Exotic structure of unstable nuclei revealed through a γ - ray spectroscopy technique

--- *with a emphasis on the study of the Island of Inversion nuclei*

AOI, Nori

RIKEN

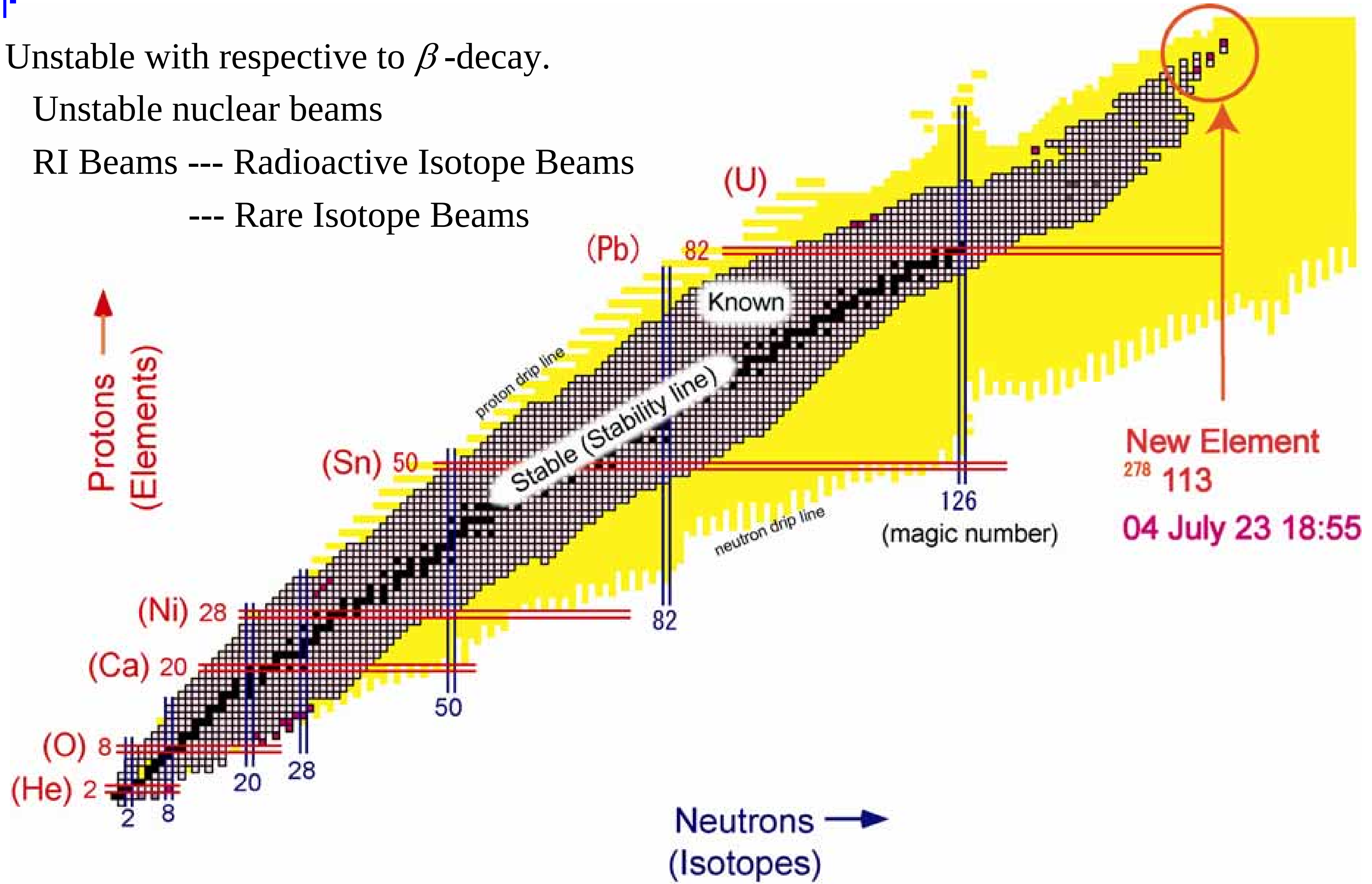
Unstable Nuclei

- Unstable with respective to β-decay.

  Unstable nuclear beams

  RI Beams --- Radioactive Isotope Beams

  --- Rare Isotope Beams

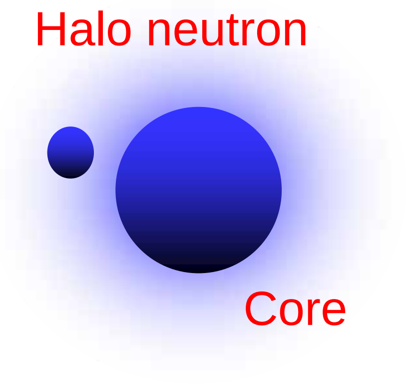


Characteristics of unstable nuclei

- Different Fermi surface of protons and neutrons
- Different single particle orbitals for valence protons and neutrons
- Different Isospin
- Weak binding

⋮

- Neutron halo
- Neutron skin
- Soft E1 mode
- Modification of effective charge
- Modification of shell structure
  - Disappearance of magic number
  - New magic number
- Decoupling of Neutron and Proton distribution



Production of Unstable Nuclear Beams

- High energy heavy ion beam

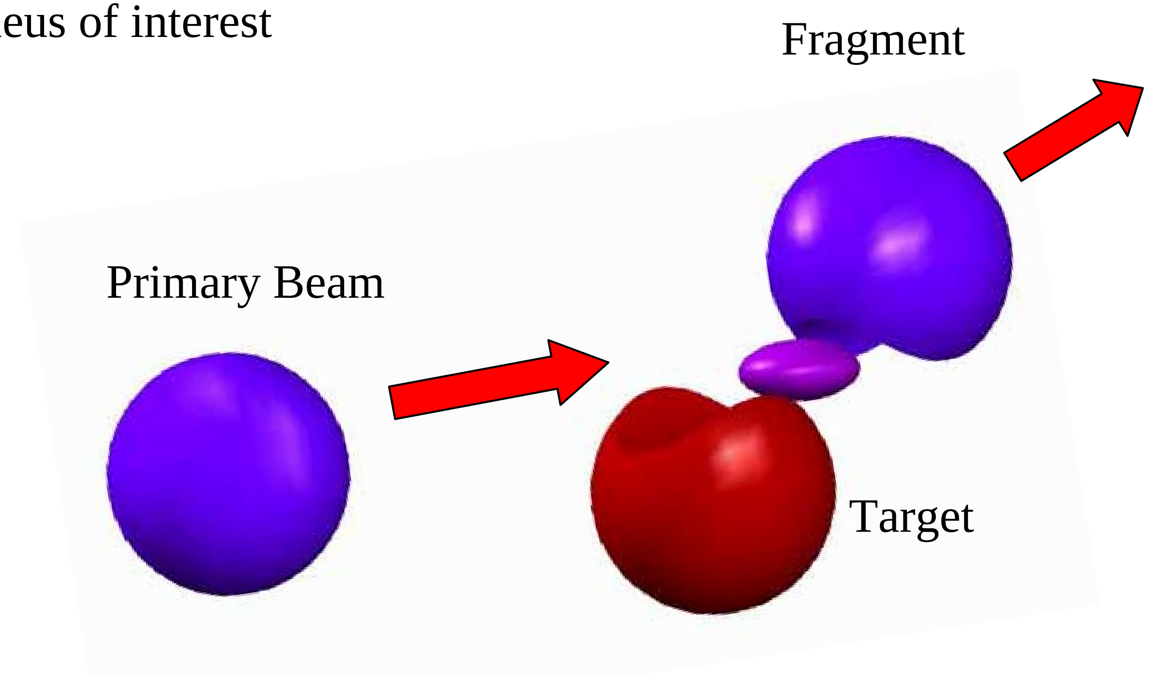
  + Production target (eg. Be)

  E_{beam} > Fermi energy ~ 40 MeV

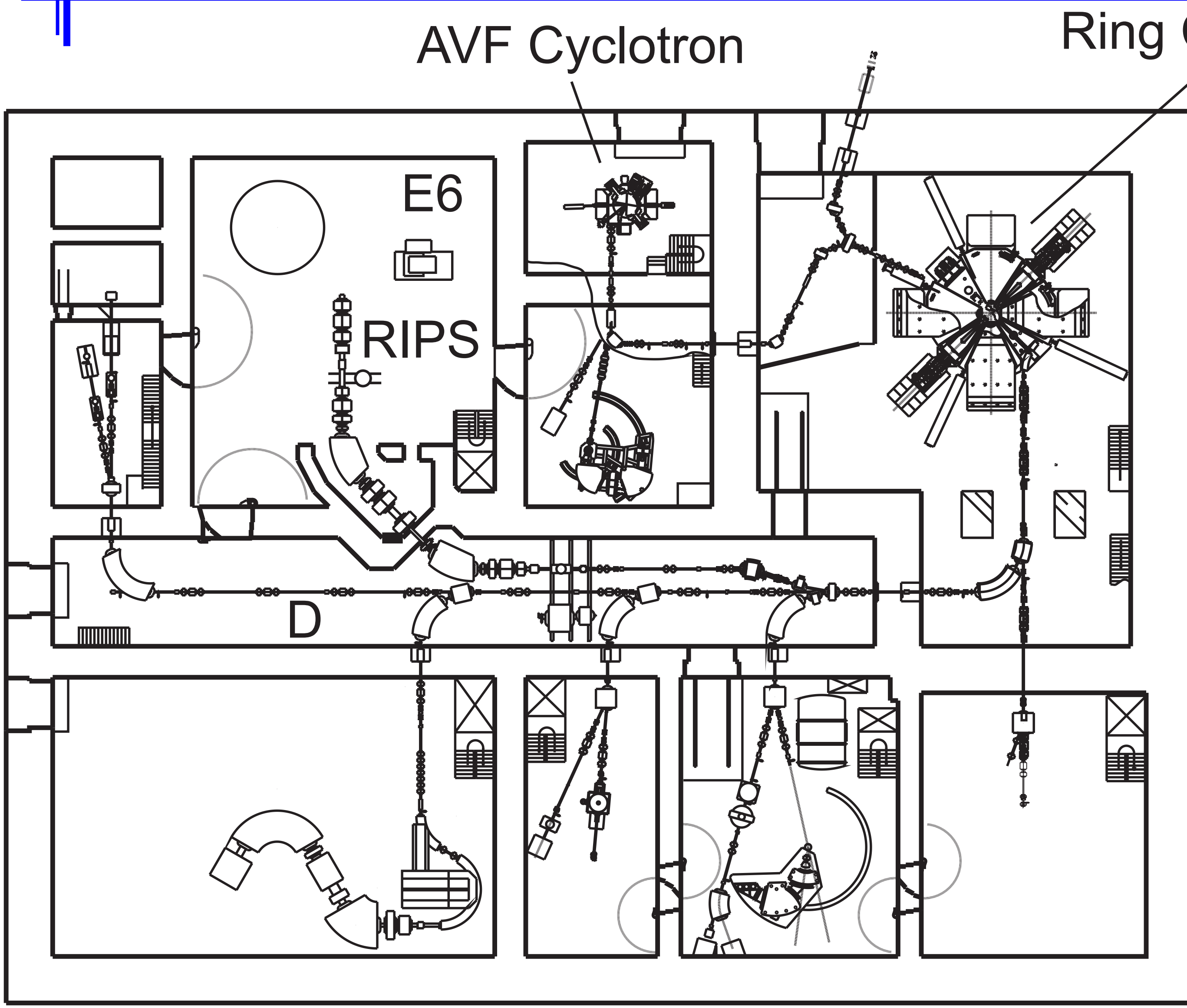
  Projectile fragmentation reaction

  ⇒ Various species of nuclei

- Collect and separate the nucleus of interest



RIKEN Accelerator Research Facility (RARF)



Heavy ion Accelerator
(Ring Cyclotron, K=540)

E = 63~135 AMeV

→RIKEN
Projectile-fragment
Separator
(RIPS)

Production of Unstable Nuclear Beams

- High energy heavy ion beam

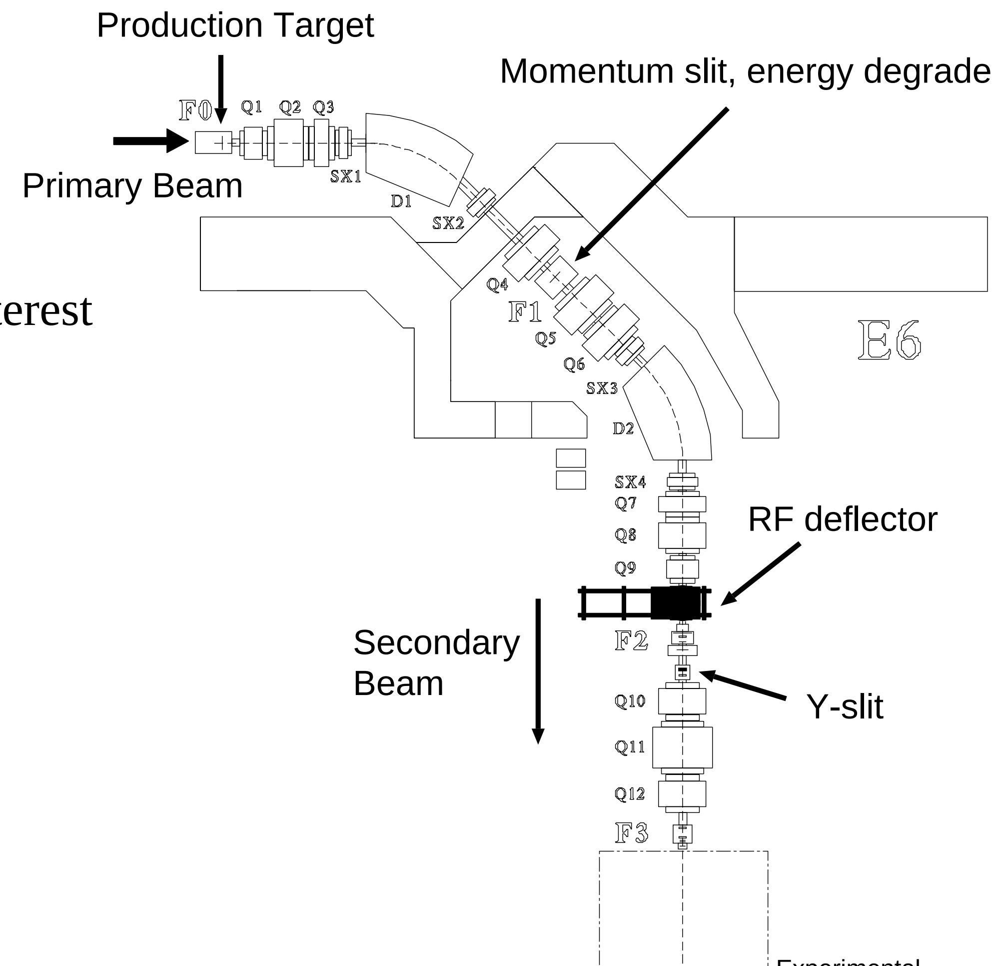
  \+ Production target (eg. Be)

  $E_{beam} >$ Fermi energy ~ 40 MeV

  Projectile fragmentation reaction

  ⇒ Various species of nuclei

RIPS
(RIKEN Projectile fragment Separator)



