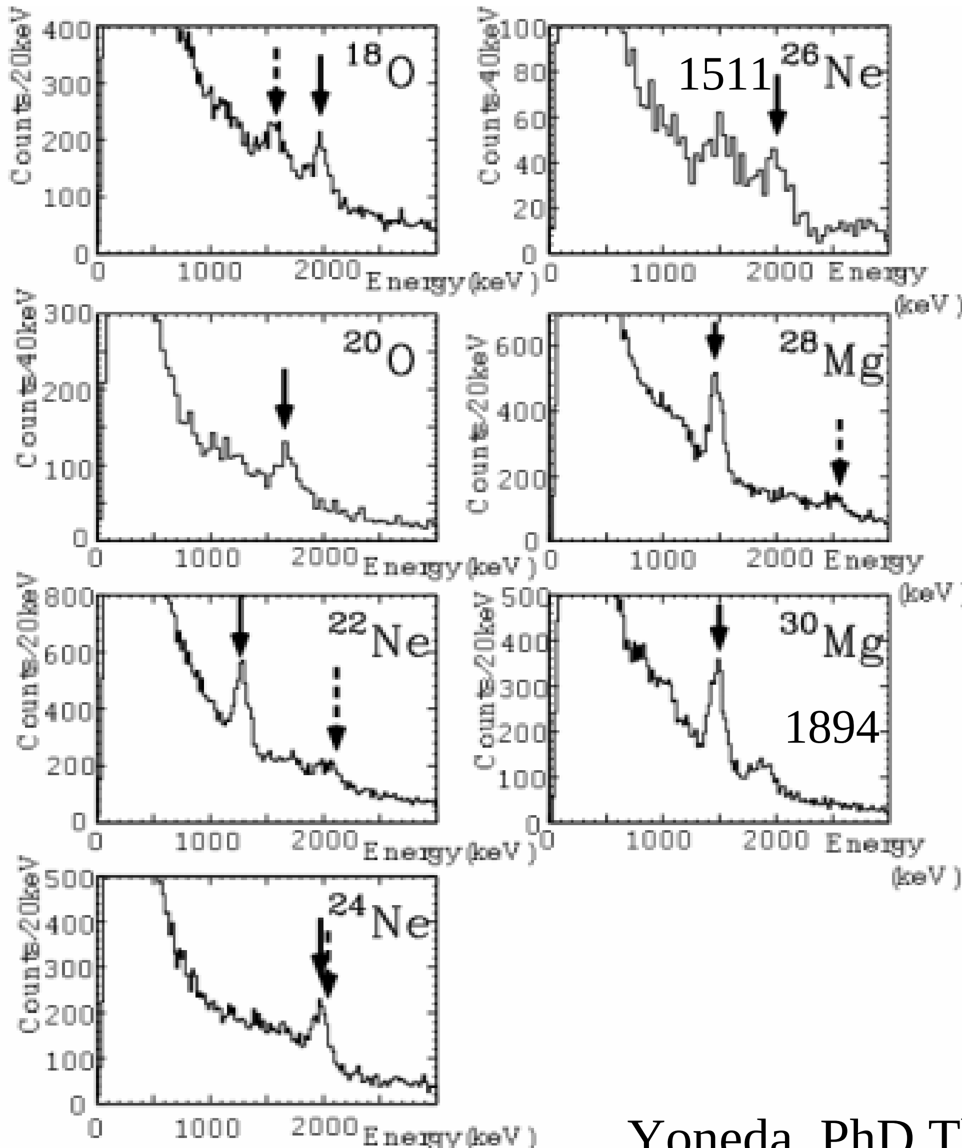
^{34}Mg $E(2_1^+)$ < ^{32}Mg $E(2_1^+)$

$E(4_1^+)/E(2_1^+) \sim 3.2$

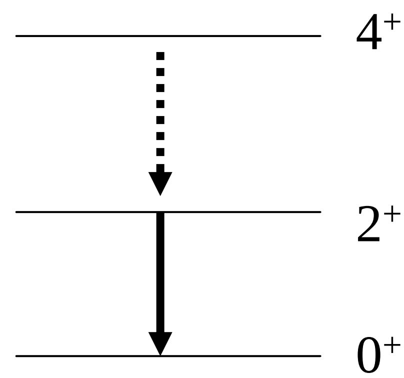
^{34}Mg larger deformation than ^{32}Mg



Doppler-corrected g-ray energy spectra for the O, Ne, and Mg isotopes

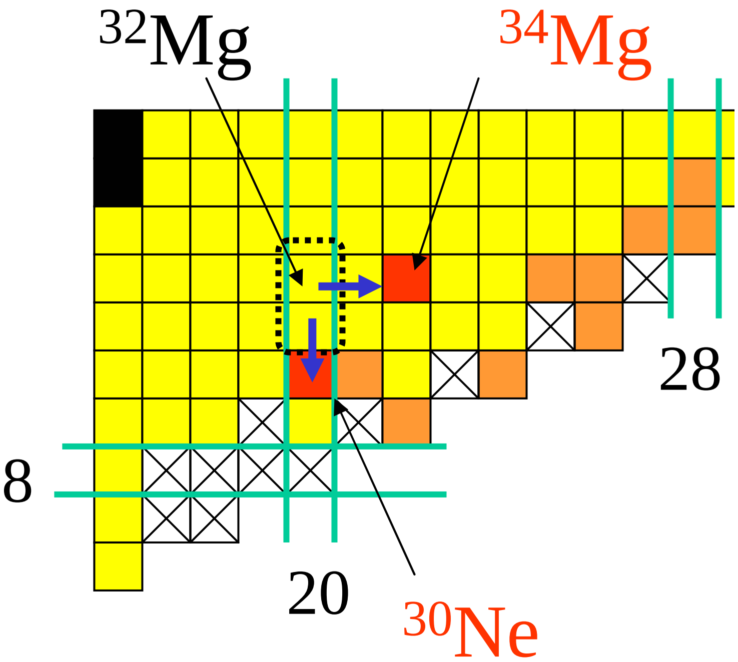


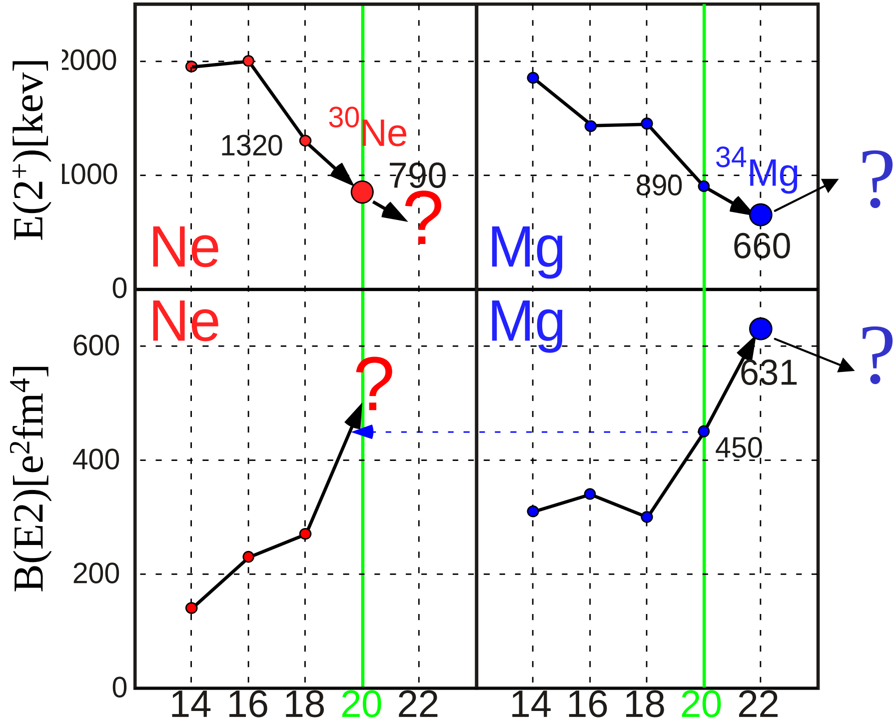
literature values

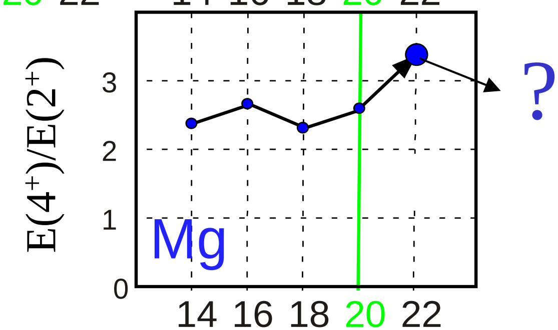


Yoneda, PhD Thesis, U. Tokyo (2003)

Spectroscopy on nuclei in the island-of-inversion region







The ^{30}Ne isotope has a larger collectivity than the ^{32}Mg isotope??

N=22 is the center of deformation??

⟶ Further investigation is necessary

Investigation on Nuclear Structure via In-beam γ Spectroscopy

- "Magicity Loss" and Collective Motion -

Present Facility RIPS

1. Magicity loss at N~20

→ 2. ^{16}C

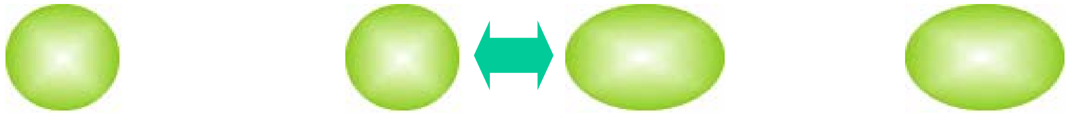
The New Facility RIBF

3. Future

Nuclear Collective Motion

closed shell ⟷ open shell
at magic number

spherical nuclei | surface vibration | deformed nuclei

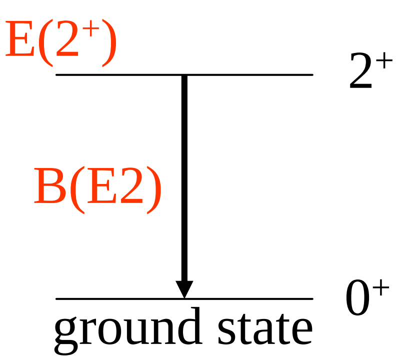


|β|~0 ← Quadrupole deformation parameter β → |β| large

degree of collectivity

Quantum Liquid Drop Model

Even-Even Nuclei



Energy of the first excited state

$E(2^+) \propto 1/\beta^2$

E2 transition probability between 2^+ and 0^+

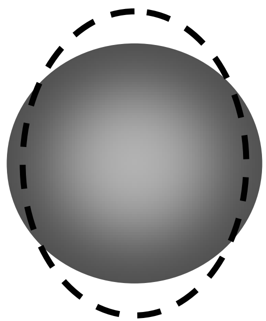
$B(E2) \propto \beta^2$

$E(2^+) \propto B(E2)^{-1}$

New type of collective motion?

“classical” picture

ONE quantum liquid drop

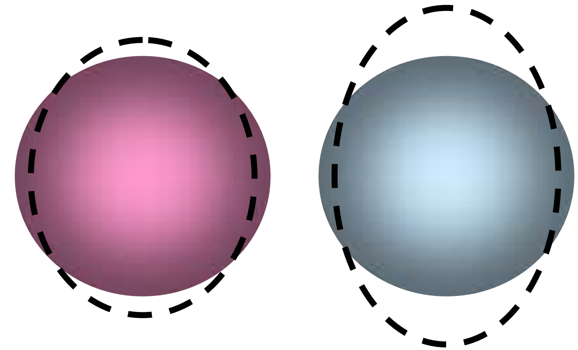


one-body nuclear matter

proton- and neutron matter’s contributions to collective motion are same.

“exotic” picture

TWO quantum liquid drops



proton matter neutron matter

proton- and neutron-matter’s contributions to collective motion are not necessarily same.

