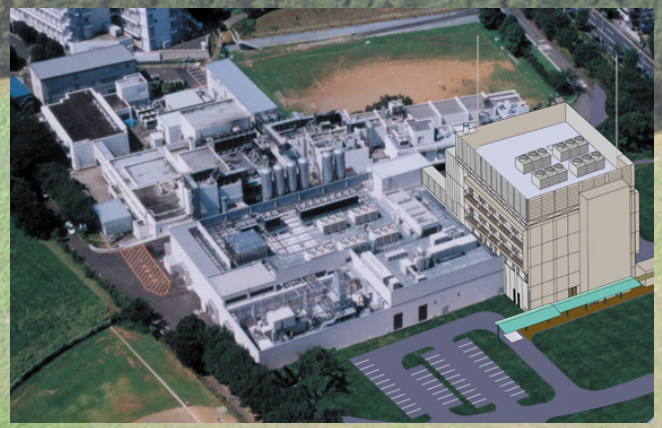
Experimental Studies with Magnetic Devices at RIBF

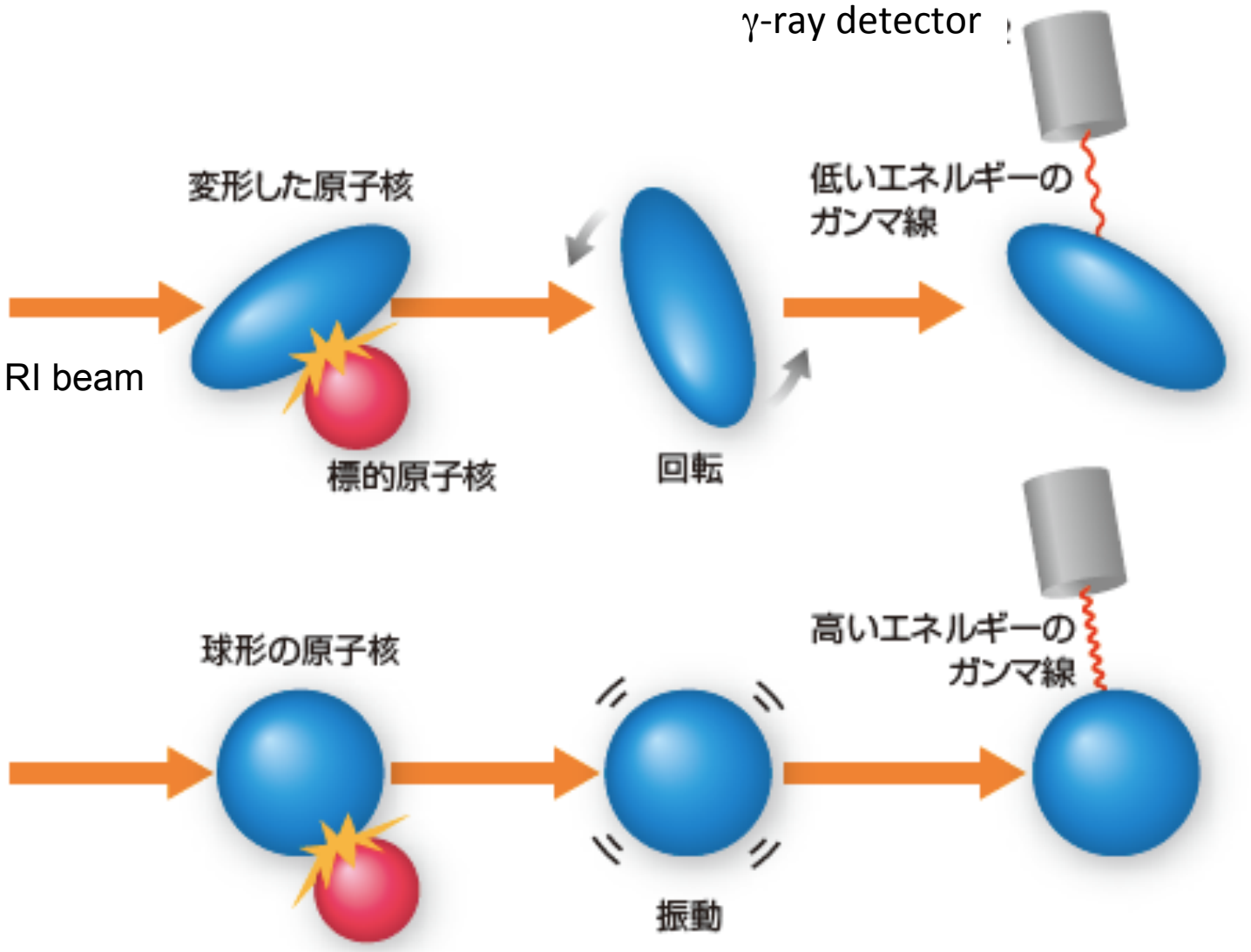
Tohru Motobayashi
RIKEN Nishina Center



- to start with
- with Zero Degree Spectrometer
- with SAMURAI
- with SHARAQ

RIKEN NiSHiNA CENTER

Inelastic scattering in inverse kinematics



$E_x \leftarrow E_\gamma$

In 1995 -- Coulomb excitation of ^{32}Mg by fast radioactive ^{32}Mg beams

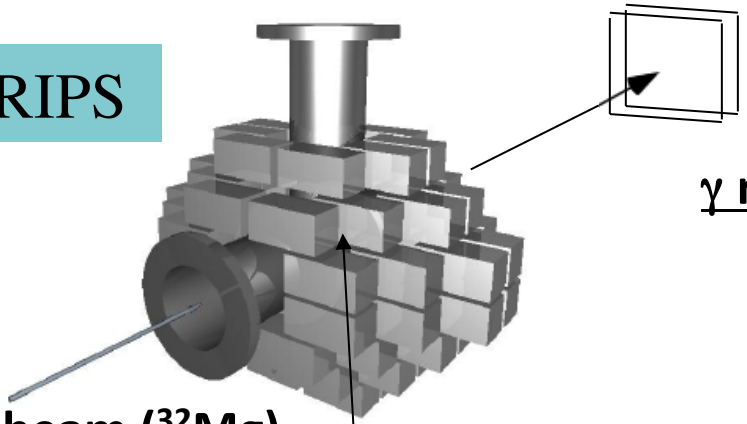