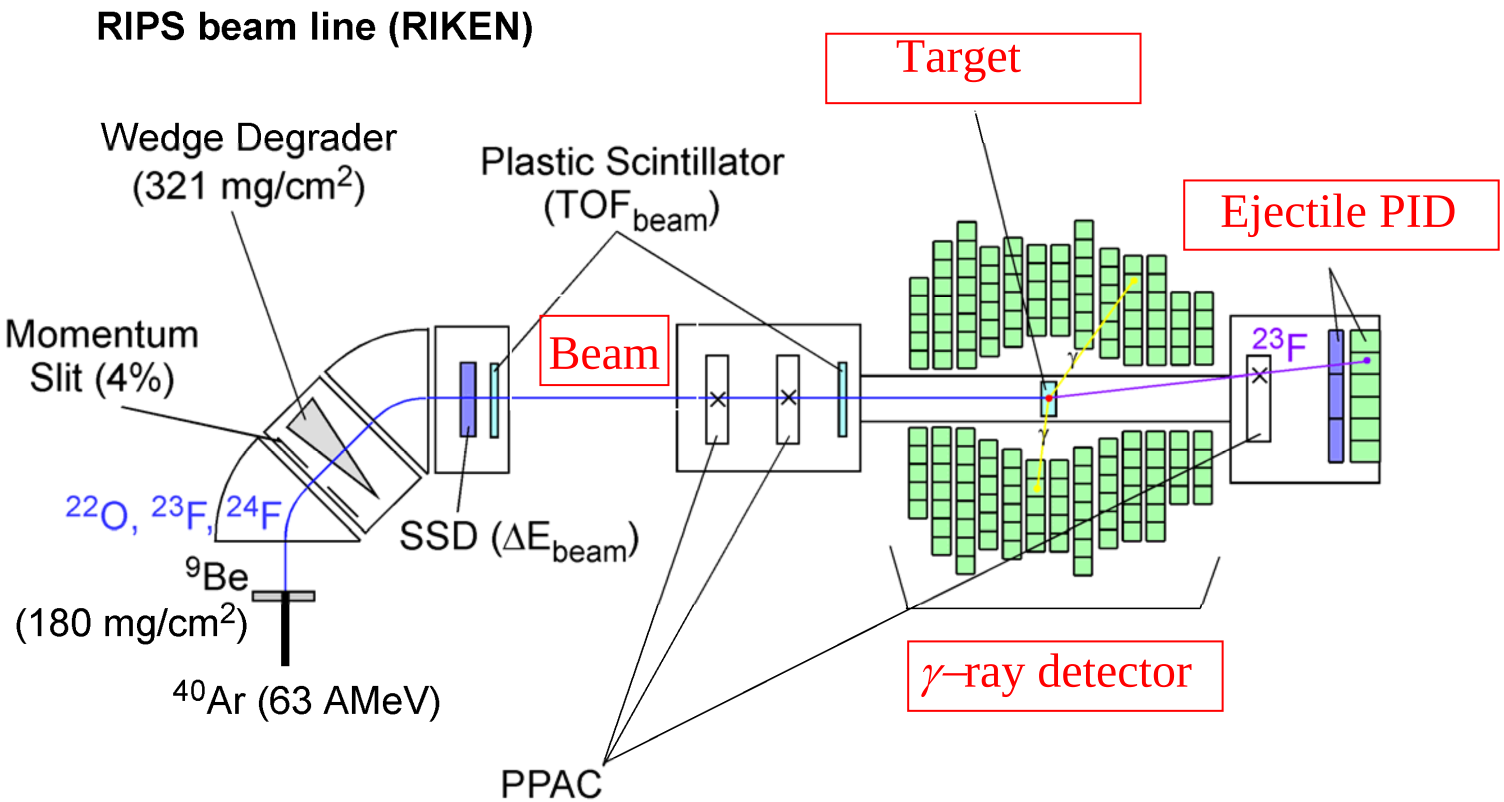
- Collect and separate the nucleus of interest

  First stage : $B\rho \sim A/Z$

  ⇩ *Energy degrador*

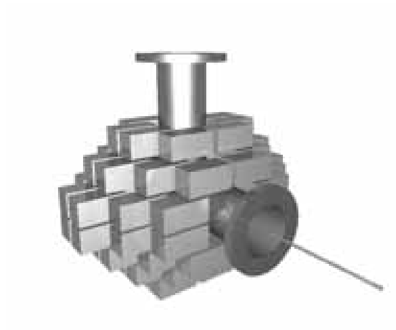
  Second stage : $B\rho \sim A^{2.5}/Z^{1.5}$

Typical Setup of γ–ray spectroscopy in inverse kinematics

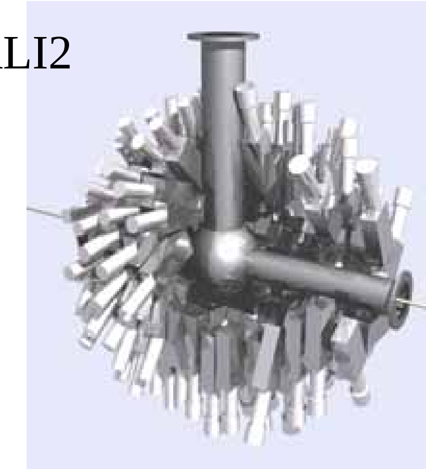


Upgraded NaI(Tl) detector array --- DALI2

DALI



DALI2



# of NaI(Tl) detectors	: 68	160
Angular resolution	: 15 deg.	8 deg.
Efficiency @ 1MeV	: 15%	21%
E resol. (β=0.3) @1MeV	: 12%	8%
Coverage (θ)	: 45~150 deg.	30~160 deg.

Experiments with high performance DALI2 detector.

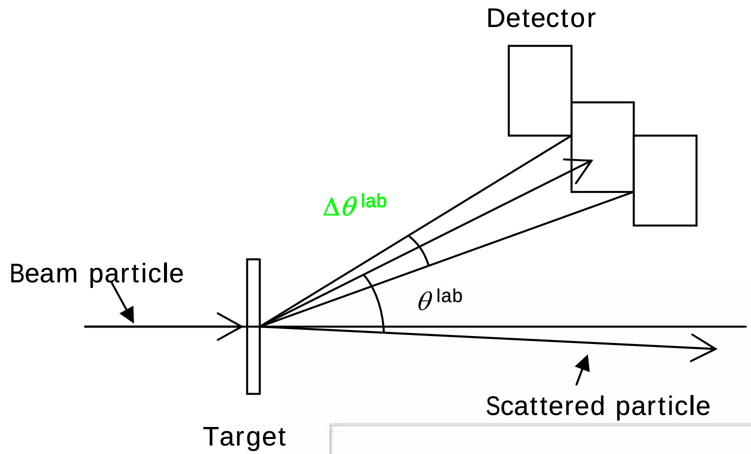
- γ–γ coincidence
- Angular distribution (particle)
- Angular distribution (γ–ray)
- γ–γ angular correlation
- Life time (Recoil Shadow Method)

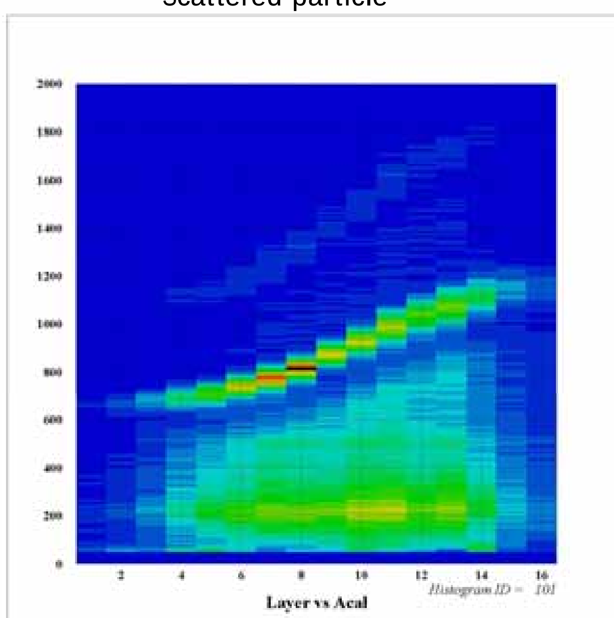
DALI2: S.Takeuchi et al., RIKEN Accel. Prog. Rep. **36**(2003)148

Upgraded NaI(Tl) detector array - DALI2

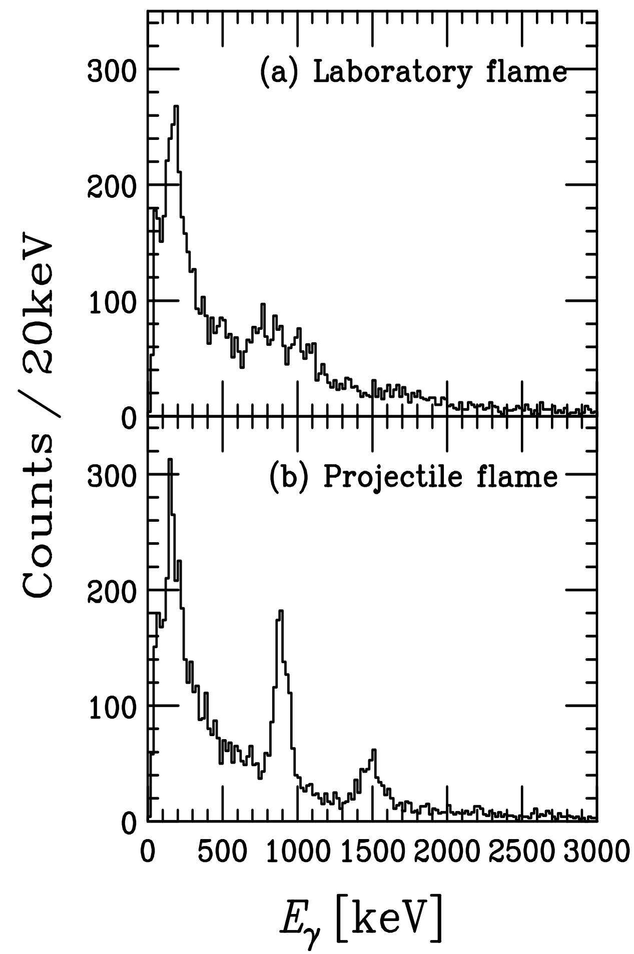
Doppler correction of γ-rays from fast RI Beam (β~0.3)

- g-ray source is moving with $\beta \sim 0.3$
  → Doppler shifted → need to be corrected for





^{32}Mg(p,p') β~0.3



H.Hasegawa, Master's thesis,

Rikkyo Univ., 2003

GRAPE
(Gamma-Ray detector Array with Energy and Position sensitivity)

CNS, Univ. Tokyo --- Shimoura et al.

S. Shimoura et al., CNS Annual Report 2001 (2002) 5.

Efficiency	5%	(4%; achieved)
Pos. resolution	2mm	(5mm; achieved)
E resolution	10keV	(16keV @ 2.1MeV, β=0.3; achieved)

Ejectile PID

- ΔE-E
  - SSD+SSD
  - SSD+NaI

- TOF-ΔE-E
  - Plastic scintillator hodoscope
  - TOF Spectrometer

γ-ray spectroscopy for unstable nuclei

$N\sim8$	^{12}Be	Magicity loss
$A=16$	^{16}C	Egg-like nucleus
$Z=9$	^{23}F, ^{27}F;	Single proton state
$N\sim20$	^{32}Mg, etc	Island of Inversion
$N\sim28$	^{42}Si, etc.	New doubly magic nuclei?
$N\sim32,34$	^{52}Ca, ^{56}Ti	New magic number?
$N\sim40$	^{64}Cr	New region of strong deformation?
$\sim^{78}Ni$	^{68,74}Ni,Ge, Se etc.	$N=50$, $Z=28$ magicity ?

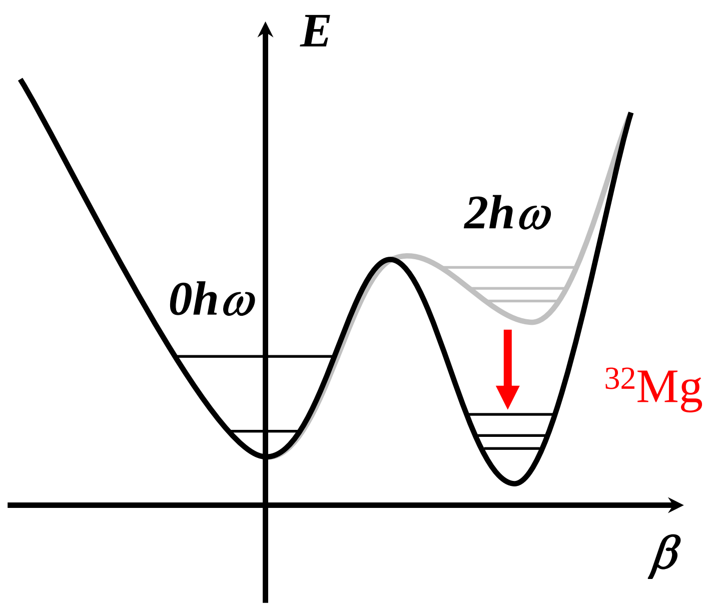
Island of Inversion

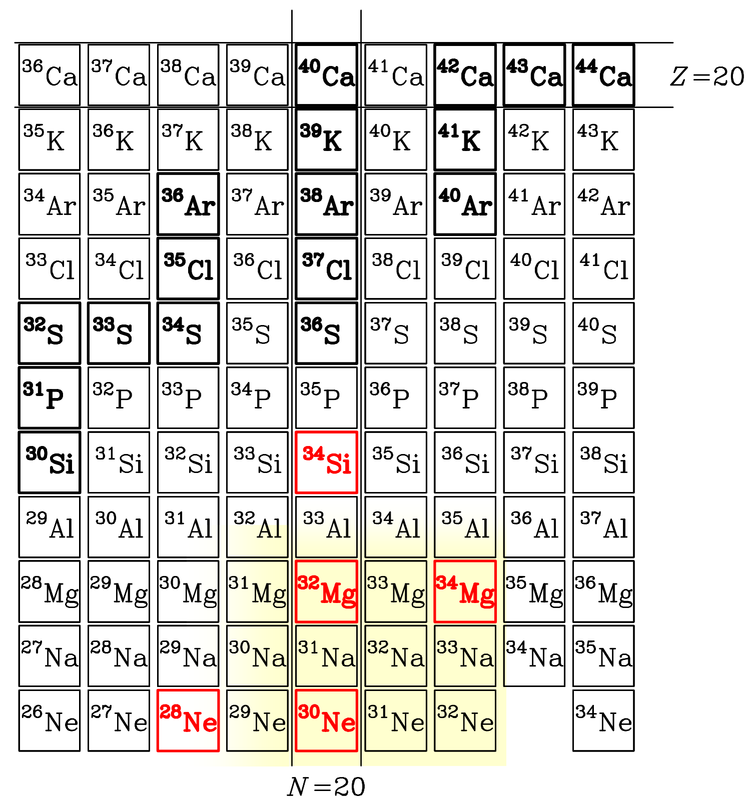
- Irregularity in Mass

  ^{31,32}Na, ^{31,32}Mg — C. Thibault et al., PRC12(75)644

  Irregularity in $E_x(2^+)$

  ^{32}Mg — C.Detraz et al., NPA394(83)378,
  E.K. Warburton et al., PRC41(90)1147.





Island of Inversion

- Irregularity in Mass

  ^{31,32}Na, ^{31,32}Mg C. Thibault et al., PRC12(75)644

  Irregularity in $E_x(2^+)$

  ^{32}Mg C.Detraz et al., NPA394(83)378,
  E.K. Warburton et al., PRC41(90)1147.

↓ Advent of In-flight RI beam facility

- Detailed γ-ray spectroscopy through properties of excited states
  via secondary reactions such as Coulomb excitation.

  Coulex → $B(\mathrm{E2}) \propto Q_0^2 \propto \beta_2^2$

  Collectivity large : B(E2) Large
  $E_x(2^+)$ small

Coulomb Excitation

Office of Naval Research, European Scientific Notes, No. 7–9, May 1, 1953

*Proposed Coulomb Excitation of Nuclei**

At a recent colloquium in the Institute for Theoretical Physics, Copenhagen, Dr. B. R. Mottelson discussed a novel proposal for producing excitation of nuclear states. Mottelson's proposal was to bombard atomic nuclei with charged particles whose energy is well below the barrier. The probability of penetrating the barrier would consequently not be appreciable, and the nucleus would experience only the Coulomb field. Thus the excitation resulting from the pulse of electromagnetic energy would reflect the properties of the target nucleus free from complication by the nuclear force between target and projectile.