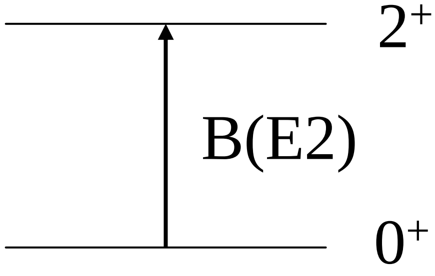
Degree of collectivity for proton- and neutron matters

β → βp proton matter

β → βn neutron matter

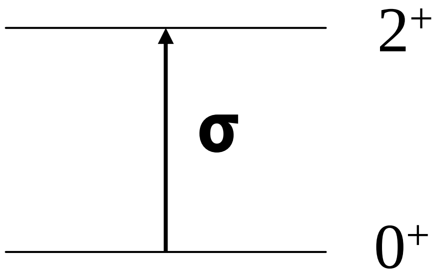
βp electromagnetic probe
e.g. Coulomb excitation

$B(E2) \propto \beta_p^2$



βn strong-interaction probe
e.g. proton inelastic scattering

$\sigma \propto \beta_n^2$

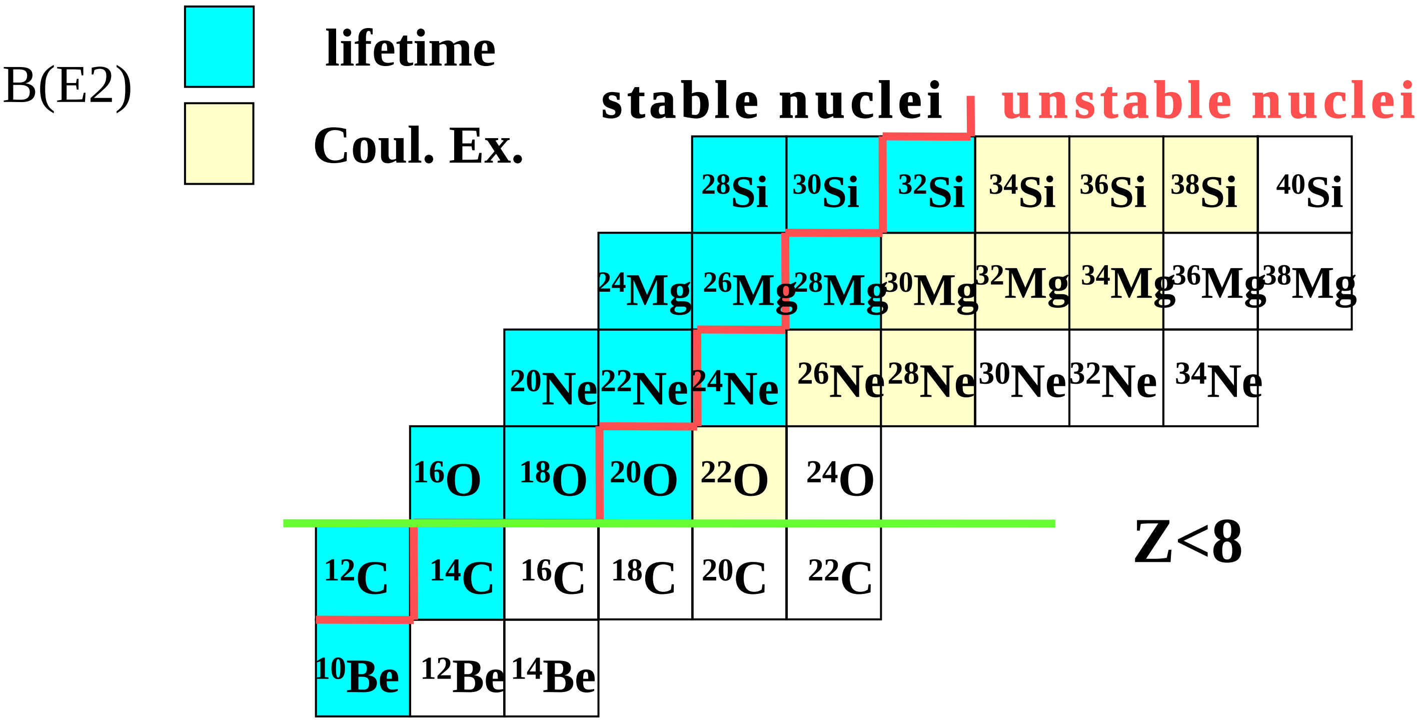


$\sigma(pn) \sim 2\ \sigma(pp)$

Since 1980's, large difference between β_n and β_p has been searched for,
but $|\beta_n|/|\beta_p| \sim 1$ for stable and unstable nuclei observed so far .

even for ^{32}Mg, too

B(E2) measurement for the light mass region



No data for the neutron-rich Be and C isotopes

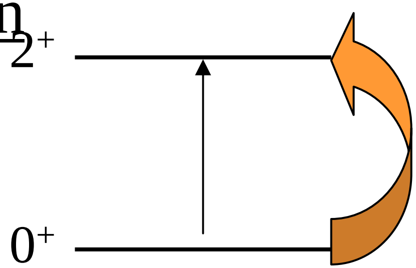
How to measure B(E2)?

Intermediate energy Coulomb excitation

for unstable nuclei

inelastic scattering on heavy target such as Pb

E2 excitation: Coulomb dominant if **Z>10**

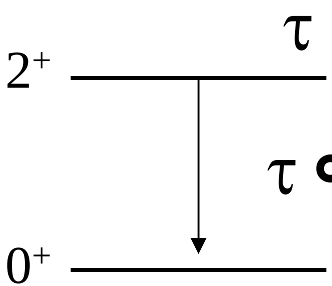


$\sigma \propto B(E2)$

Z<8 Coulomb Ex. ≲ Nuclear Ex.

Lifetime measurement of 2^+ state

for stable nuclei or nuclei close to stability line



$\tau \propto 1/B(E2)$

(p,p' γ), (t, pγ), and etc...

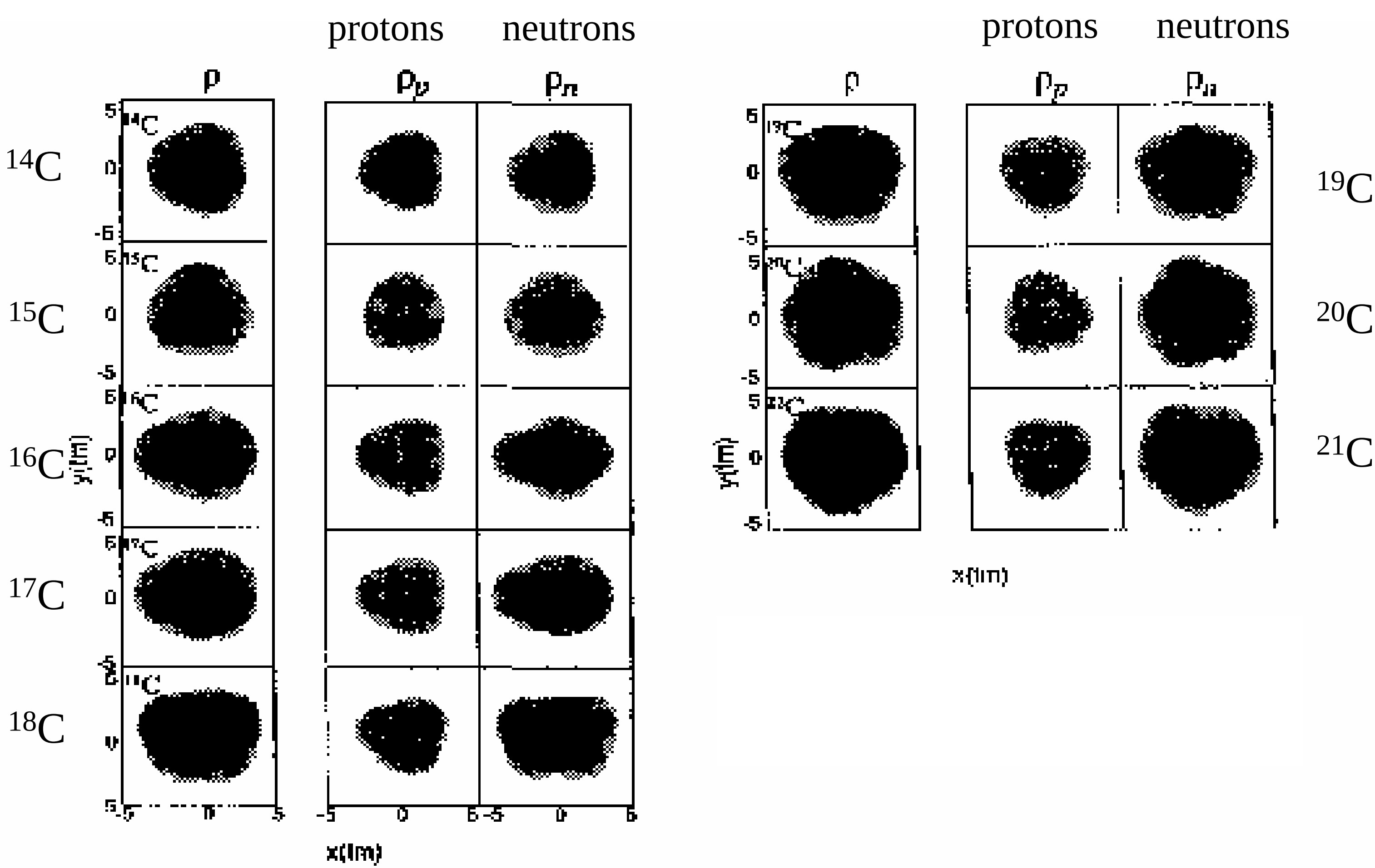
+

Doppler Shift Attenuation

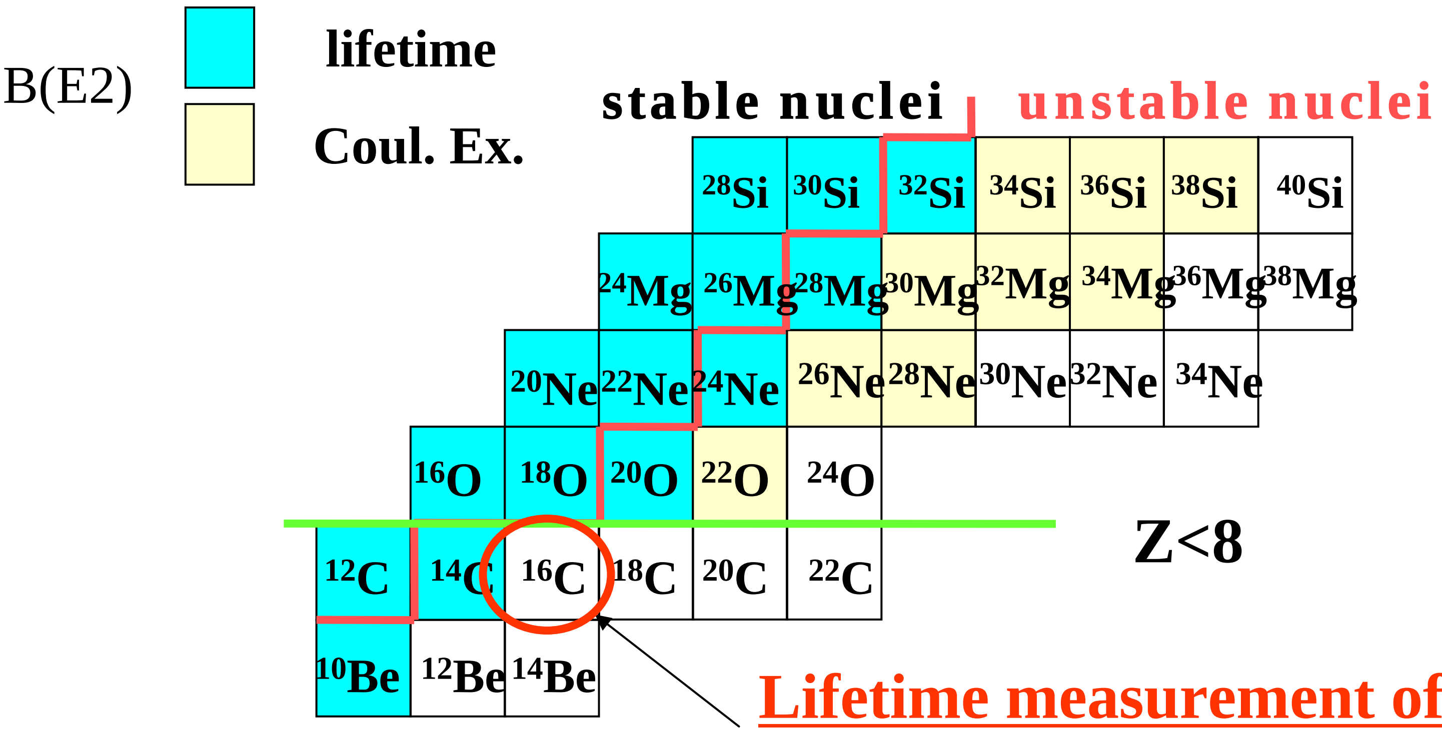
1970's

Density distributions for the C isotopes

AMD calculation by Kanada-En'yo and Horiuchi



B(E2) measurement for ^{16}C via a new techniques



Lifetime measurement of 2^{+} state

New method appropriate for fast RI beam should be developed

"Recoil-Shadow-Method"