Large *B*(E2) of $0^+ \rightarrow 2^+$ in ^{32}Mg (*N*=20)
-- Island of inversion

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

Charged particles (Si stack - *ΔE-E*)

no spectrometer

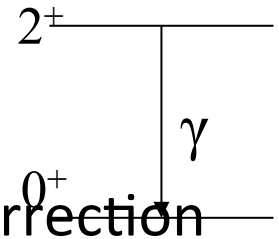
RIPS



particle ID for ejectiles (^{32}Mg)

γ rays (DALI -NaI(Tl) array)

γ-ray energy => state ID
emission angle
=> Doppler correction



RI beam (^{32}Mg)

300 s^{-1}
~50 *A* MeV

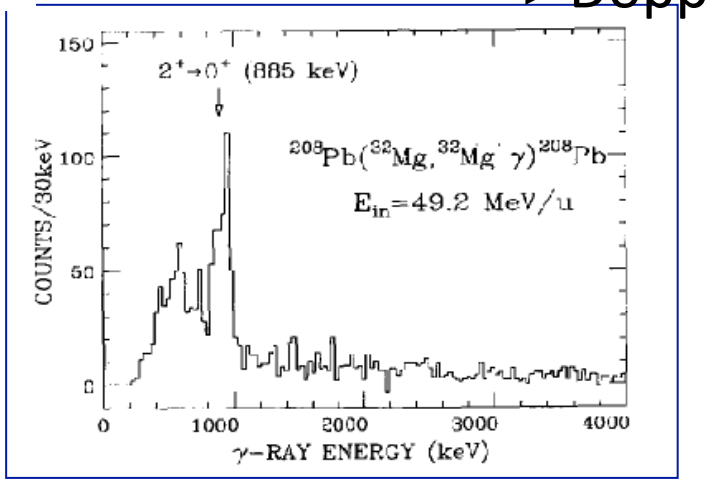
Target (^{208}Pb)