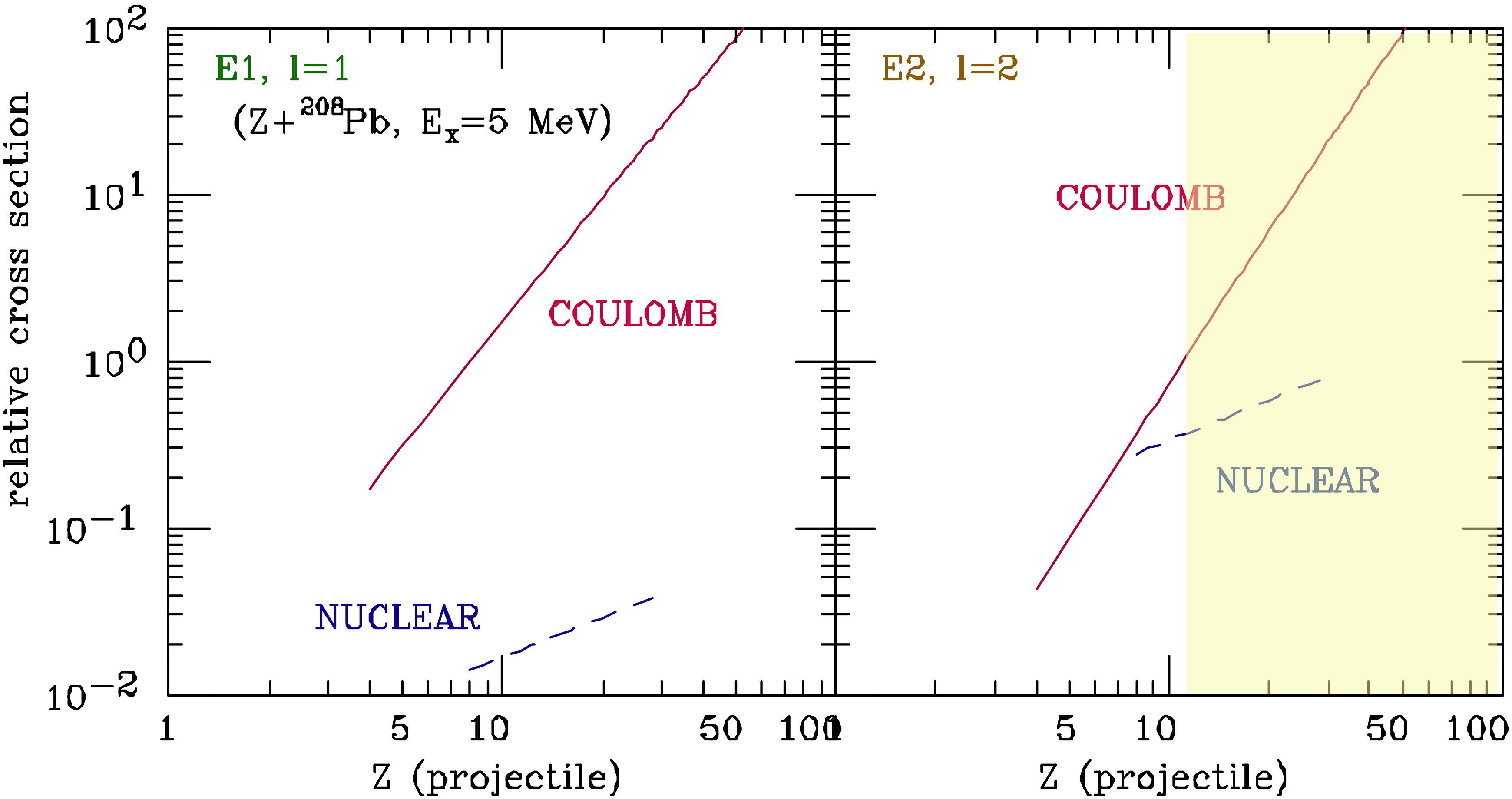
- Energy of in-flight RI beam is much higher than

  Coulom barrier = 4.0*A*MeV (^{32}Mg+^{208}Pb)

RIKEN,GANIL	~ 50*A* MeV
MSU,GSI	100 ~ 200*A* MeV
RIBF	~ 250*A* MeV

- For nuclei with Z>10, σ(Coulomb) > σ(nuclear)

  Huge Cross section ~ a few 100 mb

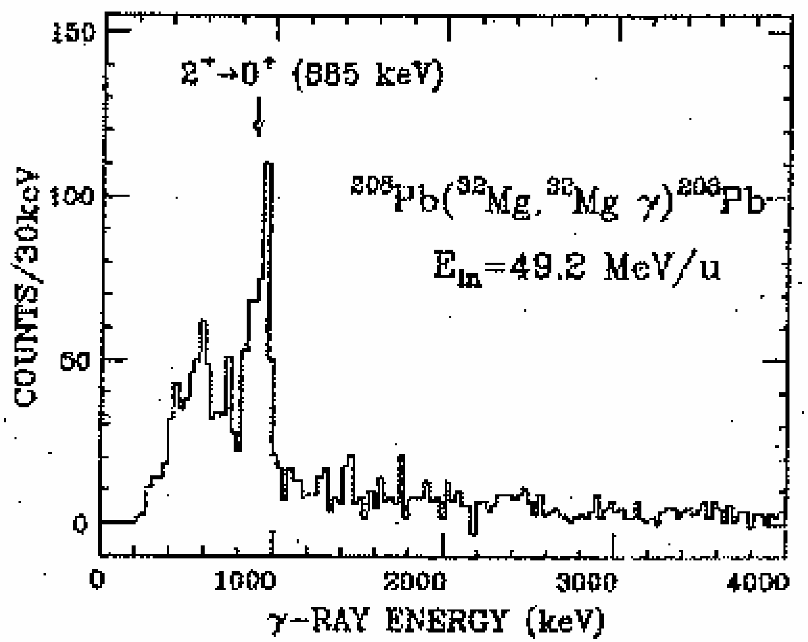


C > N

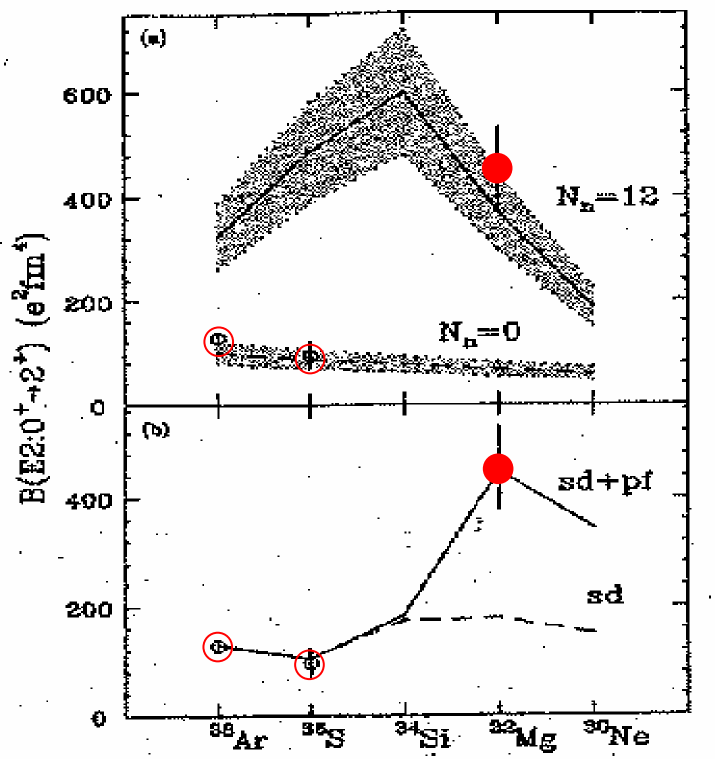
C ~N

E_{in} = 50 MeV/nucleon, a fixed deformation

^{32}Mg Coulex --- dawn of γ–ray spectroscopy of unstable nuclei



T. Motobayashi et al., Phys. Lett. B346,



Fukunishi et al., PLB 296, 279(92)

^{32}Mg beam: 300 cps

Exhibit: Strong deformation of ^{32}Mg
Usefulness of Int. Energy Coulex

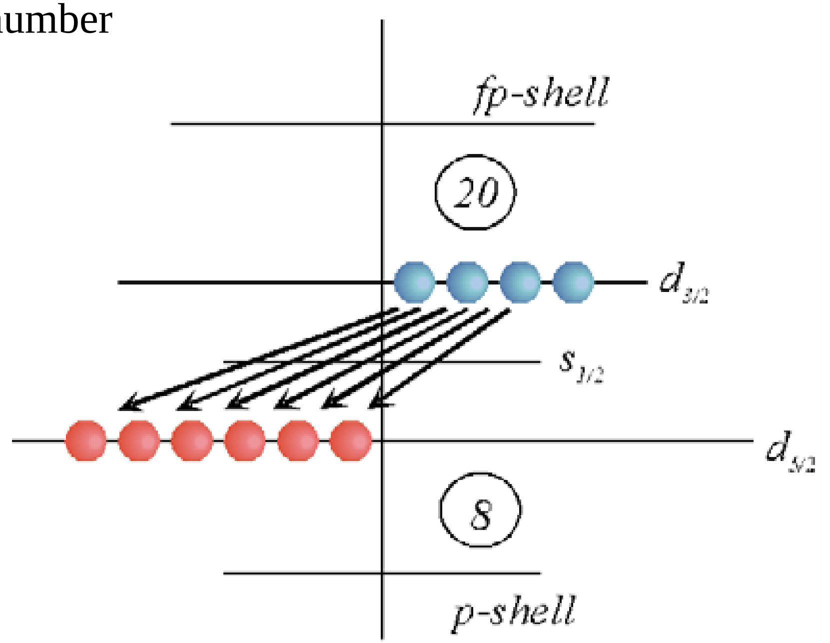
Strong deformation of ^{32}Mg

- Strong $\sigma\tau$ *N*-*N* Interaction ($(d_{5/2})_p$ -$(d_{3/2})_n$)

  T. Otsuka et al., PRL **87**, 082502 (2001).

  Y. Utsuno et al., PRC 60, 054315(1999)

  - Change of the effective single particle energies
  - Disappearance of *N*=20 magicity
  - *N*=16 new magic number



^{34}Si

Strong deformation of ^{32}Mg

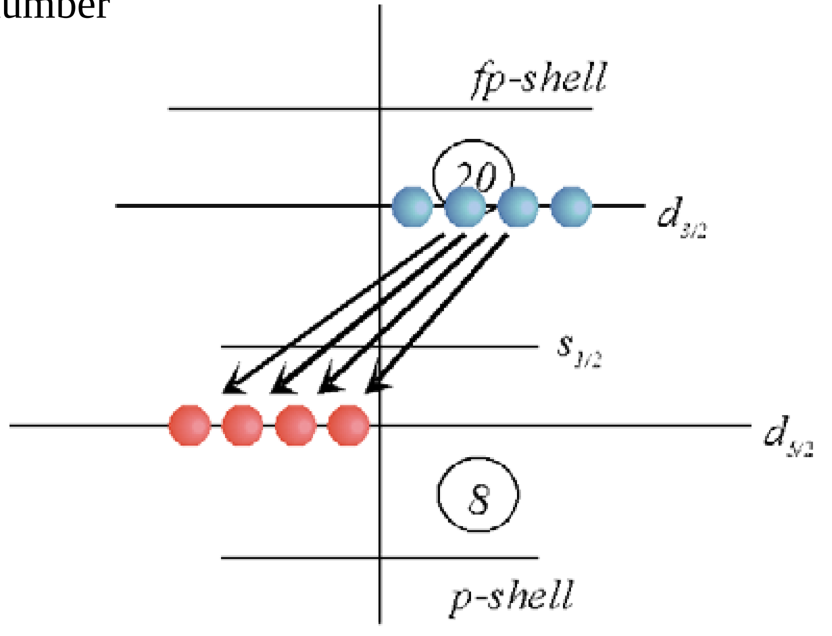
- Strong $\sigma\tau$ *N*-*N* Interaction ($(d_{5/2})_p$ -$(d_{3/2})_n$)

  T. Otsuka et al., PRL **87**, 082502 (2001).

  Y. Utsuno et al., PRC 60, 054315(1999)

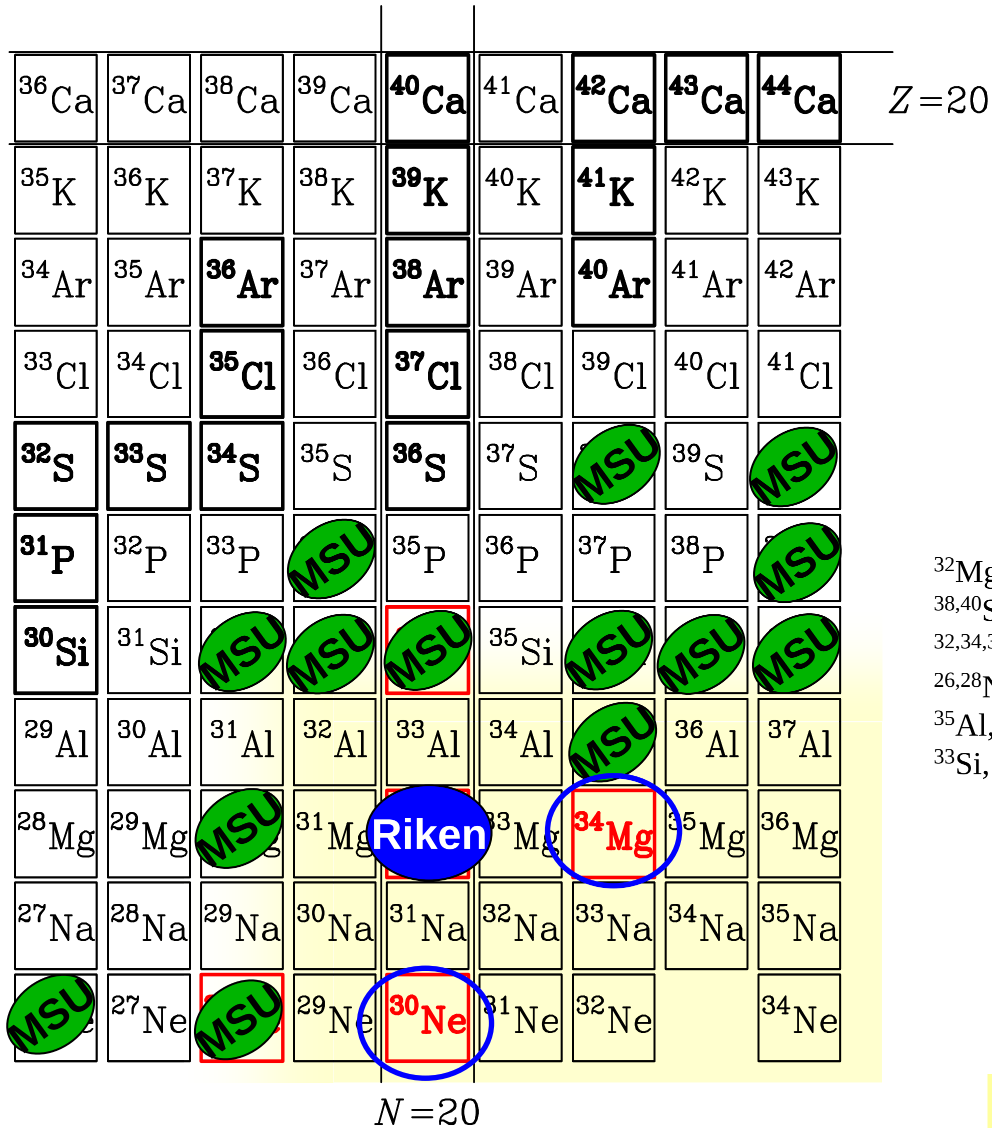
  - Change of the effective single particle energies
  - Disappearance of *N*=20 magicity
  - *N*=16 new magic number

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



^{32}Mg

Experiments in “Island of Inversion” region



^{32}Mg	:PLB346(95)9
^{38,40}S	:PRL77(96)3967.
^{32,34,36,38}Si	:PRL80(98)2081.
^{26,28}Ne, ^{30}Mg	:PLB461(99)322.
^{35}Al, ^{37}Si, ^{39}P	:PRC59(99)642.
^{33}Si, ^{34}P	:PRC62(00)051601(R).