Recoil-shadow-method

- **Inelastic Scattering of RI beams**
- **High velocity (β=0.3)**

⇨ $\lambda = \beta\gamma\tau c$

$\approx 1.0\mathrm{cm}(\tau = 100\mathrm{ps}, \beta = 0.3)$

- **Thick lead shield**

⇨ γ-ray path is different

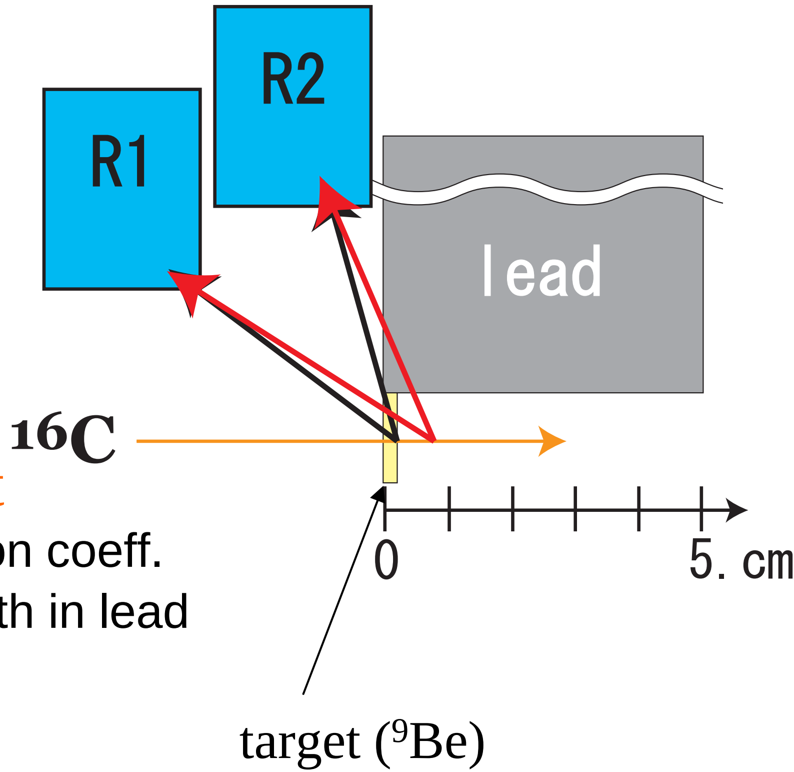
⇨ effective efficiency is different

$$\mathcal{E} = \exp(-\mu\, l)$$

μ: attenuation coeff.

l : path length in lead

R1, R2 gamma detectors



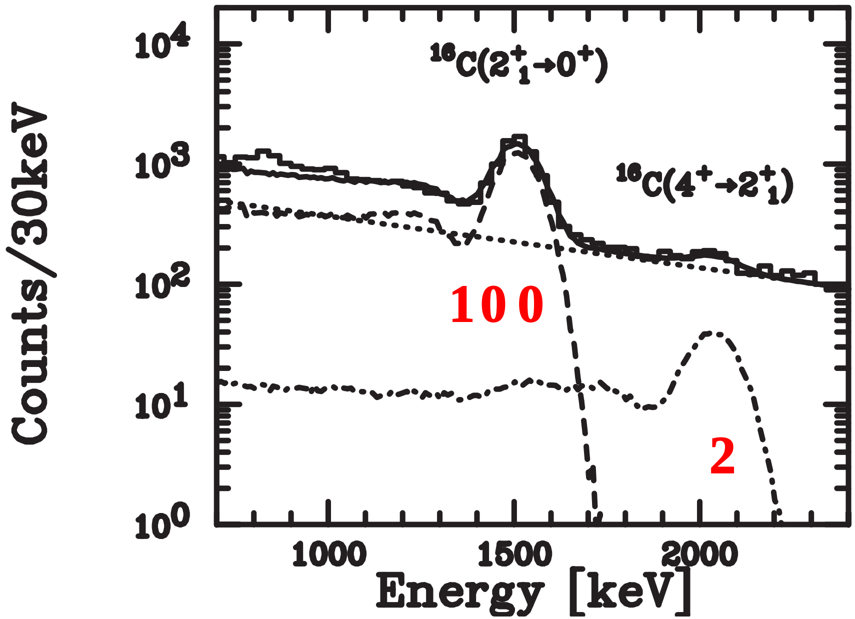
R1/R2 ratio has mean life dependence

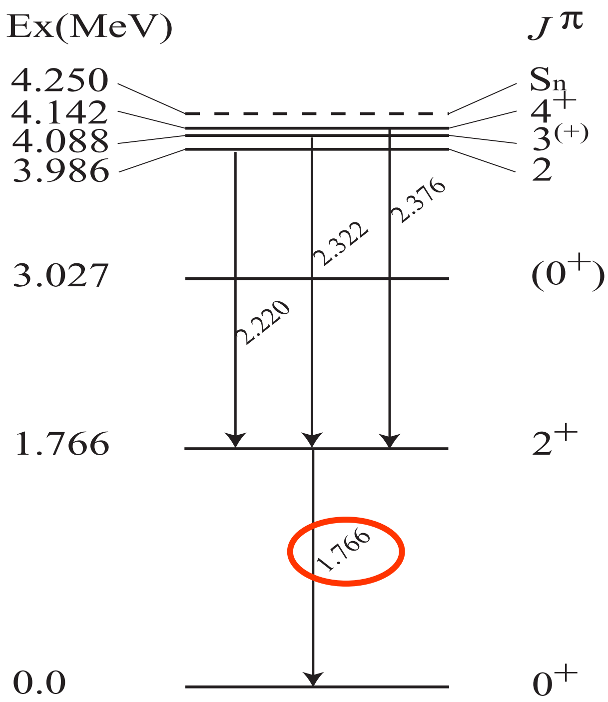
Energy spectrum of γ ray

Doppler uncorrected Spectrum of R1

Shape: GEANT simulation

Background: Exponential





Level scheme of ^{16}C

R1/R2 vs τ curve

GEANT code

Geometry

energy dependence (^{137}Cs, ^{22}Na, ^{60}Co)

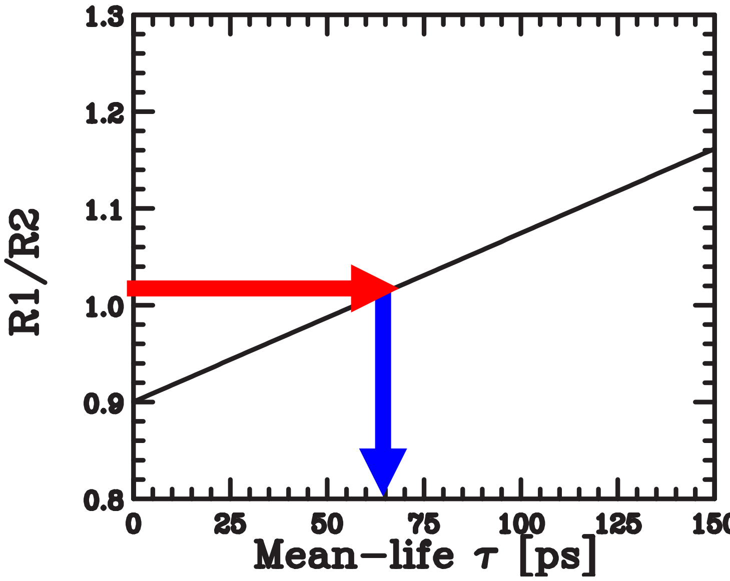
position dependence (^{22}Na z=0.0-2.0cm)

Beam profile

experimentally obtained parameters for emittance and scattering angles

Angular distribution of γ rays

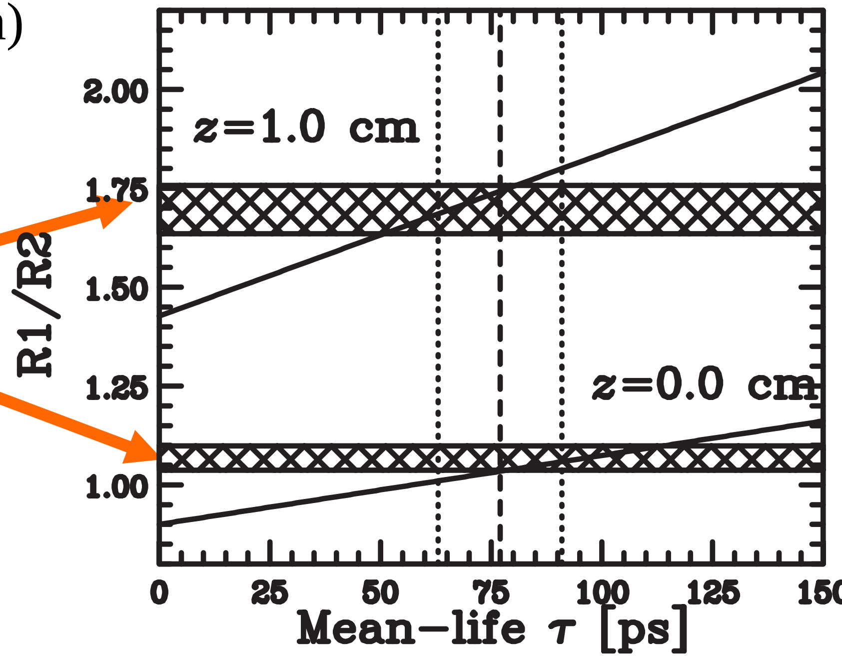
ECIS79 with optical potential sets for $^{12}C+^{12}C$ @35AMeV and $^{16}O+^{12}C$@38AMeV



Mean lifetime of $^{16}C(2^+)$

Cross check (Target: Z=0.0 and 1.0 cm)

	R1/R2	τ [ps]
Z=1.0	1.70±0.06	63±17
Z=0.0	1.06±0.03	92±22



Hatched zone: measured R1/R2 ratio

Solid line: Monte Carlo simulation

Weighted average= 77±14 [ps]

Systematic error: 25%

target position (20%) + optical pot. (5%)

$$\tau = 77 \pm 14(\mathrm{stat}) \pm 19(\mathrm{syst})\ [\mathrm{ps}]$$

N. Imai et al, Phys.Rev.Lett. 92,062501('04)

Anomalously hindered B(E2) of ^{16}C

B(E2: 2^+ -> 0^+)   0.63 e^2fm^4

0.26 [W.u.]

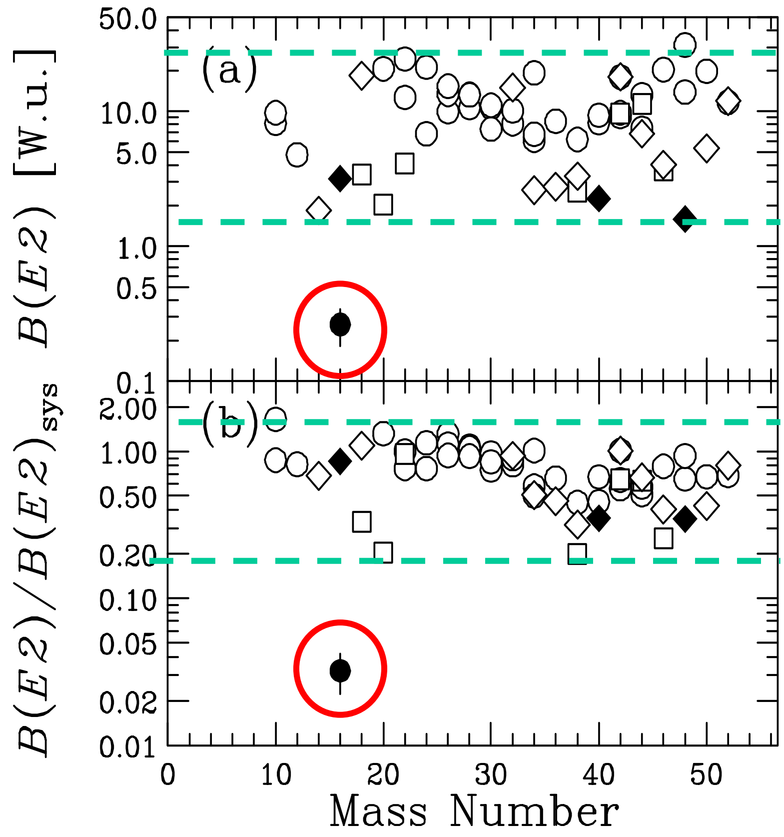
$|\beta_p|$~0.14

ONE quantum liquid drop model

S. Raman et.al.,PRC37, 805 ('88).

B(E2)sys=$6.47Z^2A^{-0.69}E(2^+)^{-1}$

B(E2) /B(E2)sys=0.03



How about β_n / β_p for ^{16}C?

- <u>Inelastic scattering on proton</u>

  Absolute value of dσ/dΩ

  ➪ $|\beta_n| \sim 4\ |\beta_p|$

  H.J. Ong et al., to be submitted

$|\beta_n|/|\beta_p| >> 1$

- <u>Inelastic scattering on Pb</u>

Interference between nucl. and Coul. Excitation

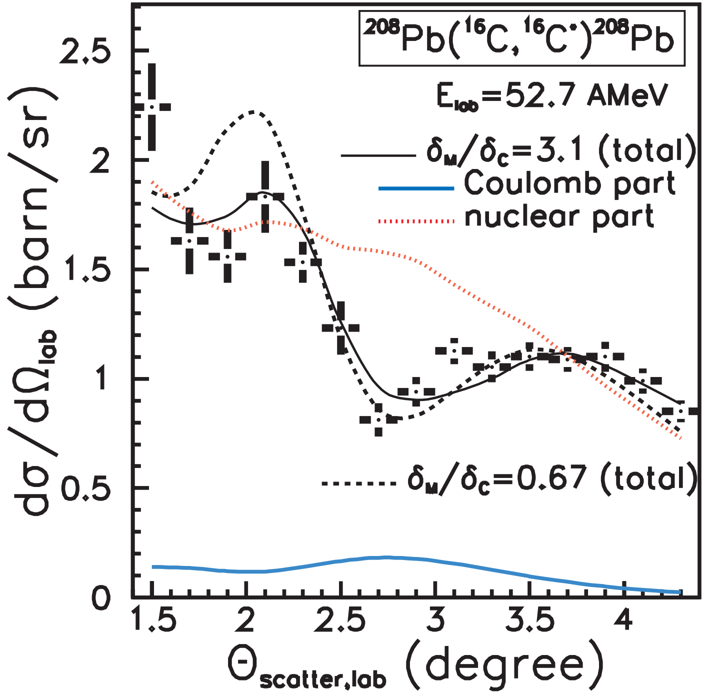
  Angular distribution of dσ/dΩ

  ➪ $|\beta_n|/|\beta_p| = 4.6$ +/- 1

  Absolute value of dσ/dΩ

  ➪ β_p $B(E2\downarrow) = 0.28(6) e^2 fm^4$

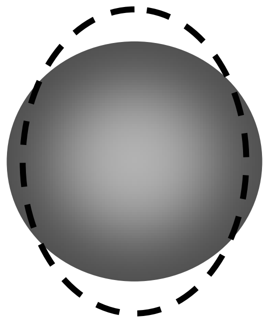
  Elekes et al., Phys.Lett.B 586, 34 (2004)



New type of collective motion?

"classical" picture

ONE quantum liquid drop

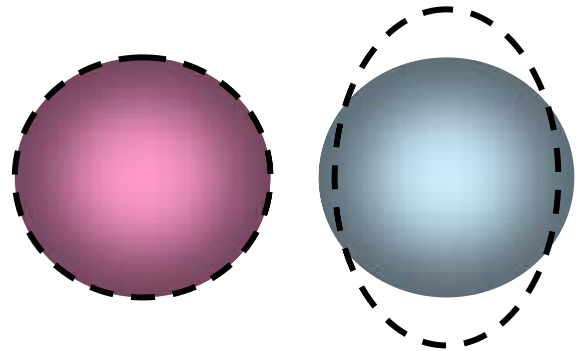


one-body nuclear matter

proton- and neutron-matter's contributions to collective motion are same.

"exotic" picture for ^{16}C case

TWO quantum liquid drops



proton matter   neutron matter

Large contribution by neutron matter, not by proton matter ??