Island of inversion

$E_x(2^+)$ measurement for ^{34}Mg by two-step projectile fragmentation method

- $E_x(2^+)$ and E_x $(4^+?)$

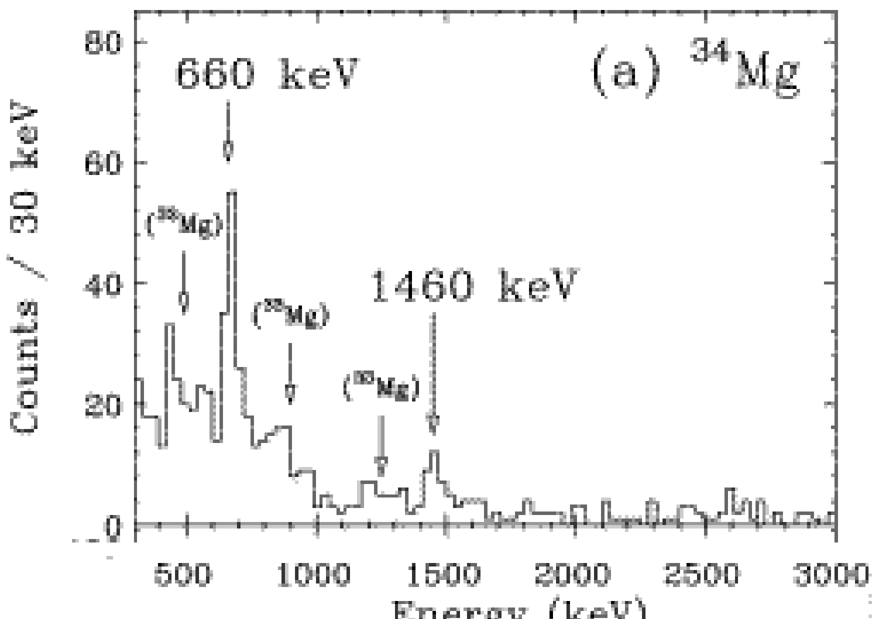
  Two-step projectile fragmentation method

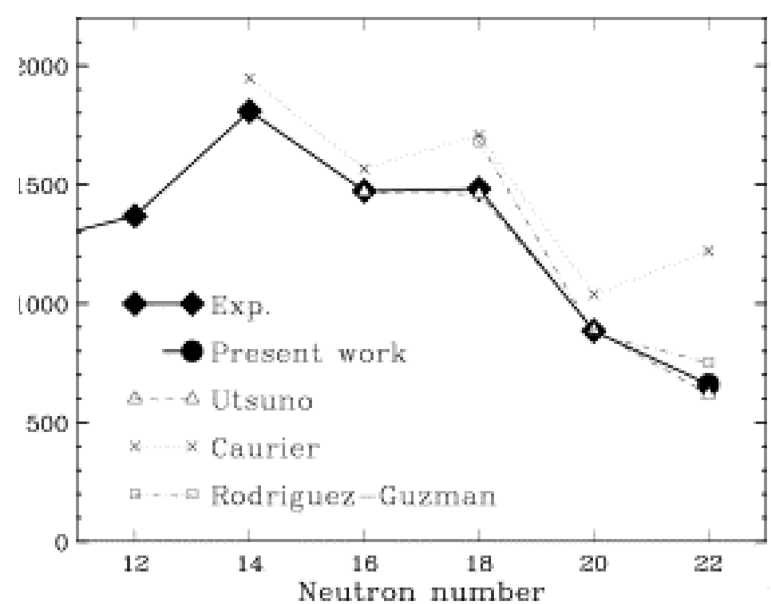
  ^{40}Ar (60pnA) → ^{36}Si (2×10^4 cps) → ^{34}Mg*

  → ^{34}Mg + γ

$E_x(2^+)$ = 660 keV   Lower than ^{32}Mg $E_x(2^+)$ = 885 keV

K. Yoneda et al., PLB499(2001) 233.





^{34}Mg *B*(E2) by Coulex

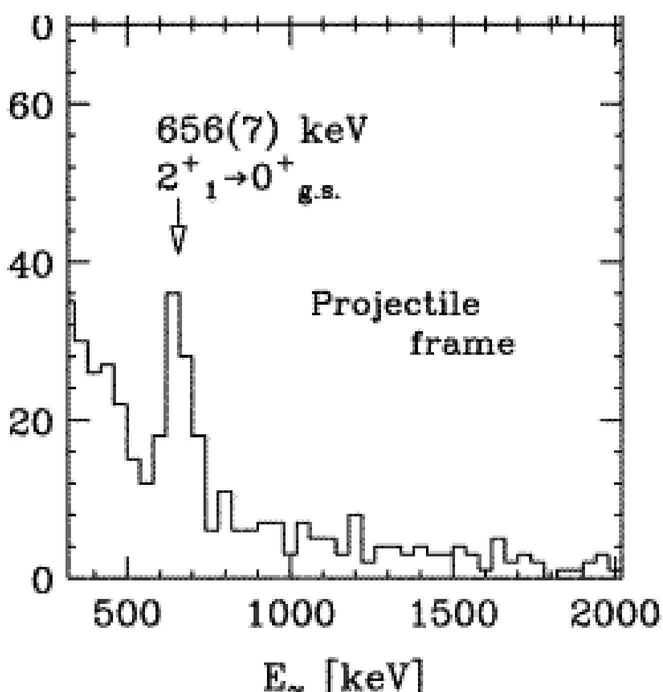
- B(E2) measurement by Coulomb excitation
  with 4 cps ^{34}Mg beam.

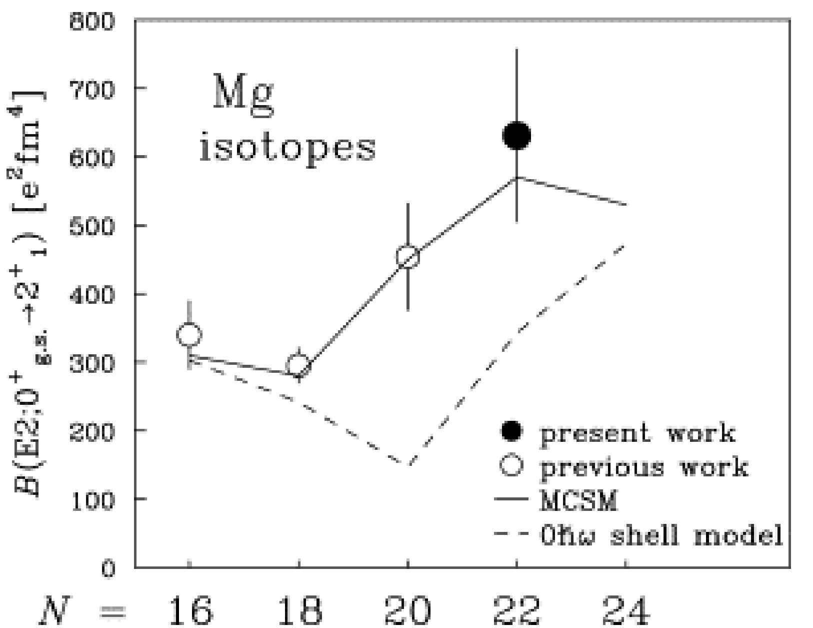
  B(E2) = 631(126)e^{2}fm^4

  Even larger than ^{32}Mg (454(78)e^{2}fm^4)

  H. Iwasaki et al., PLB522(2001)227.

^{34}Mg is located inside the Island of Inversion





^{34}Mg: 4 cps --- Succeeded

Already difficult

^{30}Ne: 0.2cps --- How do we do ?

(*p*,*p*’) using Liq. H_2 target

(p,p') with in-beam γ-ray spectroscopy tech. using Liq. H_2 target

- **Reaction mechanism**
  - **o Simple reaction mechanism:**
    - ←→ Heavy Ion induced reaction.
  - **x Complex reaction mechanism: --- Optical potential problem**
    - ←→ Coulex
  - **• Sensitive both to protons and to neutrons**
    - ←→ Coulex, → M_n/M_p
  - **• "Loose" selectivity**
    - **o** Chance to study levels with various Jp ;2^+, 1^-, 3^- , 0^+ , 4^+, 1^+,…
    - **x** Need of correction for cascade decays → γ–γ analysis, …
    - • J^{π} assignment → angular distribution, angular correlation,…
- **Experimental advantages**
  - **o Efficient-1:**
    - Largest number of nuclei in the target with energy loss equivalent thickness.
    - → Highest luminosity
  - **o Efficient-2:**
    - Large acceptance for ejectiles due to kinematical focusing.
  - **o Clean spectra-1:** (γ -ray spectroscopy)
    - Absence of background g -rays (or X-rays) originating from the target.
  - **o Clean spectra-2:**
    - Pure proton target ←→ CH_2 target – C target

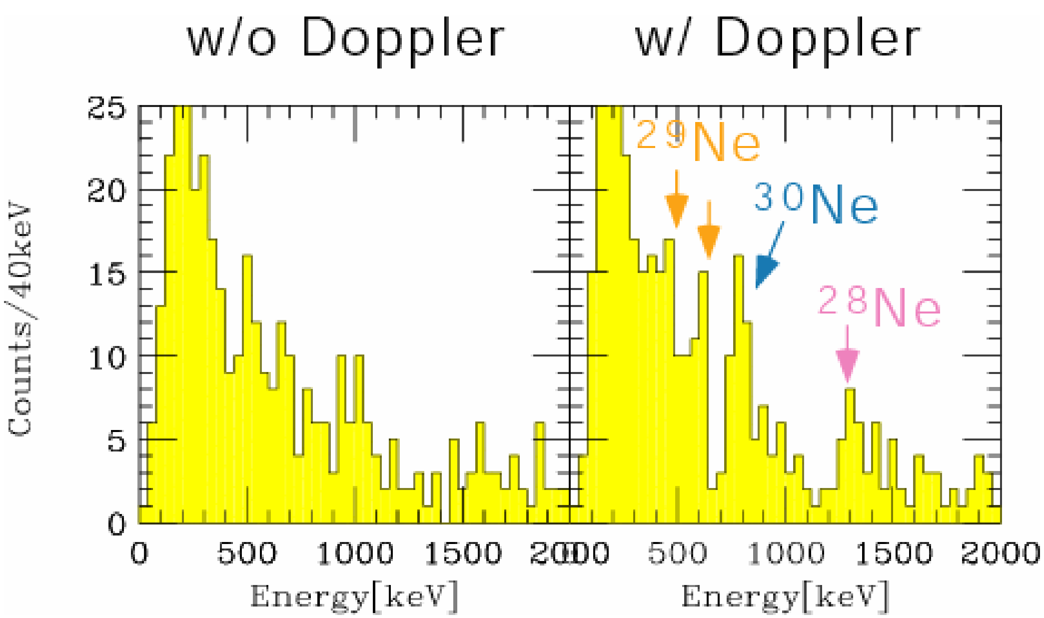
^{30}Ne $E_x(2^+)$

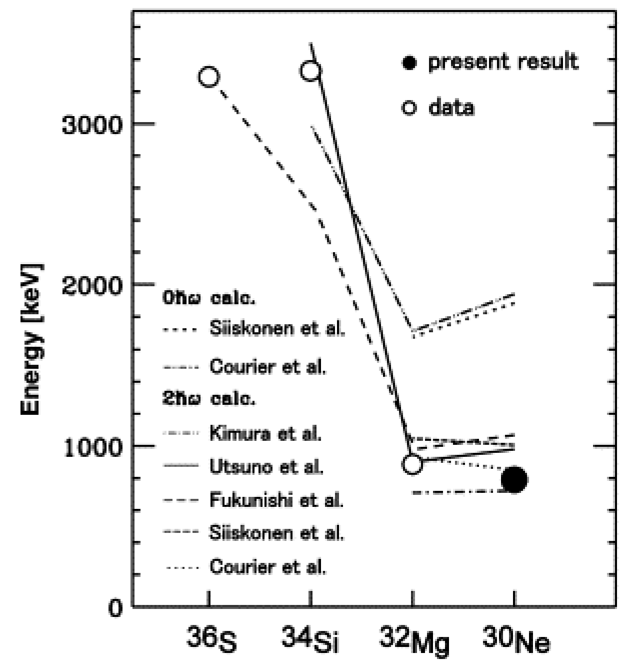
- H(^{30}Ne,^{30}Ne γ) = ^{30}Ne (p, p')

  Ex(2+) = 791(26) keV

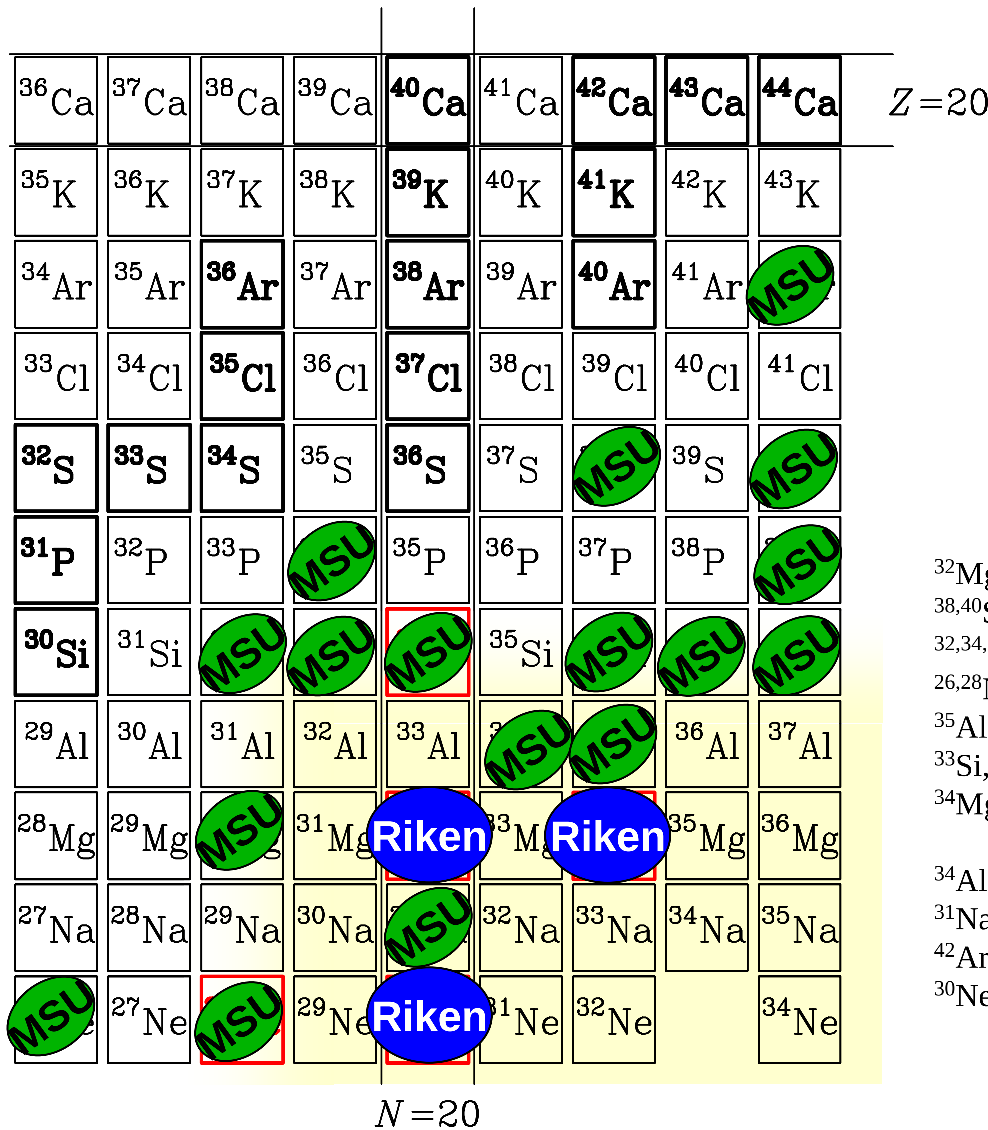
  Y.Yanagisawa et al., PLB566(02)84

  ^{30}Ne is located inside the Island of Inversion





Experiments in “Island of Inversion” region



^{32}Mg	:PLB346(95)9
^{38,40}S	:PRL77(96)3967.
^{32,34,36,38}Si	:PRL80(98)2081.
^{26,28}Ne, ^{30}Mg	:PLB461(99)322.
^{35}Al, ^{37}Si, ^{39}P	:PRC59(99)642.
^{33}Si, ^{34}P	:PRC62(00)051601(R).
^{34}Mg	:PLB499(01) 233. PLB522(01)227
^{34}Al	:PRC63(01)047308.
^{31}Na	:PRC63(01)011305(R) .
^{42}Ar	:PRC63(01)014604.
^{30}Ne	:PLB566(02)84

Island of inversion

^{34}Si --- Boundary of Island of Inversion ?