Investigation on Nuclear Structure via In-beam γ Spectroscopy

- "Magicity Loss" and Collective Motion -

Present Facility RIPS

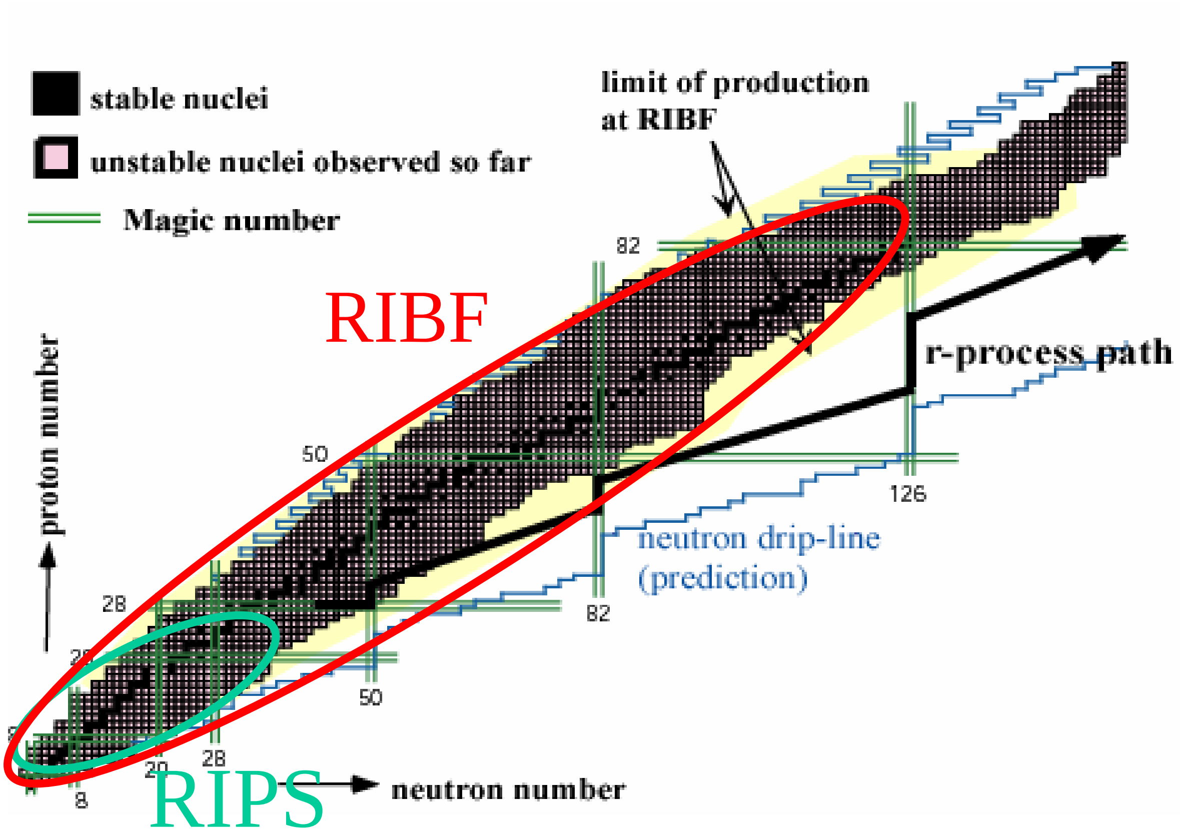
1. Magicity loss at N~20
2. ^{16}C

The New Facility RIBF

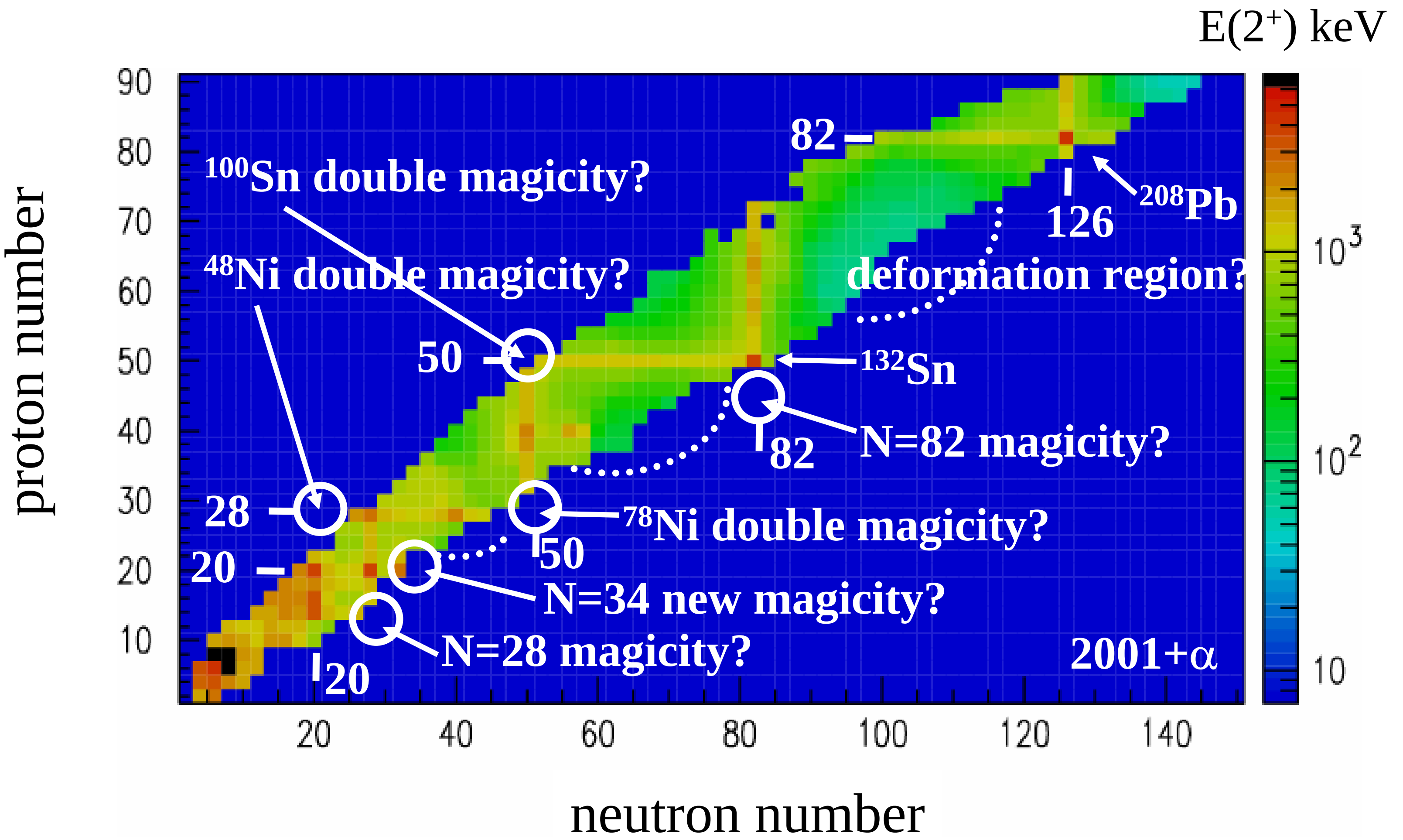
→ 3. Future

Exploration towards heavier and more proton-rich /neutron-rich region

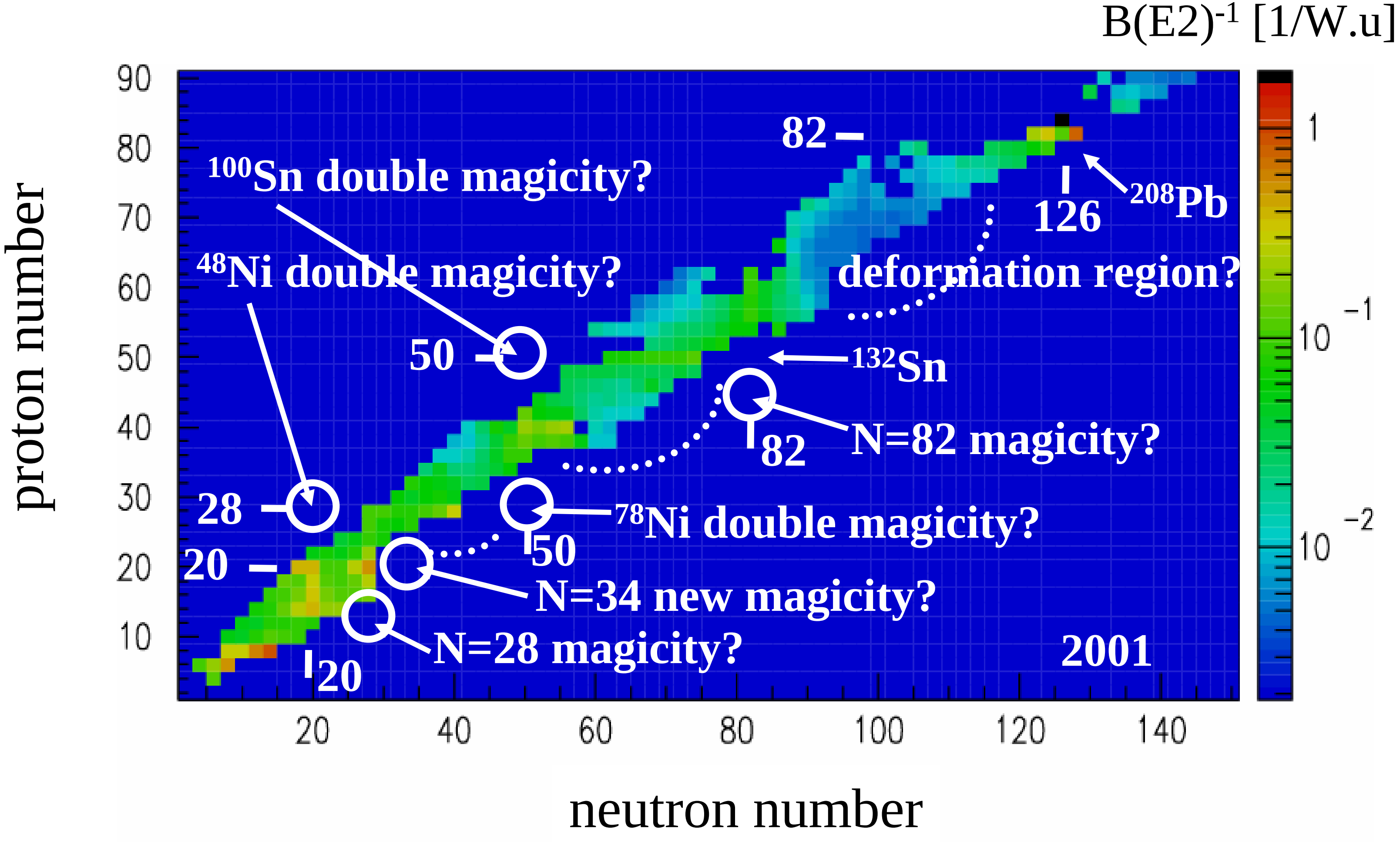
to produce a lot of data for "unified pictures"



Nuclear Structure and Collectivity ?



Large Room for B(E2)



Higher excited states and higher spin states for exotic phenomena of collectivity?

not only low lying states but also ...

for intermediate and heavy mass system

neutron skins ?

collectivity originated from neutrons in skin

pairing ?

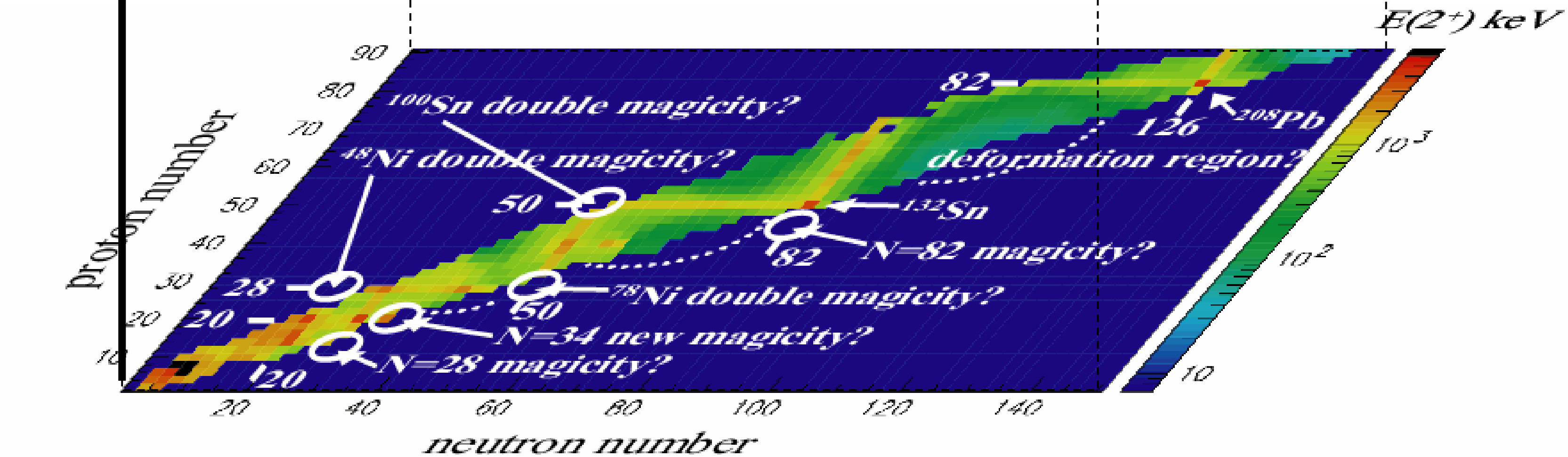
rotation energy v.s. pairing energy

exotic modes ?

originated from two asymmetric liquids

...

J, Ex



RIBF

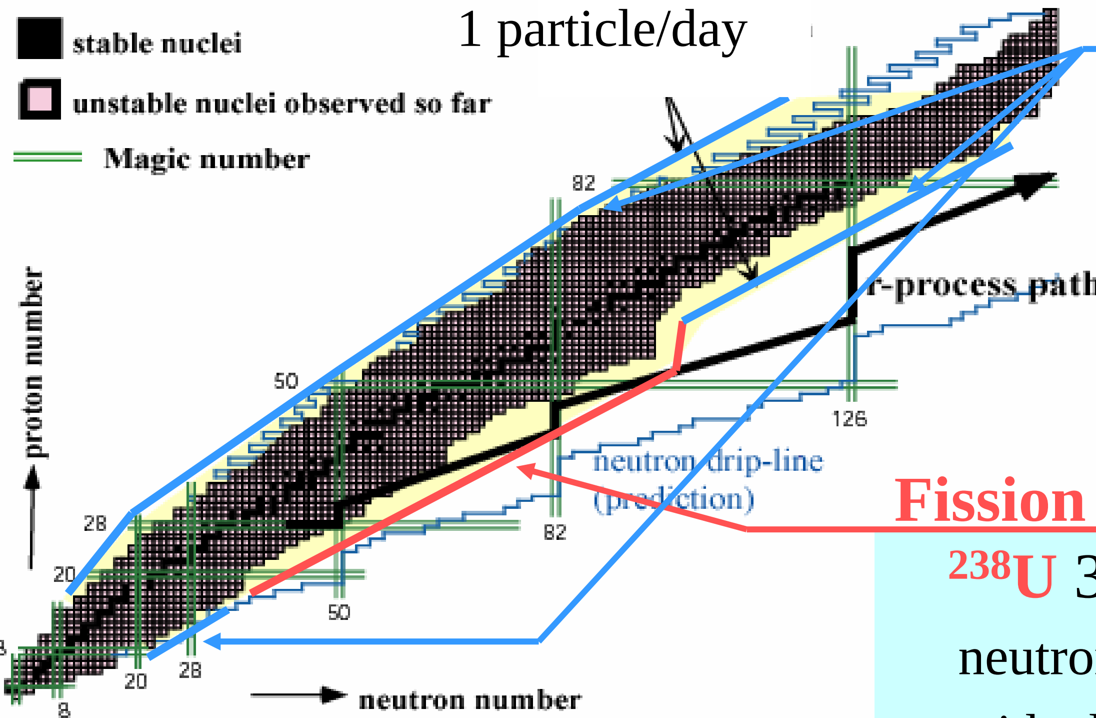
Exploration of the limits of nuclear existence - towards the drip-lines -

3rd generation of RI beam facility "Fission fragment of U"

SRC high energy and intense heavy ion beams upto U

Big-RIPS high acceptance for fission fragments

More than 300 new isotopes produced



Projectile fragmentation

^{48}Ca, ^{58}Ni, ^{78}Ge, ^{112}Sn, ^{204,208}Pb, ^{238}U, ...

350~400*A* MeV

proton-rich side

neutron-rich *A*<50 or *A*>160

Fission

^{238}U 350*A* MeV

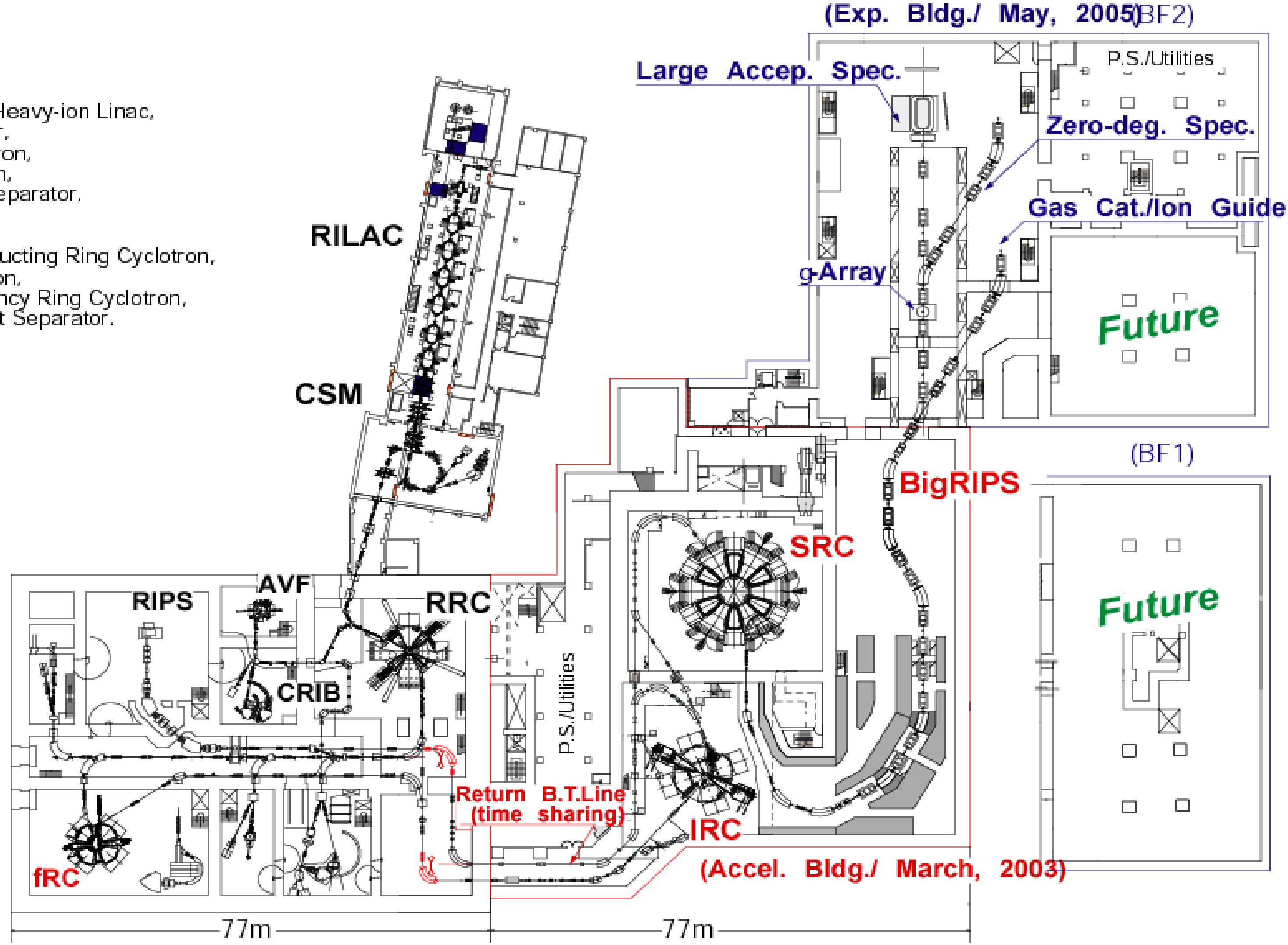
neutron-rich side 20<*Z*<60

wide dynamic range

Layout of the RI Beam Factory (RIBF)

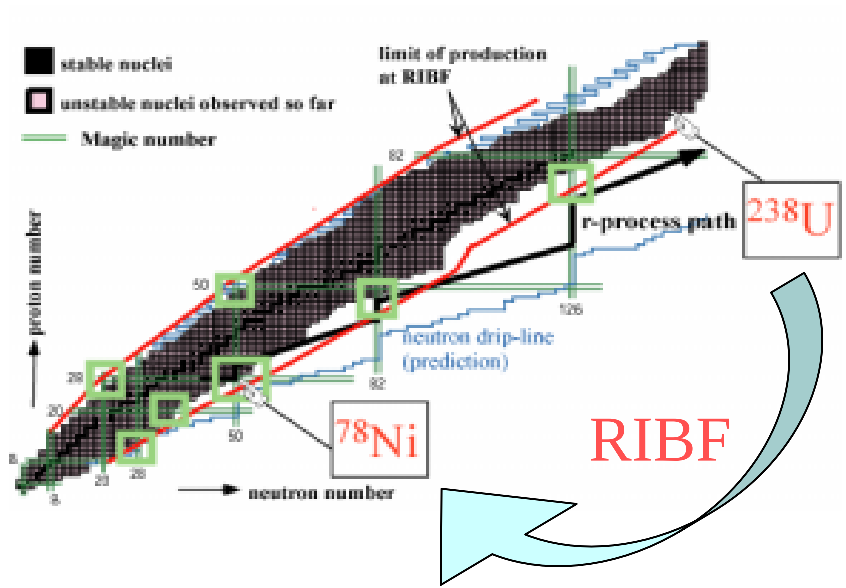
Existing Facility:
RILAC: Frequency-variable Heavy-ion Linac,
CSM: Charge State Multiplier,
RRC: K540MeV Ring Cyclotron,
AVF: K70MeV AVF Cyclotron,
RIPS: Projectile Fragment Separator.

RIBF Phase I:
SRC: K2500MeV Superconducting Ring Cyclotron,
IRC: K980MeV Ring Cyclotron,
fRC: K520MeV Fixed-frequency Ring Cyclotron,
BigRIPS: Projectile Fragment Separator.



A Flag-ship Region on the Nuclear Chart
- ^{78}Ni and vicinity -

Nuclear Structure
  double magicity ?
Nuclear Matter
  neutron-skin?
Nuclear Collectivity
  exotic modes?
Nuclear Astrophysics
  r-process path
  crust of neutron star



^{78}Ni >0.1 particles/sec ⇦ 350*A* MeV ^{238}U >10pnA

challenges to observe exotic phenomena beyond N=50

β-spectroscopy	$T_{1/2}$, $E(2_1^+)$ and others, mass, ...
in-beam γ spectroscopy	$E(2_1^+)$, $E(4_1^+)$, B(E2), β^M_2, ...
transmission	radii

Reactions for in-beam γ spectroscopy with fast RI beam

RI beam energy [*A* MeV]

250 **RI beam at RIBF**

- Intermediate energy Coulomb excitation
  - 2^+, B(E2), 1^-, B(E1),...
- Proton inelastic scattering
  - 2^+, β^M_2, 3^-, β^M_3...
- Projectile fragmentation
  - 2^+, 4^+, 6^+, 8^+, 10^+...
- Knock-out reaction
- .....

deceleration of RI beam
w/ materials

Transfer reaction (α, t)

30 Fermi energy

Transfer reaction (d, p) type

Deep inelastic

Fusion

5 Coulomb barrier

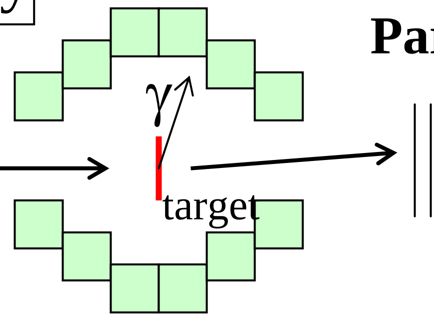
γ–γ coincidence
lifetime measurement
...

Experiment at RIBF

At present facility

Particle Identification for Ejectiles

RI beams



charged particle detectors

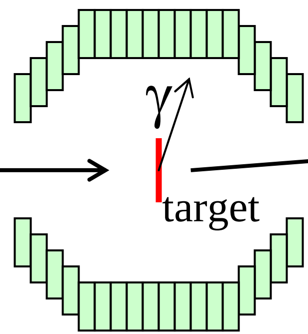
A<~50

β ~ 0.3

gamma-ray detectors

At RIBF

RI beams



high resolving power for heavy mass region

Zero-degree forward spectrometer

A<~200

β ~ 0.6

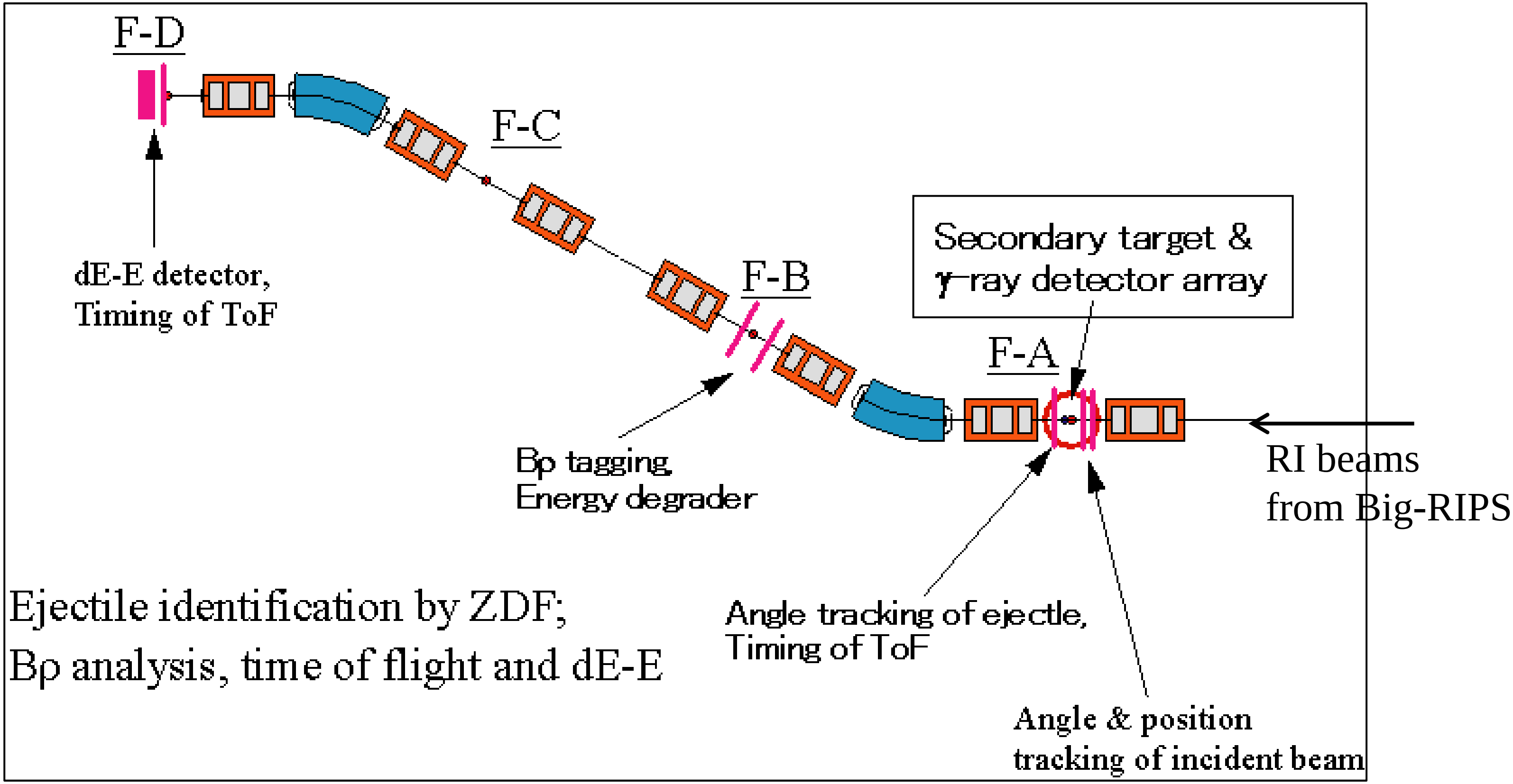
high segmentation and/or
high resolution

DALI2 (NaI)
CNS-GRAPE (Ge)

To determine final channels
To achieve good S/N ratios
for low-intensity RI beams

→ Nice quality of data

Zero-degree Forward Spectrometer at RIBF



1. Achromatic large acceptance mode

2. Achromatic high resolution mode
   (x,p)/(x,x) ~ 2100
3. Dispersive spectrometer mode
   (x,p)/(x,x) ~ 4500

total flight path length ~ 36m
angular acceptance $\Delta\theta$ =+/- 45mrad, $\Delta\phi$=+/- 30mrad
cf. 250A MeV neutron-rich RI beams
grazing angle ~ 20 mrad for Pb targets
momentum acceptance $\Delta p/p$ =+/- 3%
momentum resolution (x,p)/(x,x) = 1240
maximum magnetic rigidity 7.3 Tm
5 sigma separation in A at A=200