- Coulomb excitation @ MSU

  R.W.Ibbotson et al., PRL 80(98)2081

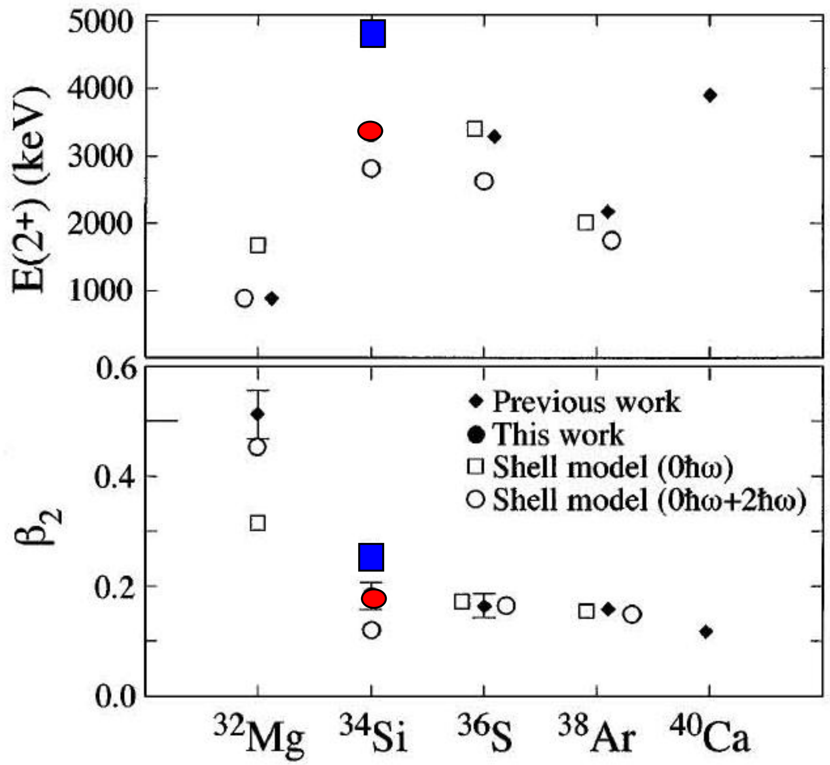
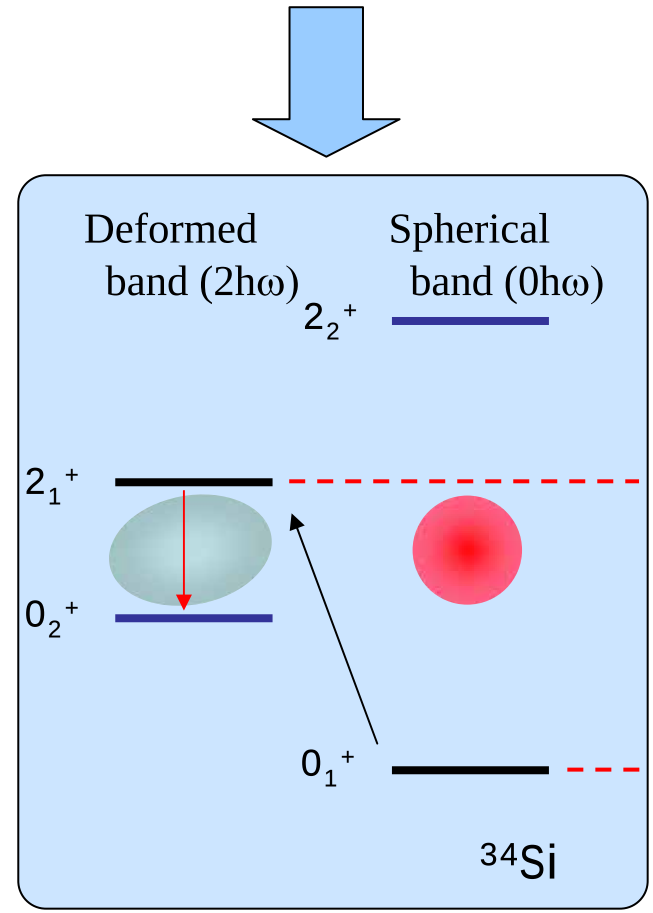
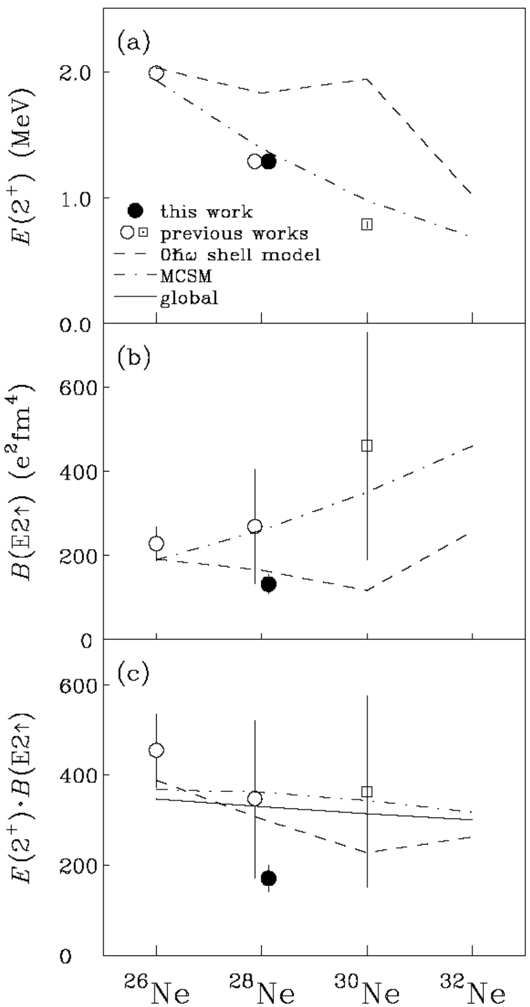


FIG. 3. The deformation parameter β_2 extracted from the known $B(E2\uparrow)$ values in the $N = 20$ nuclei. The ^{34}Si measurement is from the present work.

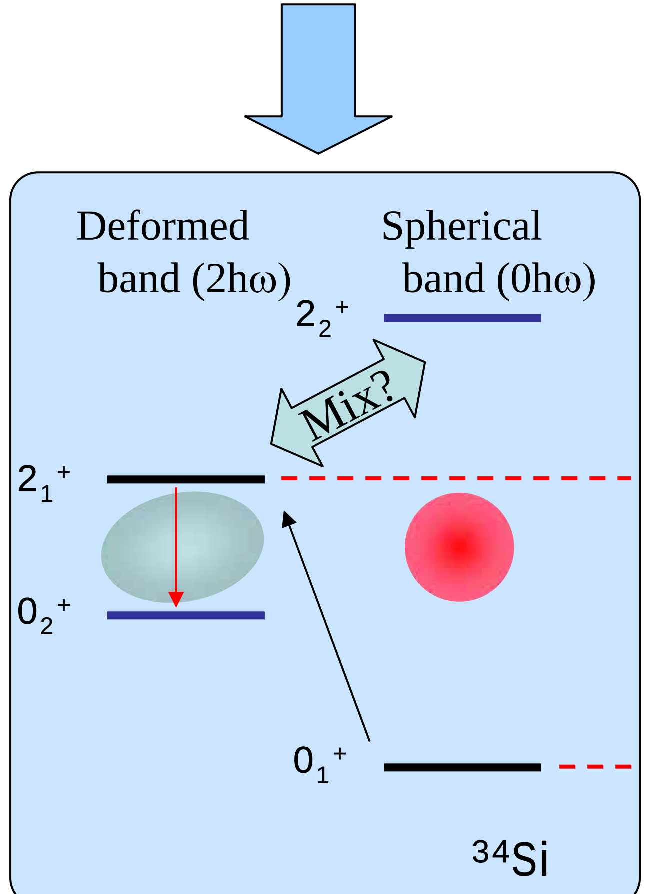
B(E2) (β_2) is smaller than the value predicted from $E_x(2^+)$



^{28}Ne --- Boundary of Island of Inversion ?

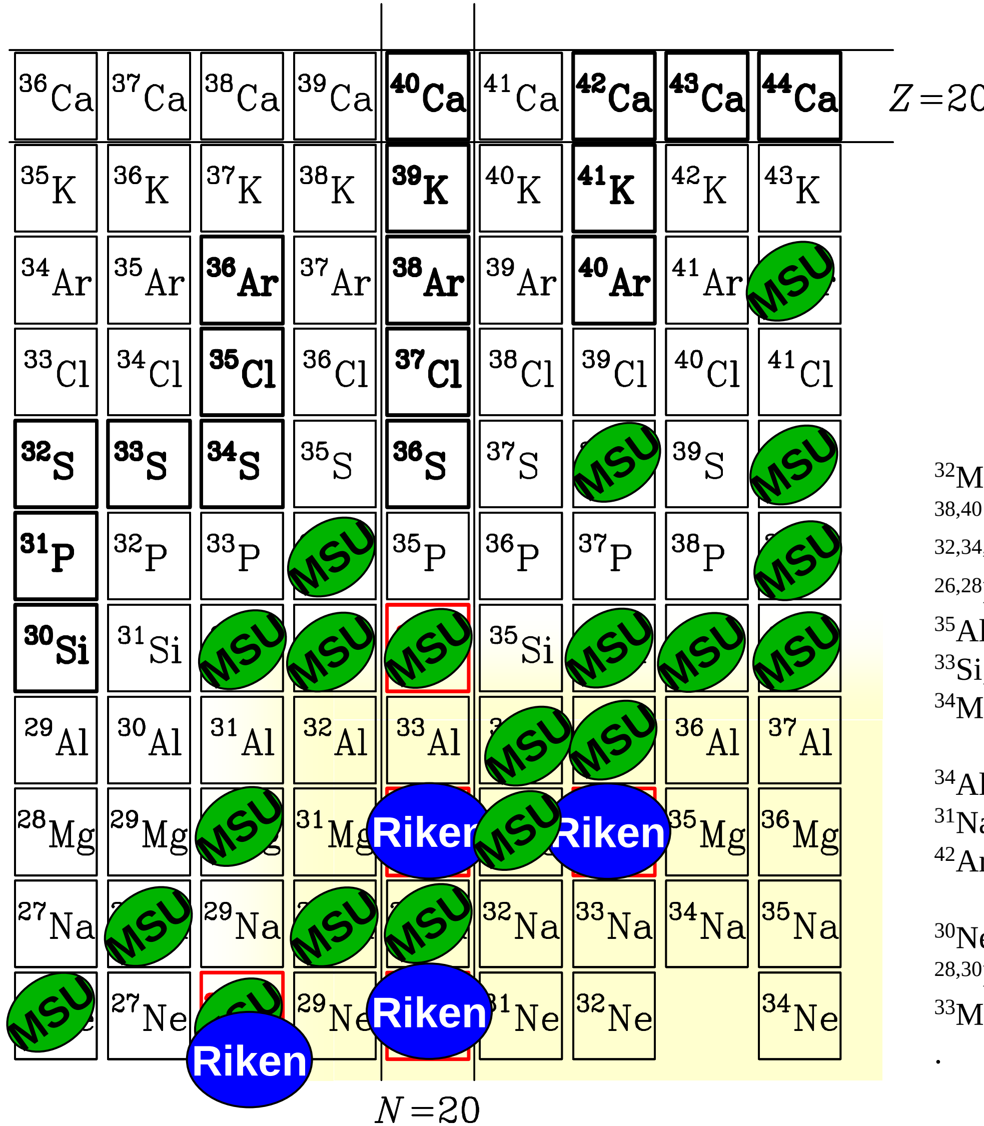


Ex(2$^+$): agree with 2hω calculation
B(E2): agree with 0hω calculation



H. Iwasaki *et al.*, *PLB* **620** (2005)118.

Experiments in “Island of Inversion” region



^{32}Mg	:PLB346(95)9
^{38,40}S	:PRL77(96)3967.
^{32,34,36,38}Si	:PRL80(98)2081.
^{26,28}Ne, ^{30}Mg	:PLB461(99)322.
^{35}Al, ^{37}Si, ^{39}P	:PRC59(99)642.
^{33}Si, ^{34}P	:PRC62(00)051601(R).
^{34}Mg	:PLB499(01) 233. PLB522(01)227
^{34}Al	:PRC63(01)047308.
^{31}Na	:PRC63(01)011305(R) .
^{42}Ar	:PRC63(01)014604.
^{30}Ne	:PLB566(02)84
^{28,30}Na	:PRC66(02)024325.
^{33}Mg	:PRC65(02)061304(R).

.

Island of inversion

More elaborate study for the nuclei

in and around the Island of Inversion

Possibility of shape coexistence in ^{32}Mg and ^{34}Si

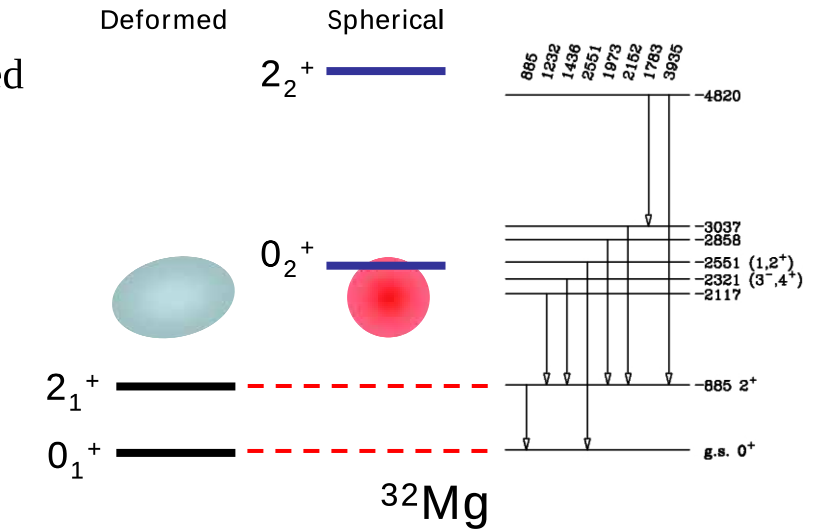
S. Takeuchi et al.

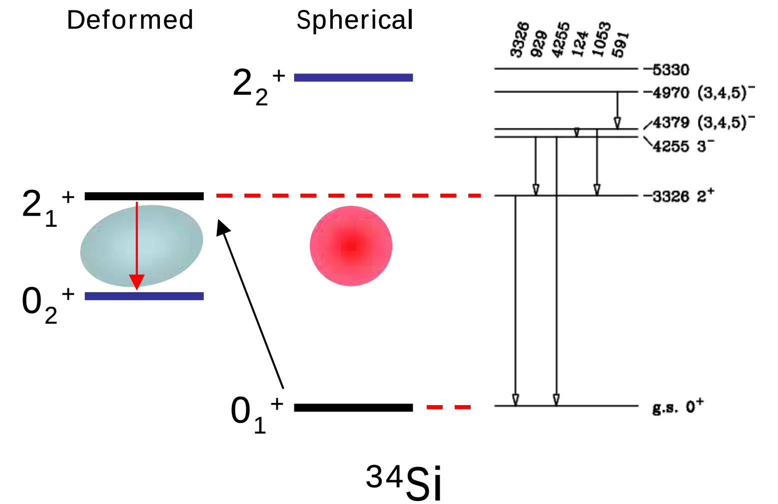
^{32}Mg, ^{34}Si

Shape co-existence has not yet been established experimentally nor directly.

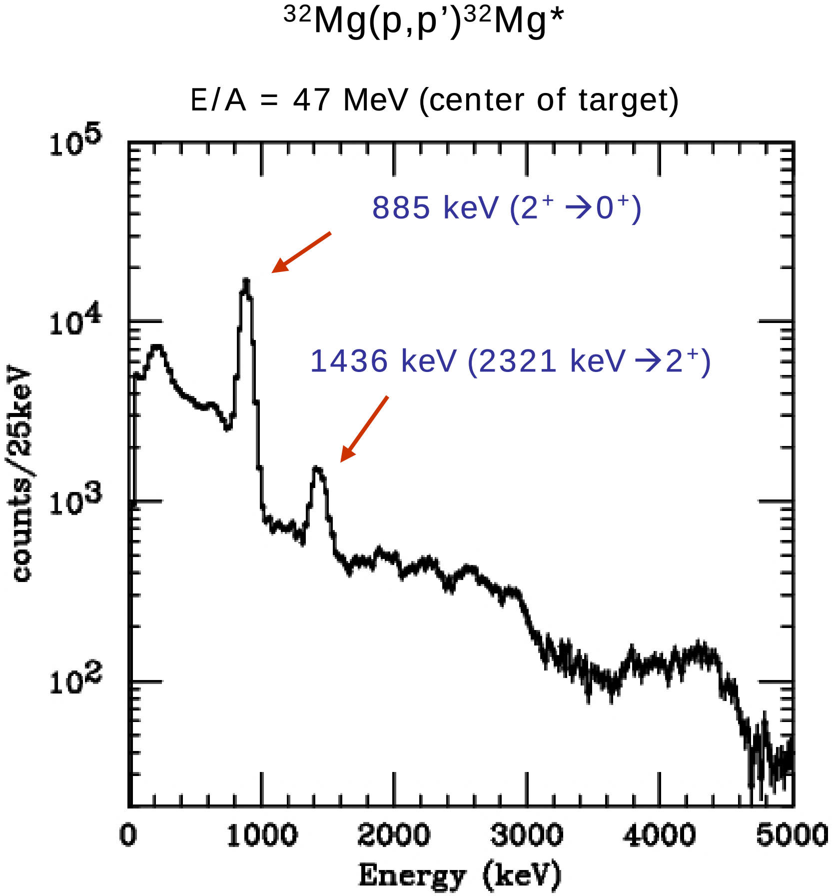
→ detailed spectroscopy with (p,p')

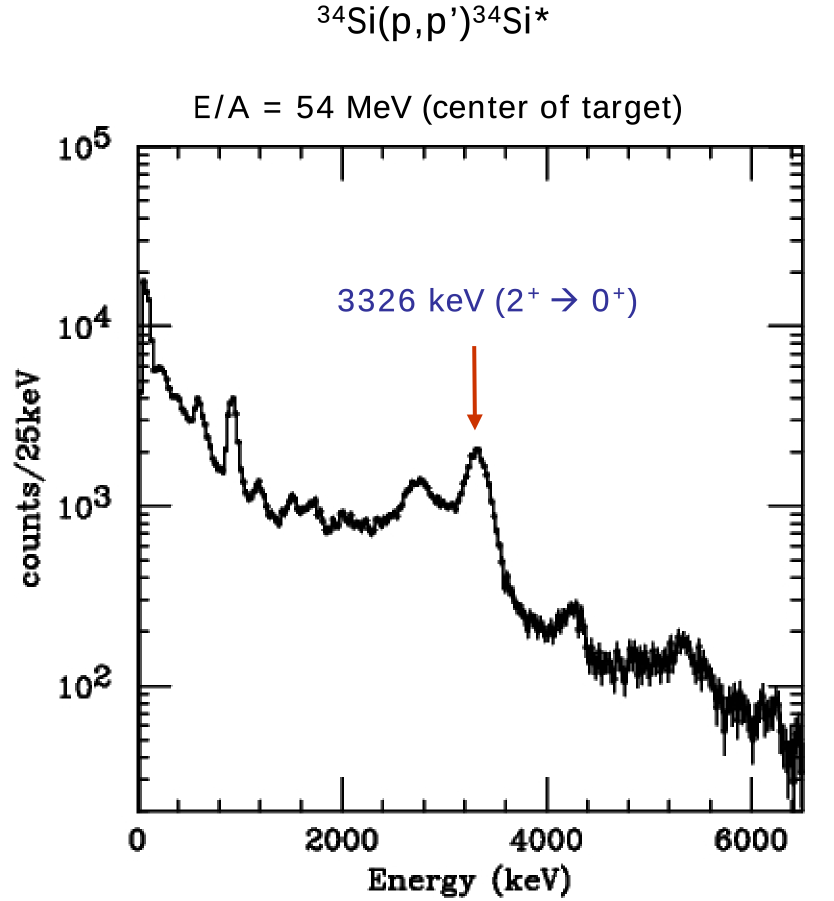
- J^{π} determination
- $d\sigma/d\Omega(\theta)$
- γ ray angular distirubution
- γ–γ angular correlation
- M_n/M_p (p,p')+Coulex