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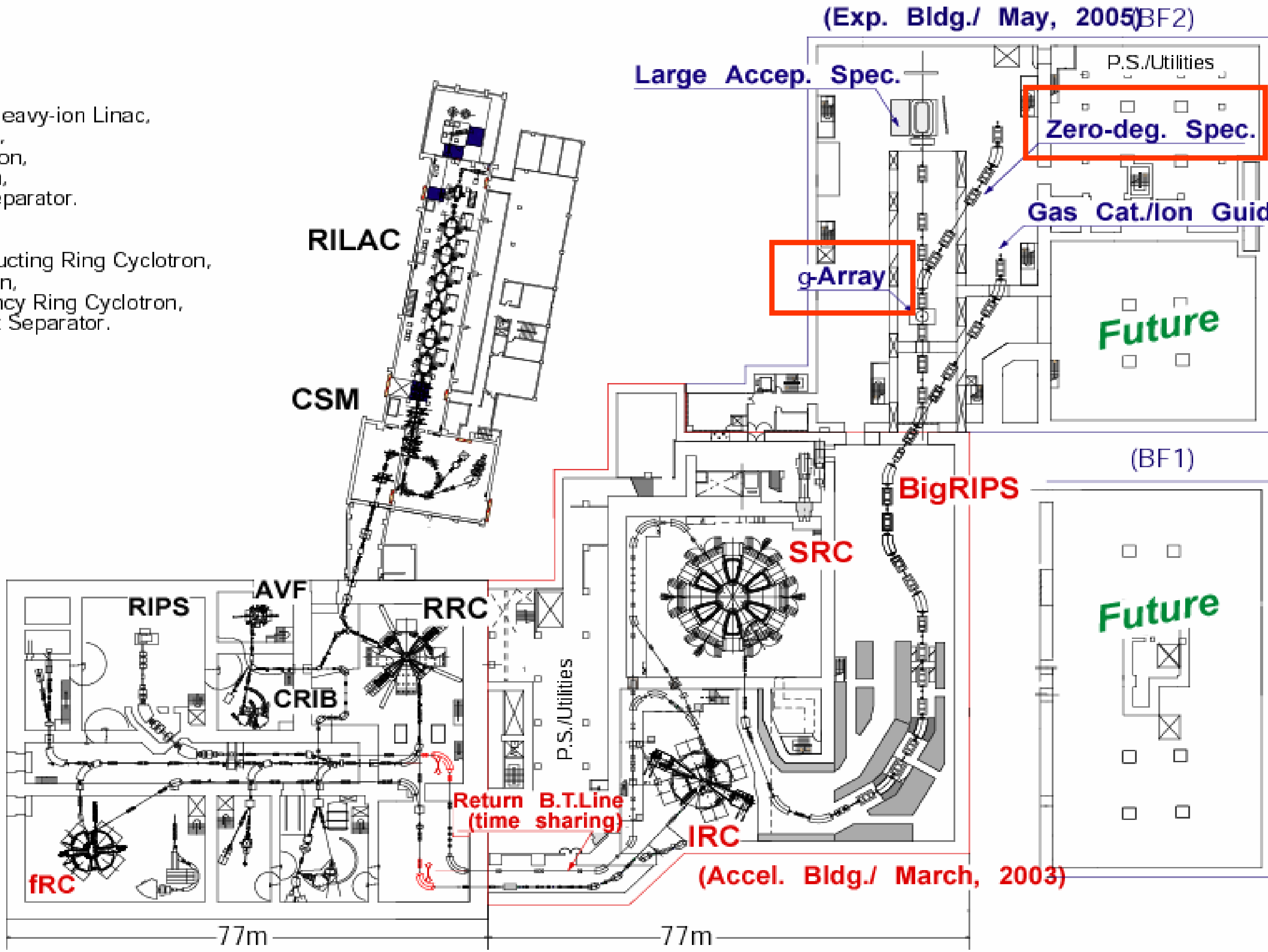
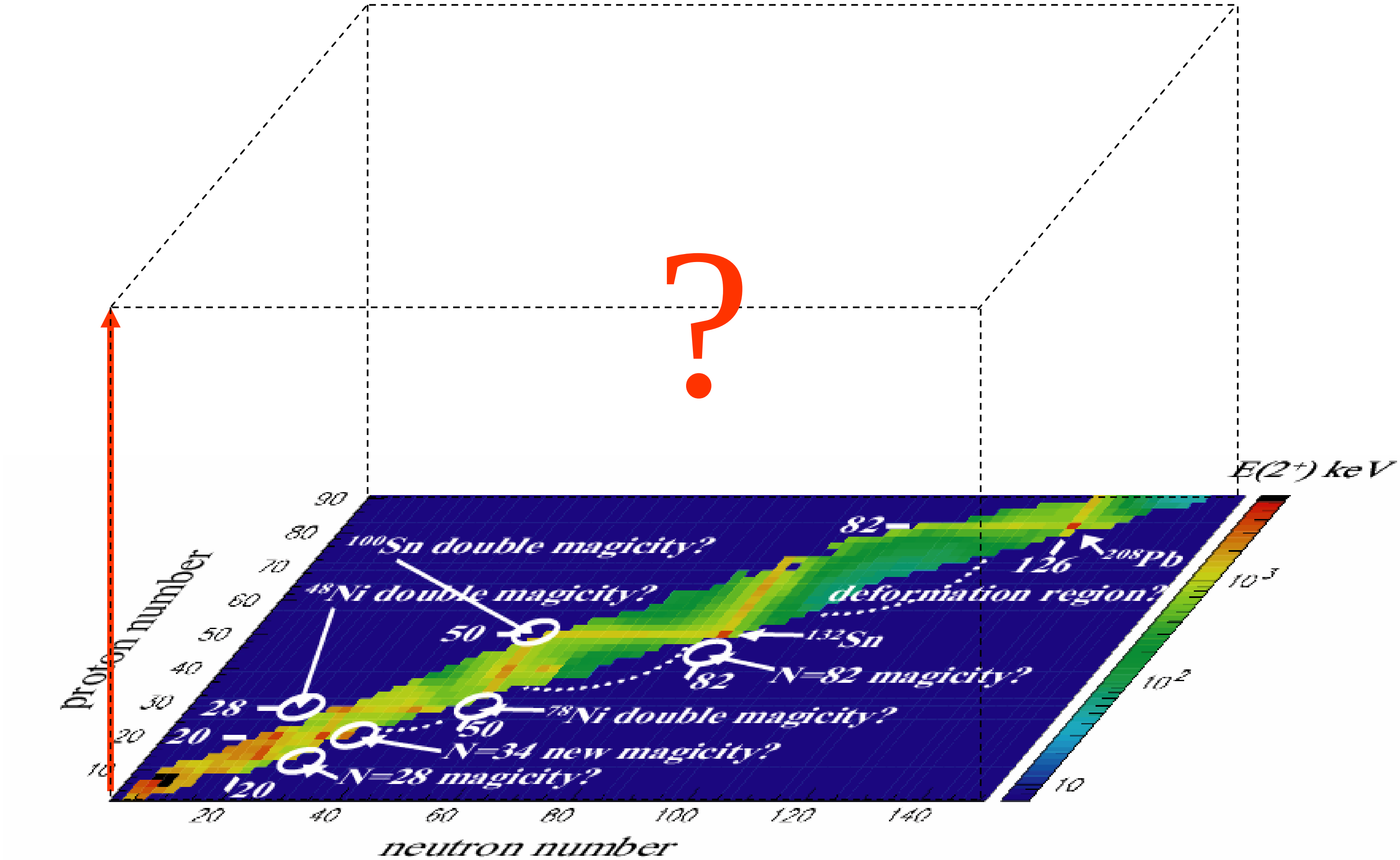
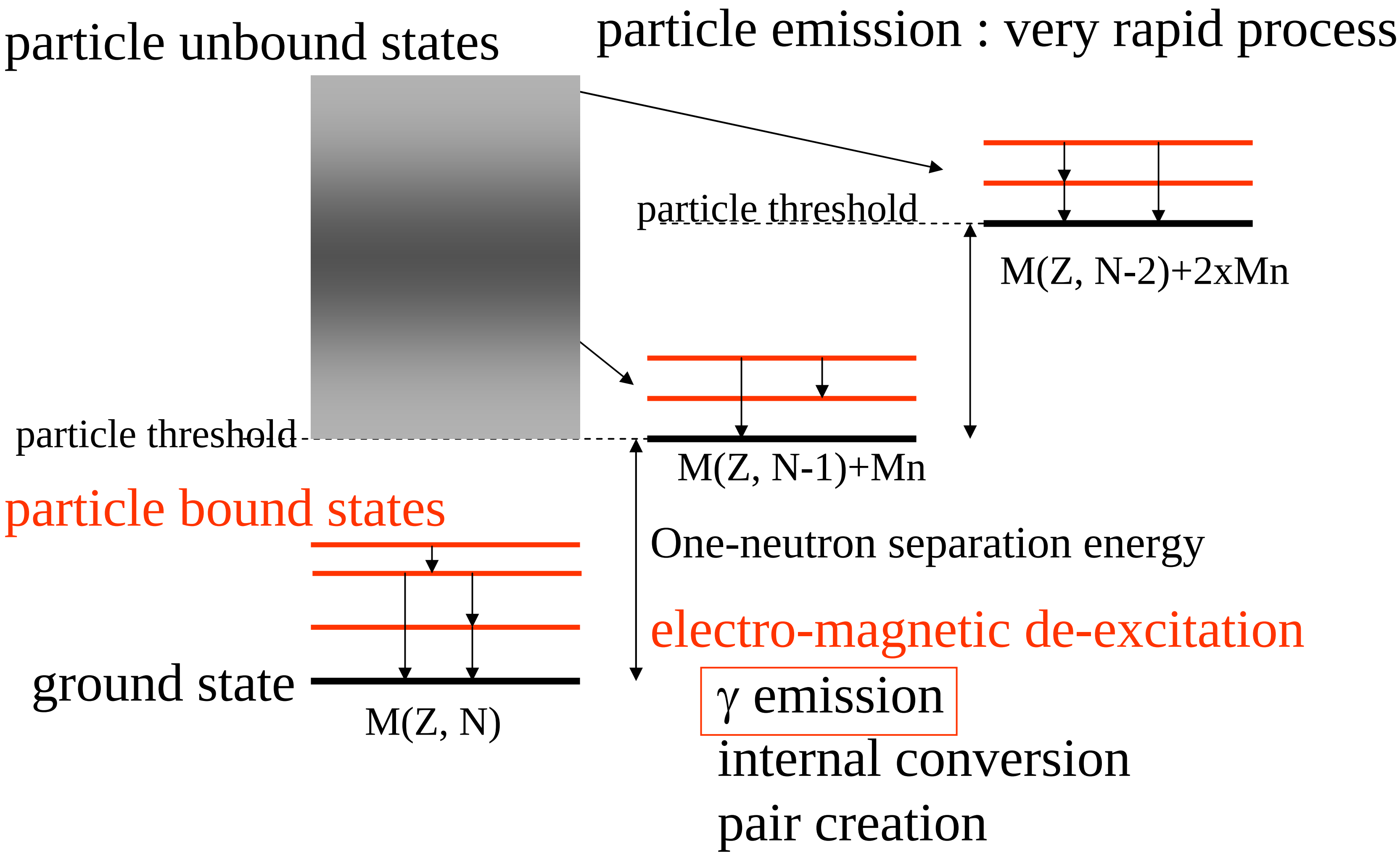


Put your favorite variable on nuclear chart and
Draw your "picture" inside the box

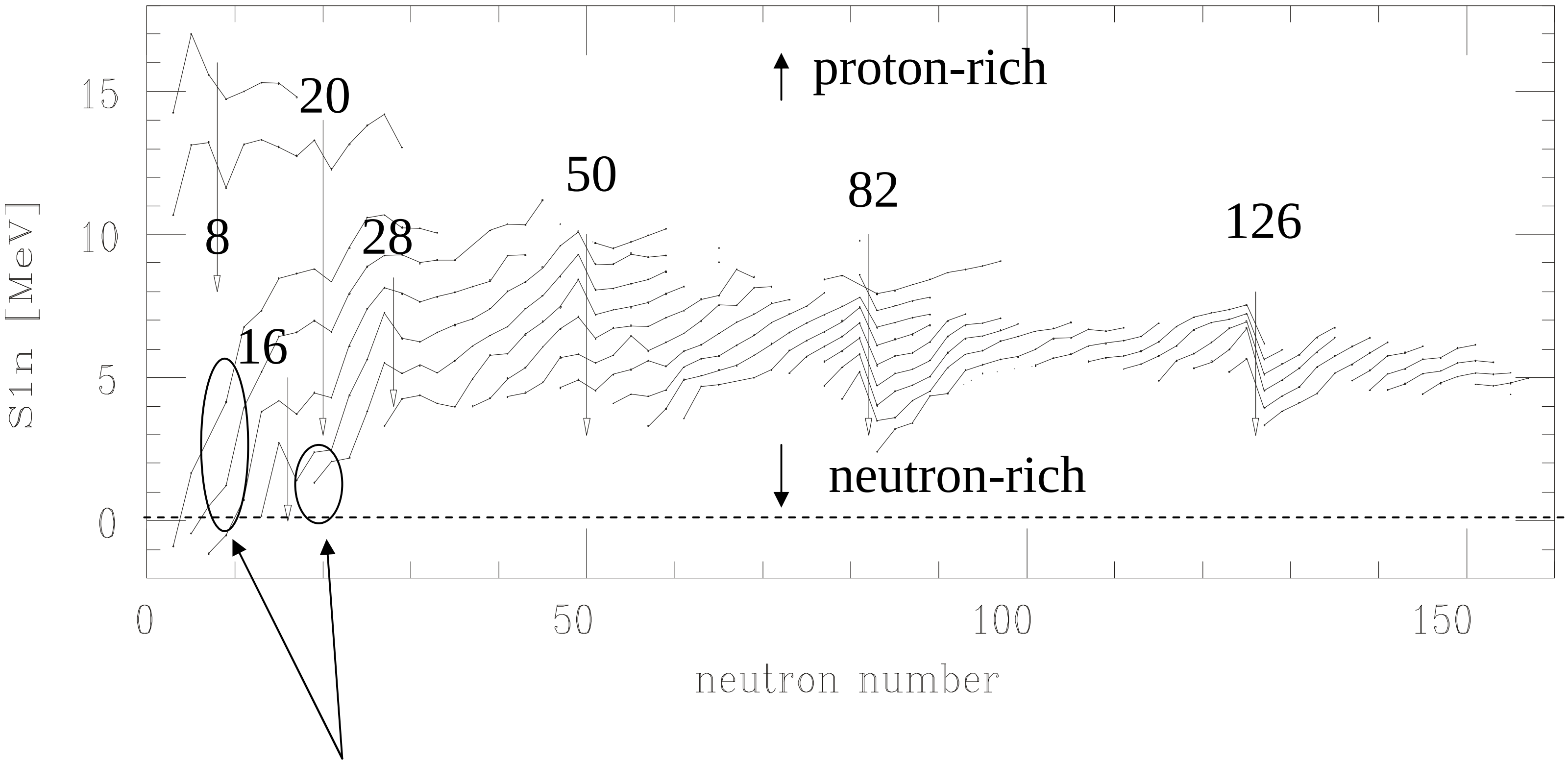


Excited states of nuclei



Magic numbers and Binding energies

Tz connection for one neutron separation energy S_{1n}



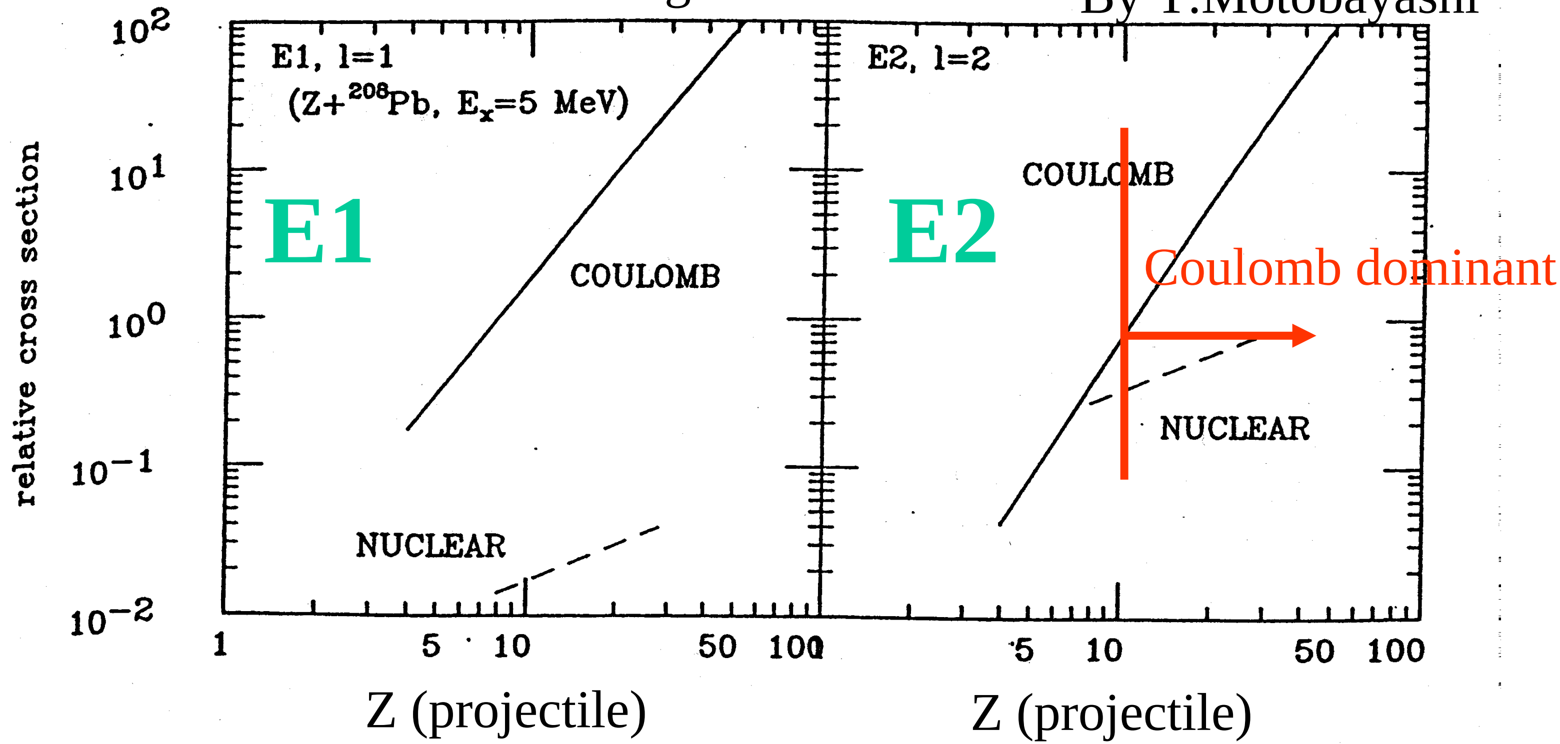
magicity loss at N=8 and 20

Intermediate-energy Coulomb excitation

E >> Vc : Coulomb barrier

E=70A MeV Pb target

By T.Motobayashi



high energy beams -> thick target

kinematical focusing -> high efficiency

high velocity -> single step excitation

Bernstein's prescription

PLB103, 255('81)

$$\delta^{F} = \frac{4\pi}{3eR_0} \frac{b_p^F M_p + b_n^F M_n}{b_p^F Z + b_n^F N}$$

Eg.1) F: electromagnetic

b_p=1.0 b_n=0

$$\delta^{em} = \frac{4\pi}{3eR_0} \frac{M_p}{Z} = \frac{4\pi}{3eR_0} \frac{1}{Z} \sqrt{B(\mathrm{E2})}$$

Eg.2) F: proton

b_p=0.3 b_n=0.7

$$\delta^{p,p'} = \frac{4\pi}{3eR_0} \frac{0.3M_p + 0.7M_n}{0.3Z + 0.7N}$$

New frameworks for the new region of nuclear chart

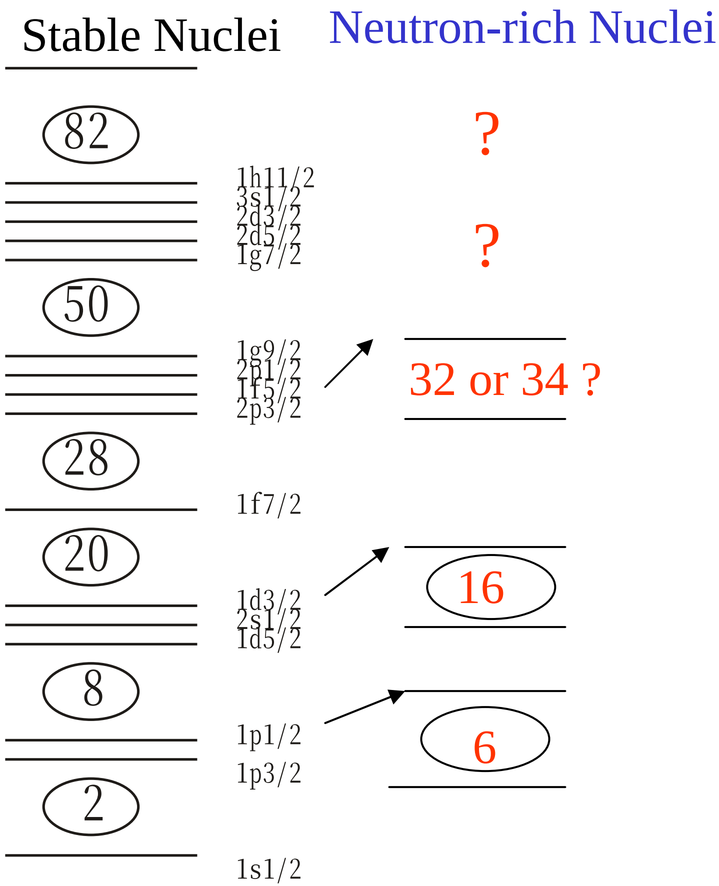
from **stable nuclei** to **neutron-rich** nuclei

Nuclear Structure

"magicity loss" N=8, 20, ...

"new magic numbers" N=6, 16, ...

large changes of shell structures



Nuclear Matter

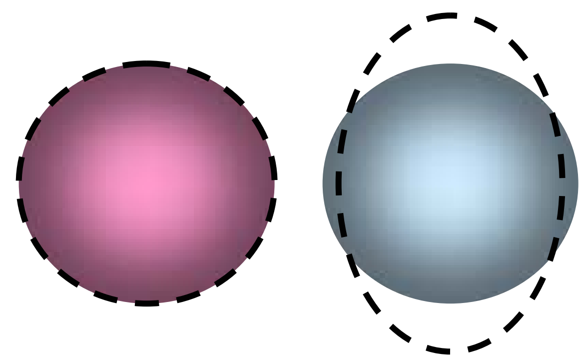
isospin dependence of nuclear radii $r = r_0 \times A^{1/3}$ (r_0=1.2 fm) ?

new forms of nuclear matters

neutron-skin nuclei   neutron-halo nuclei

Nuclear Collectivity

Two quantum liquid drops ?



r - process path

one of processes for nucleosynthesis beyond iron

Interdisciplinary field between nuclear physics and astrophysics

<u>Nuclear Physics</u>
- mass
- $T_{1/2}$
- Pn
- ...

<u>Astrophysics</u>
- Q-value for reactions
- mean free time
- reaction chain
- ...