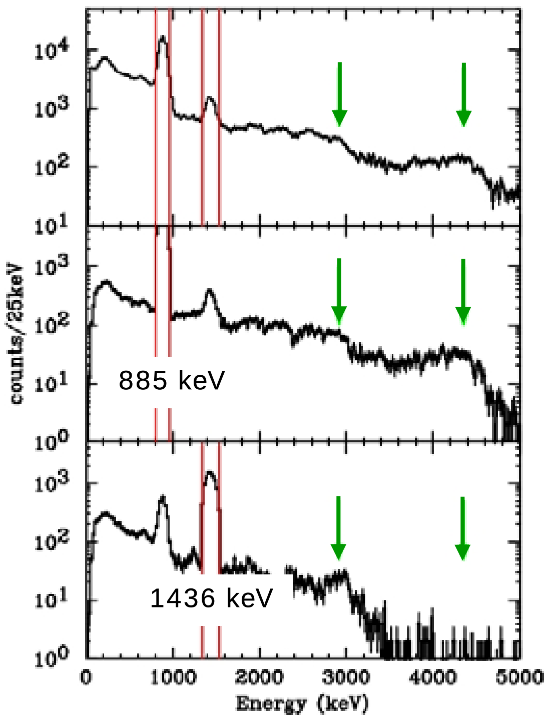
γ-ray spectra of $^{32}Mg(p,p')^{32}Mg^*$ and $^{34}Si(p,p')^{34}Si^*$

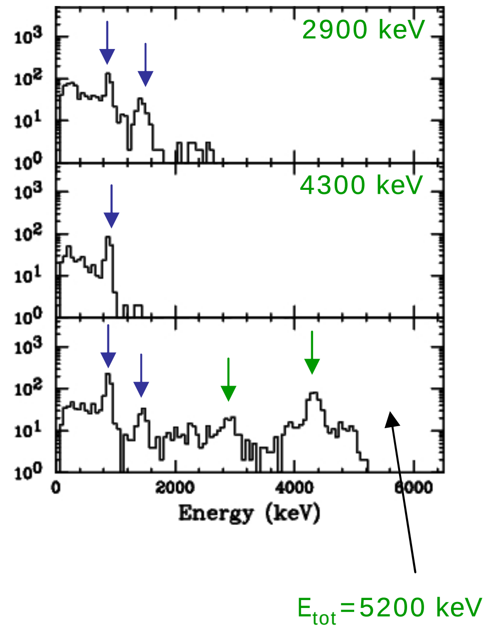


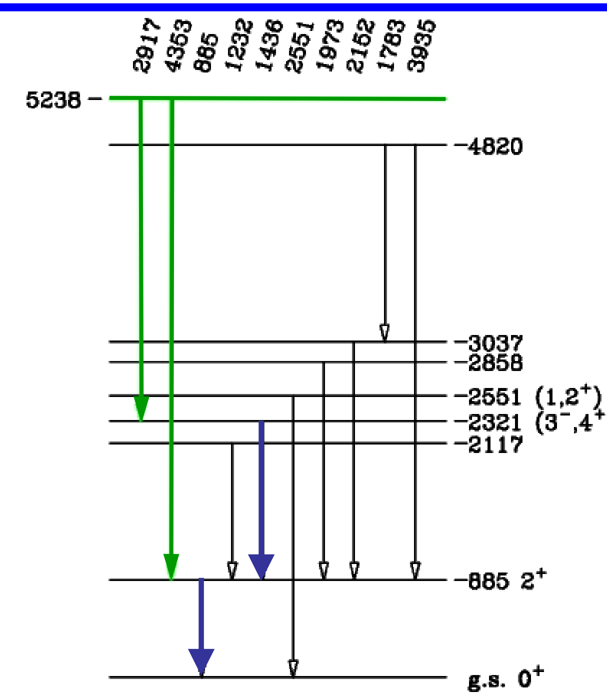


- γ-ray spectra were obtained after Doppler corrected by DALI2 for each reactions.
- In order to obtain cross sections, γ-γ analysis was performed to estimate cascading contributions.

γ-ray spectra -^{32}Mg-







2900 keV γ ray is coincident with both 885 and 1436 keV γ rays.

2900 keV + 1436 keV + 885 keV = 5221 keV

4300 keV γ ray is coincident with 885 keV γ ray while it disappear in 1436 keV gate spectrum.

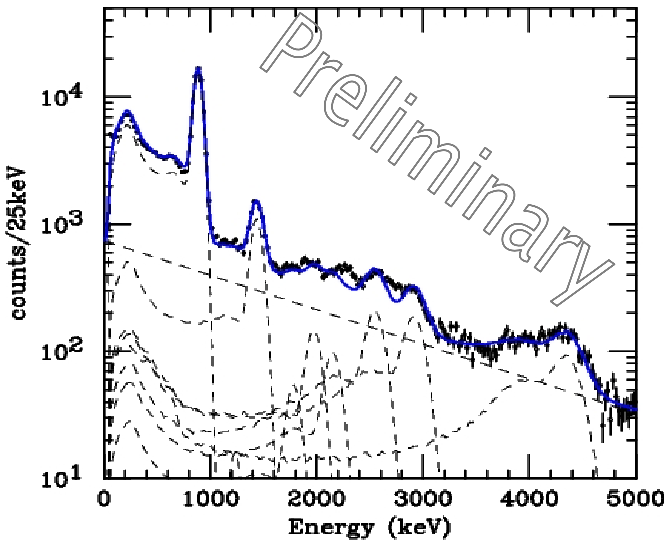
4300 keV + 885 keV = 5185 keV

Peak energies are obtained γ-γ spectrum with 5200 keV gate on total energy spectrum as follows:

4353 keV, 2917 keV.

Assuming those γ rays are transitions from same level, level energy is assigned to be 5238 keV preliminary.

Cross sections $-^{32}$Mg-



$\sigma(0^+ \rightarrow 2^+)$ = 43.8(56) mb

$\sigma(0^+ \rightarrow 3^-/4^+)$ = 3.8(9) mb

Deformation parameter and deformation length are deduced from DWBA calculation (ECIS97) with CH89 optical parameters.

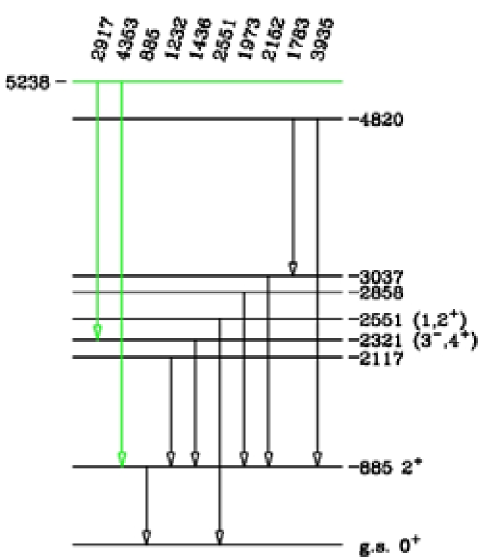
$\beta_2^{pp'}$ = 0.472(30), $\delta_2^{pp'}$ = 1.768(112) fm for 2^+ state.

Adopted value*

β_2 = 0.473(43), δ_2 = 1.802(164) fm (r_0 = 1.2fm)

* S. RAMAN et al., Atomic Data and Nuclear Data Tables **78**(2001)1

(Mn/Mp)/(N/Z) = 0.955



E_x (keV)	J^π	C.S. (mb)
5238		5.4(12)
4820		0.4(2)
3037		0.6(4)
2858		1.4(4)
2551	$(1,2^+)$	2.6(5)
2321	$(3^-,4^+)$	3.8(9)
2117		0.1(1)
885	2^+	43.8(56)

Discussion about E_x = 2321 keV state

$J^\pi = 3^-$ case : Deformation parameter β_3 is deduced from DWBA calculation and experimental cross section assuming one-phonon state as follows.

$\beta_3^{pp'}$ = 0.162(14)

$J^\pi = 4^+$ case : Cross section is estimated to be 1.2 mb by DWBA calculation with $\beta_2^{pp'}$ = 0.472 assuming two-step transition.

“Safe Coulomb excitation”

Coulomb excitation

^{30}Mg + Ni

at around Coulomb barrier, 2.25AMeV

@ REX-ISOLDE

Smaller B(E2) …

PRL **94**, 172501 (2005) PHYSICAL REV

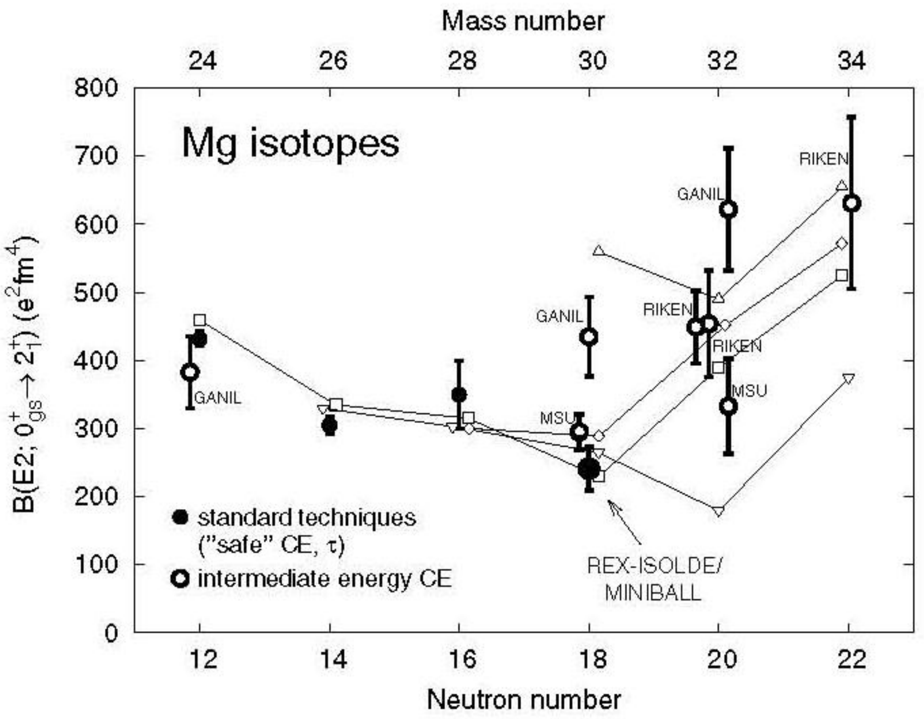


FIG. 2. Experimental (open and filled circles) and theoretical $B(E2)\uparrow$ values (connected by thin lines to guide the eye) for the even Mg isotopes. The experimental data are from Refs. [5–8,23] and the present experiment; the theoretical values are from □ [11], ◇ [9], ▽ [10,26] (normal), △ [10] (intruder).

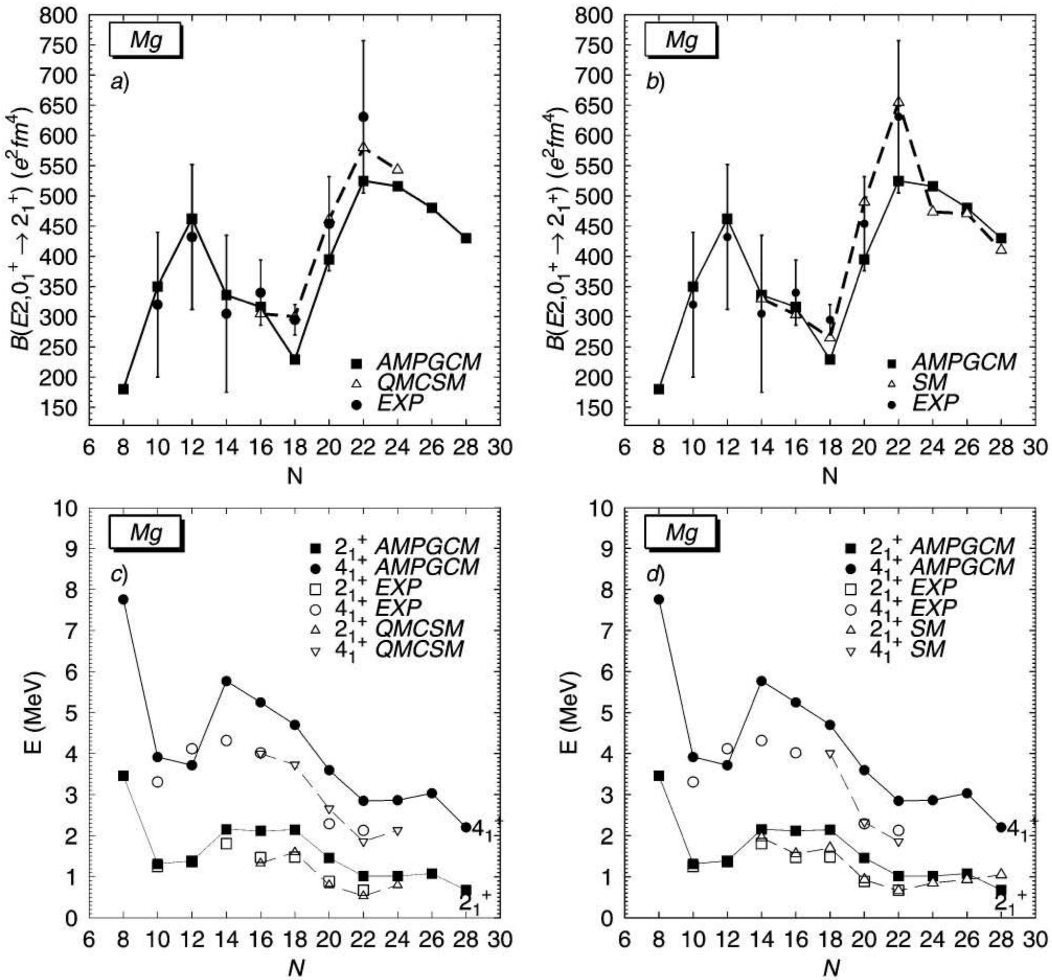
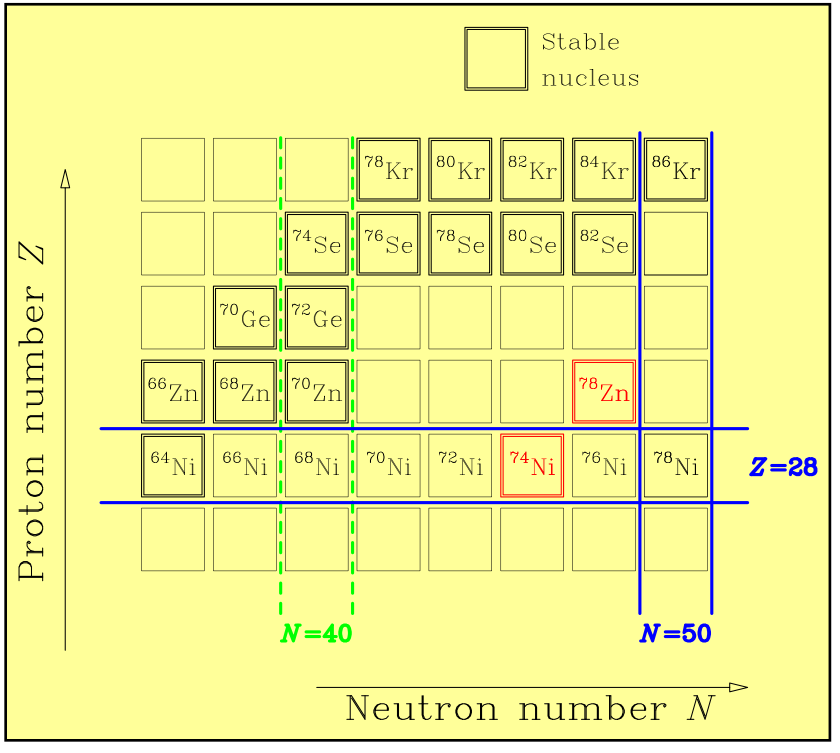
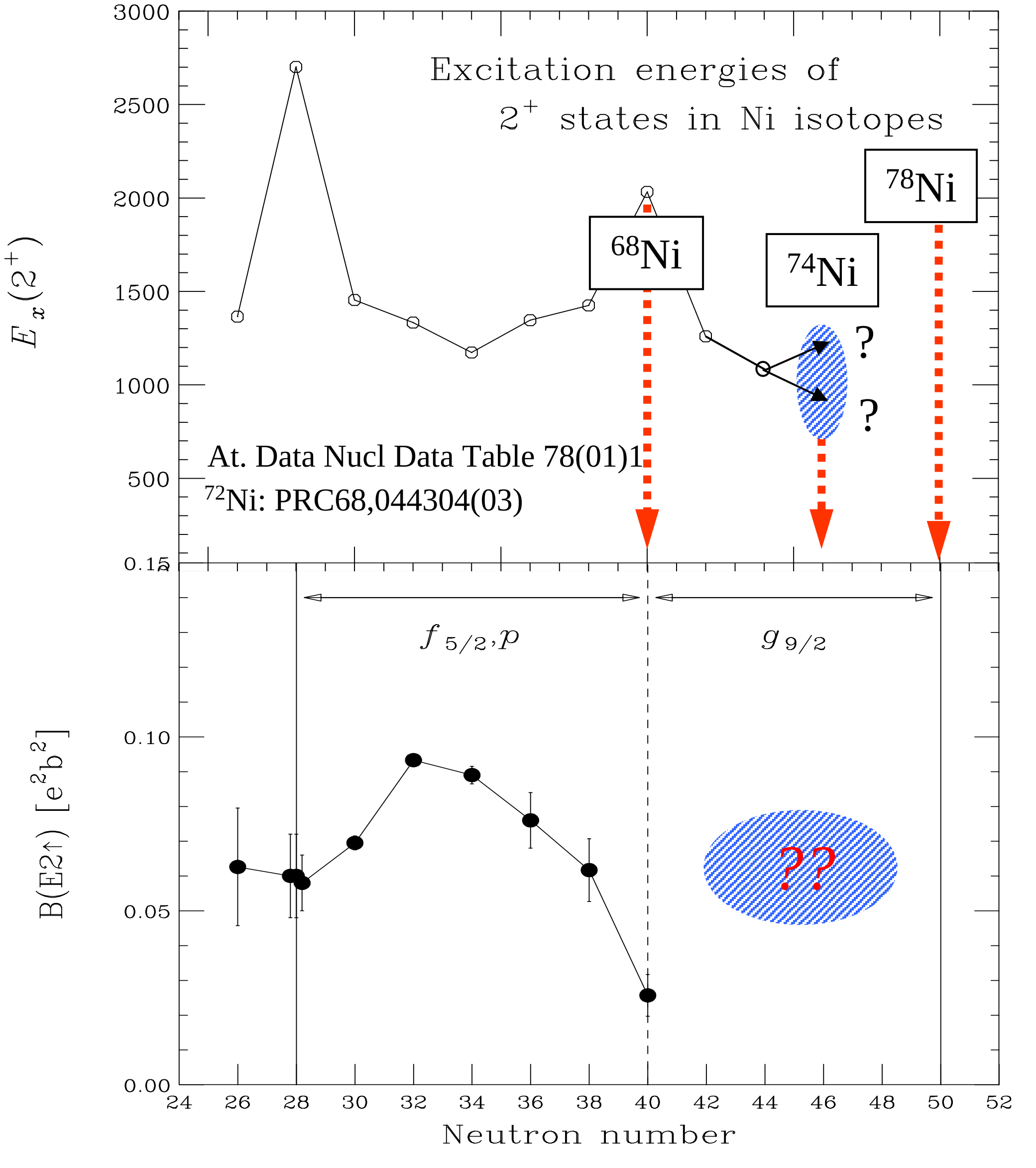


Fig. 13. The excitation energies of the states 2_1^+ and 4_1^+ provided by the AMPGCM and the $B(E2, 0_1^+ \rightarrow 2_1^+)$ transition probabilities in $^{20-40}$Mg are compared with the available experimental data [15,16,19,20,22,23,25] and with the theoretical predictions of the Quantum Monte Carlo Shell Model [45] and the Shell Model [44,46].

^{74}Ni (p,$p'\gamma$) experiment

S. Kanno et al.





^{74}Ni: $E_x(2^+)$ unknown

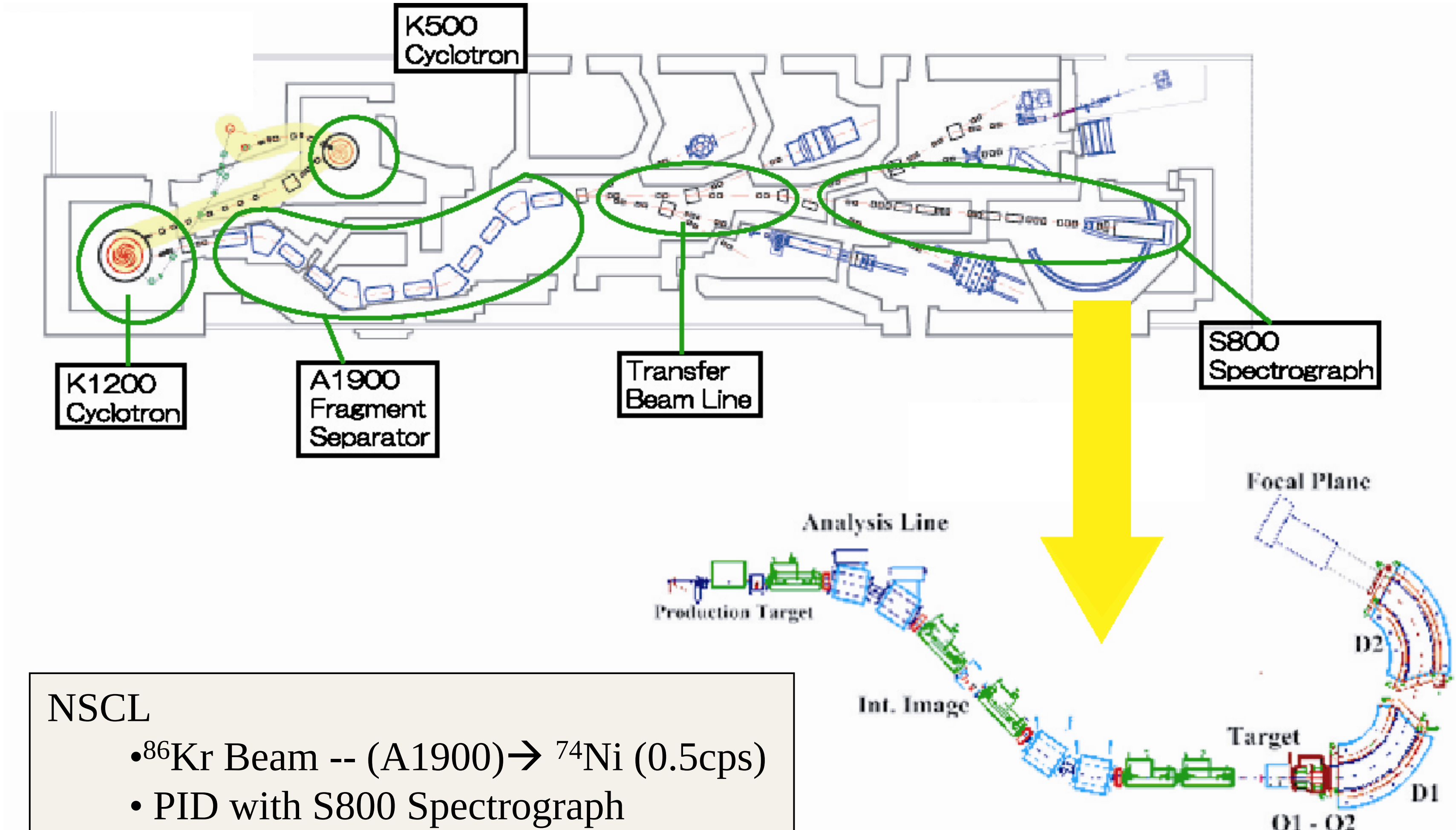
(cf. GANIL gr. @ ENAM04)

B(E2) unknown

^{78}Zn: $E_x(2^+)$ known

B(E2) unknown

MSU National Superconducting Cyclotron Lab.



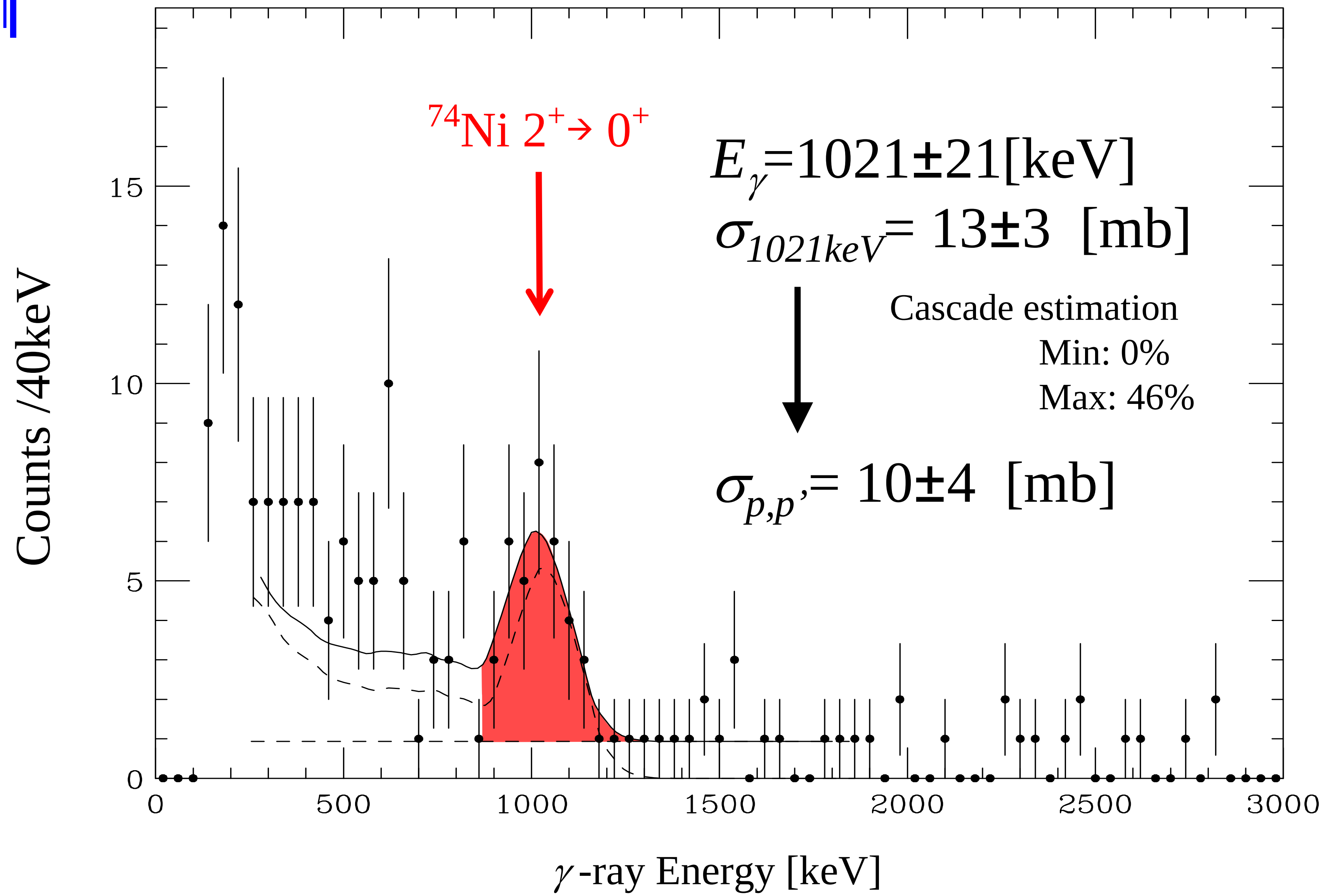
NSCL

- ^{86}Kr Beam -- (A1900)→ ^{74}Ni (0.5cps)
- PID with S800 Spectrograph

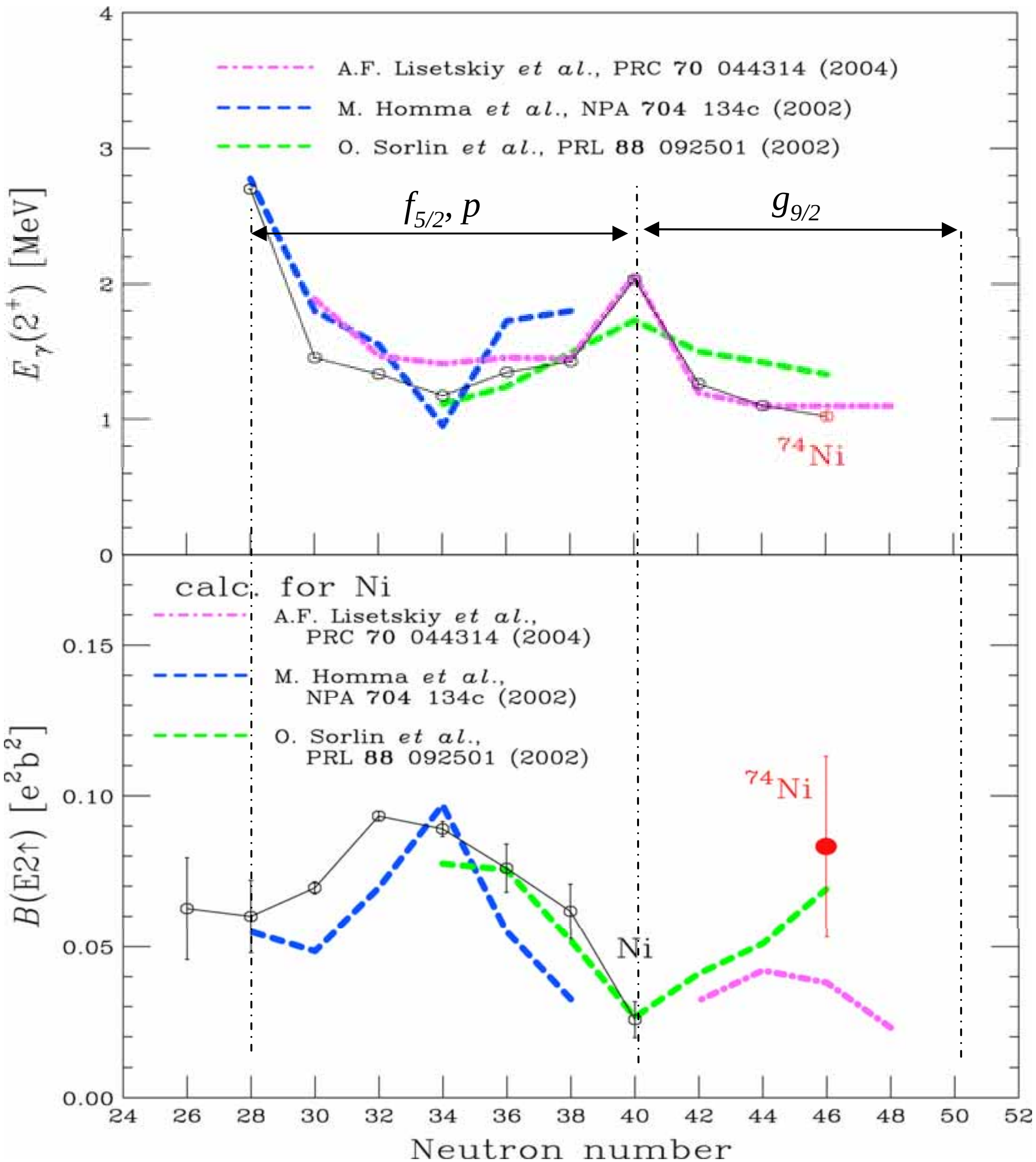
+

Liq. H_2 target

^{74}Ni(p,$p'\gamma$) γ-ray spectrum



Systematics of $Ex(2^+)$ and $B(E2\uparrow)$ for Ni isotopes



$\sigma_{p,p'}$ = 10 ± 4 [mb]
$\beta_{p,p'}$ = 0.17 ± 0.04
$B(E2)\uparrow$ = 0.08 ± 0.03 [e^2b^2]

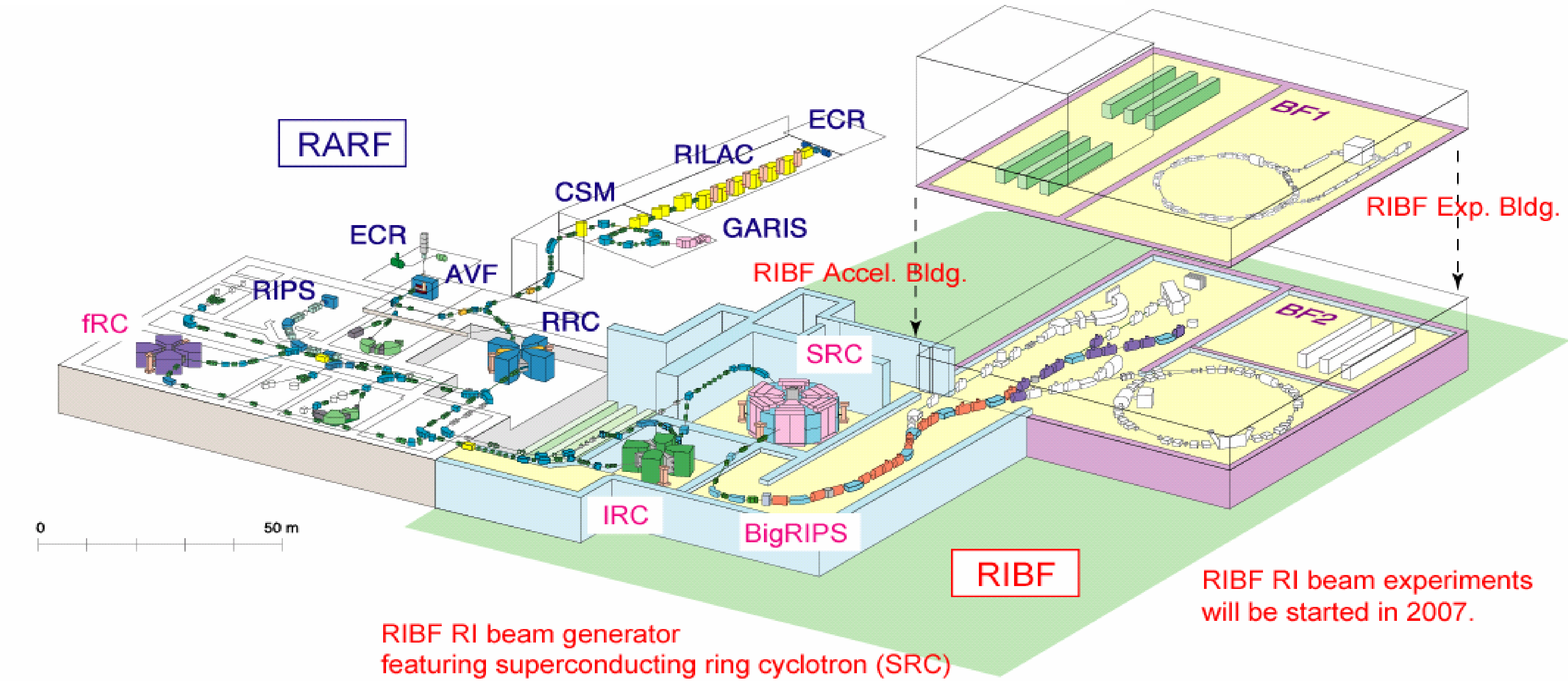
Core; ^{56}Ni
$\nu\ p_{3/2}p_{1/2}f_{5/2}g_{9/2}$
e_n =1.0e

Core; ^{40}Ca (Full *pf*-shell)
MCSM+FDA+GF40A
e_p = 1.23e, e_n = 0.54e

Core; ^{48}Ca
$\pi\ f_{7/2}p_{3/2}p_{1/2}f_{5/2}$
$\nu\ p_{3/2}p_{1/2}f_{5/2}g_{9/2}$
e_p = 1.5e, e_n = 0.5e
(e_{pol}=0.5)
TBME A.Poves et al., NPA **694** 157 (2001)

Toward heavier region at RIBF

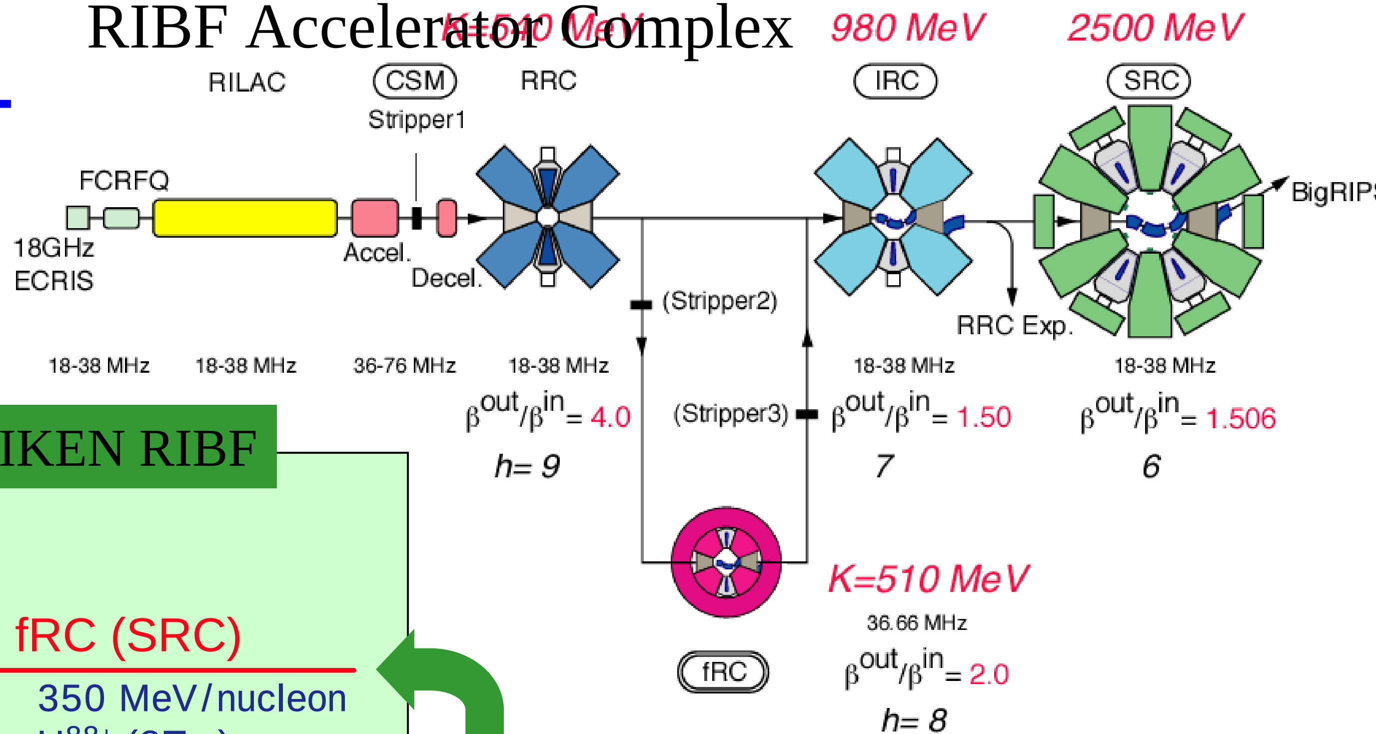
Schematic view of RI Beam Factory



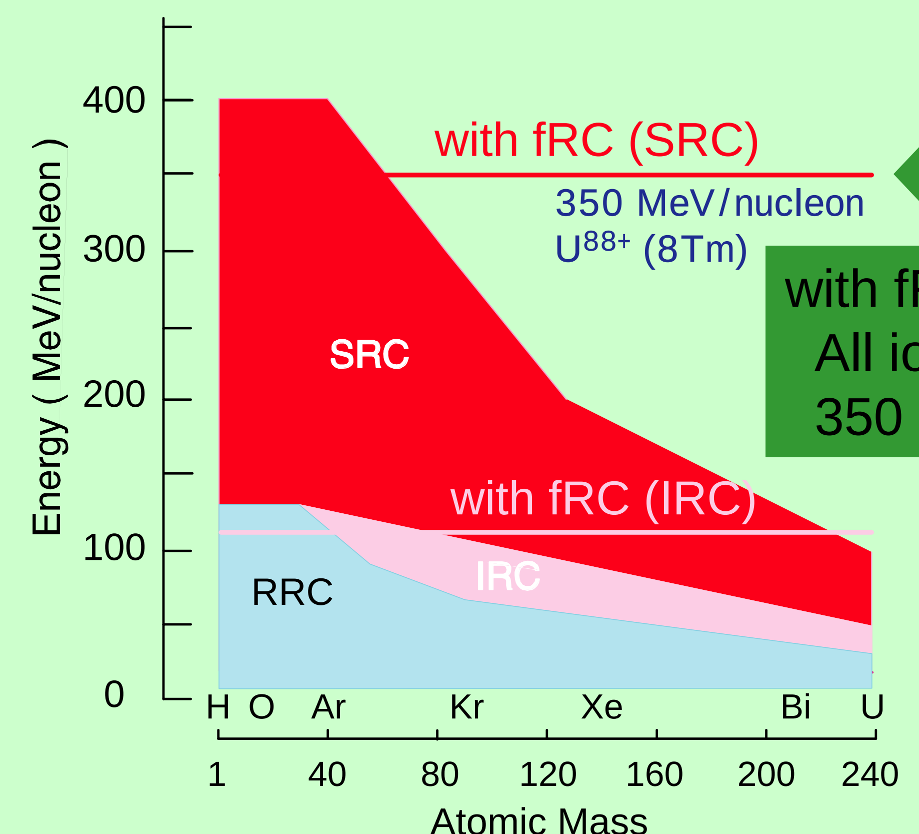
RIBF RI beam generator
featuring superconducting ring cyclotron (SRC)
and projectile fragment separator (BigRIPS)
will be commissioned in 2006.

RIBF RI beam experiments
will be started in 2007.

RIBF Accelerator Complex



Max. beam energy at RIKEN RIBF



with fRC
All ions up to U
350 MeV/u (fixed)

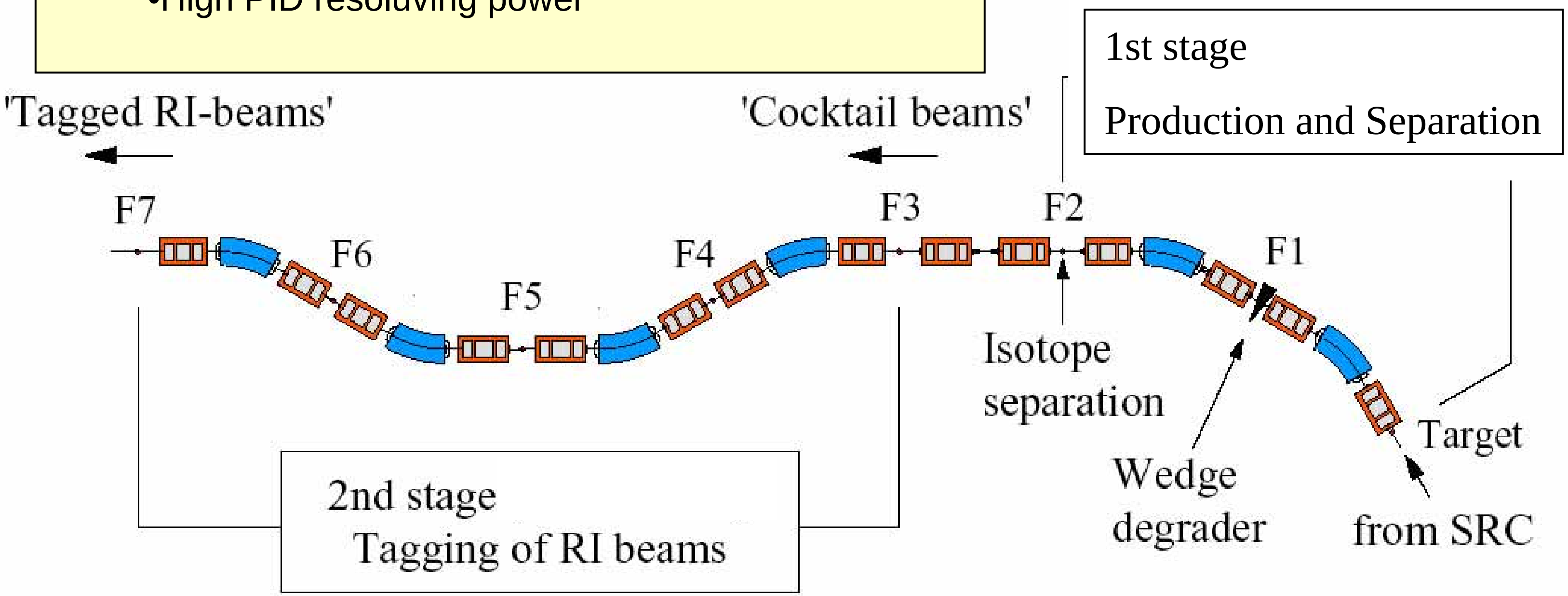
Beam Intensity

goal:	1pμA for all ions	
2007:	10pnA	^{238}U
	0.3pμA	^{136}Xe
	1pμA	^{86}Kr

Fragment Separator BigRIPS

- Production Method
  - Projectile fragmentation
  - In-flight fission of U ← Large Acceptance
- Tandem Separator for TAGGING
  - High PID resoluving power

Nucl. Instr. and Meth. B 204 (2003) 97.

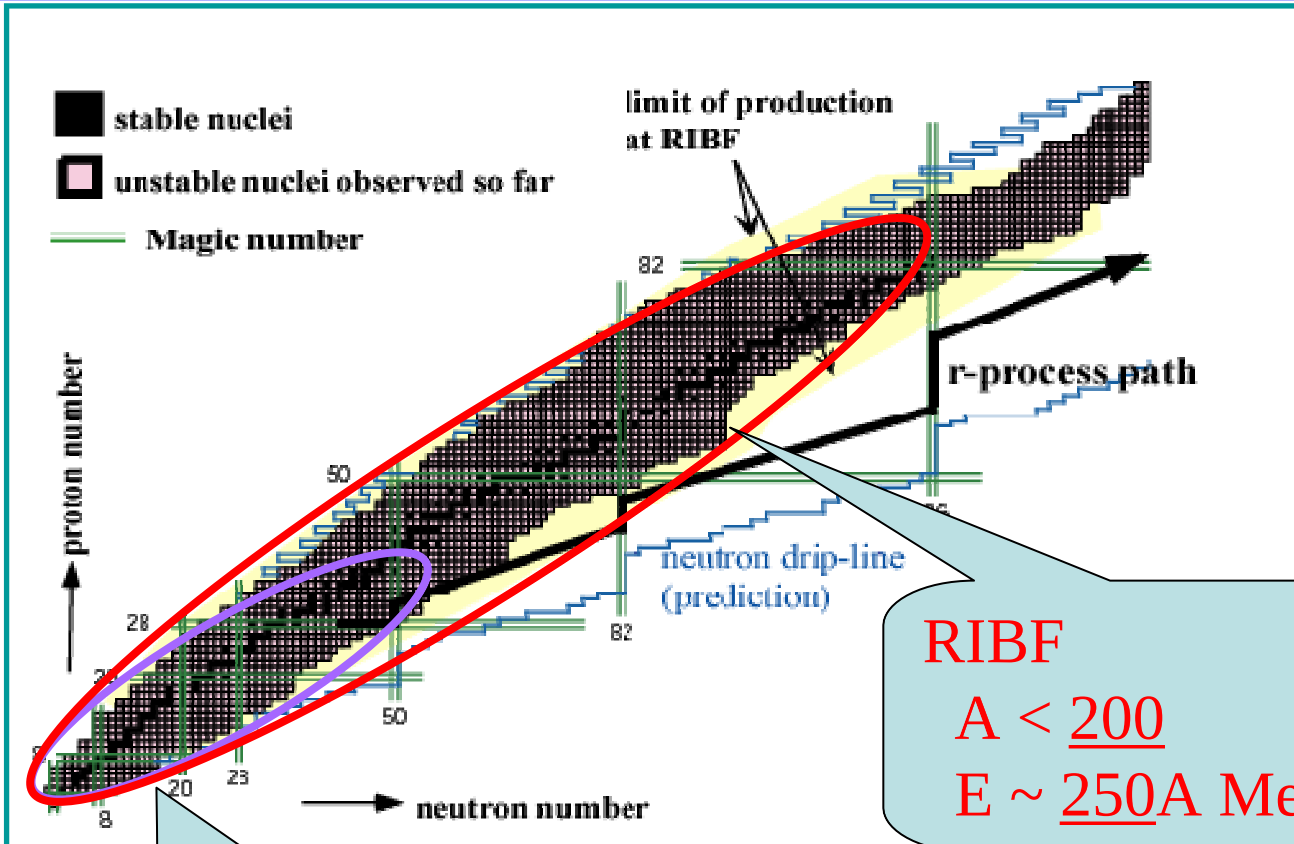


TOF, Bρ, ΔE → Z, A/Q (A, Q), P

Momentum Acceptance	±3%
Angular Acceptance	±50 mrad
Maximum Rigidity	9 Tm
1st order resolving power	1290 (Separation section)
	3300 (Tagging section)

RIBF

RI Beam Factory : the 3rd generation facility



RIBF
A < 200
E ~ 250A MeV

RIPS
A < 50
E ~ 50A MeV