350 mg/cm^2

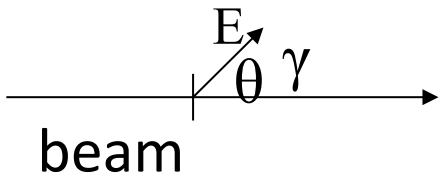
weak

fast

thick



Doppler-shift corrected spectrum



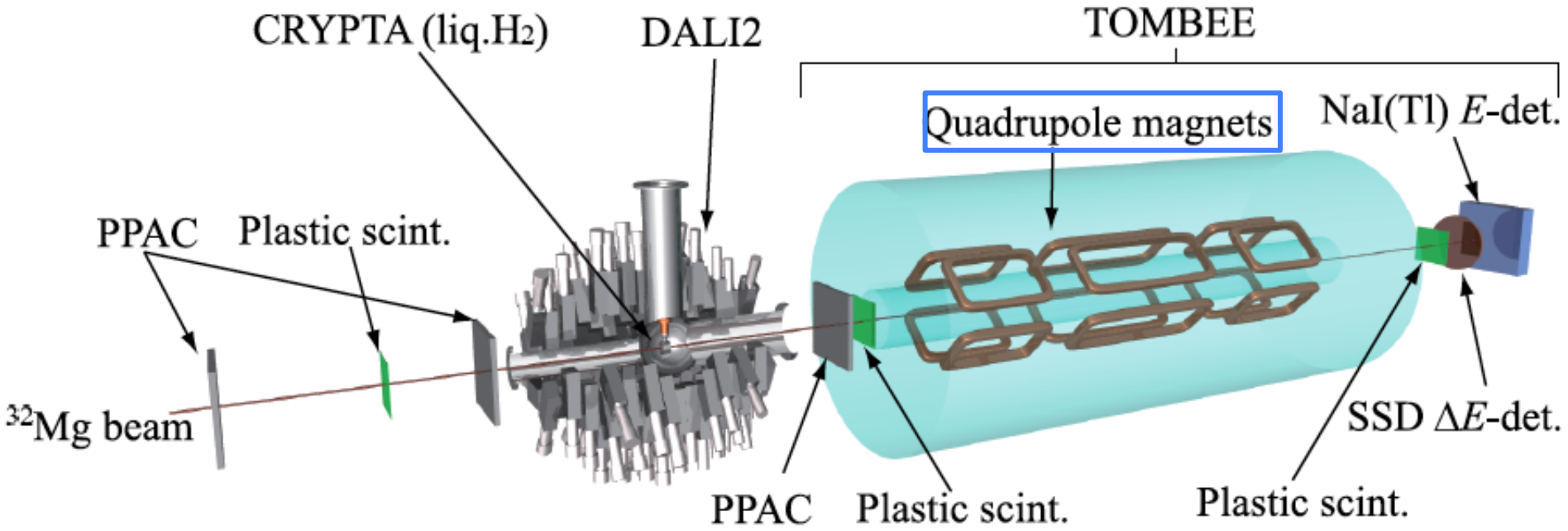
One peak!

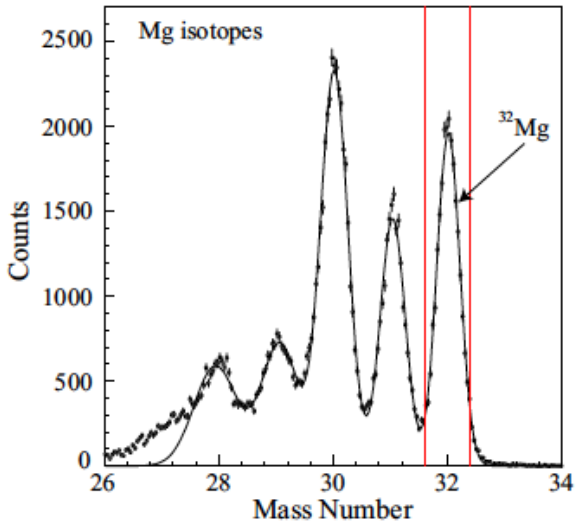
high E (fast) coulex
E2 sensitive

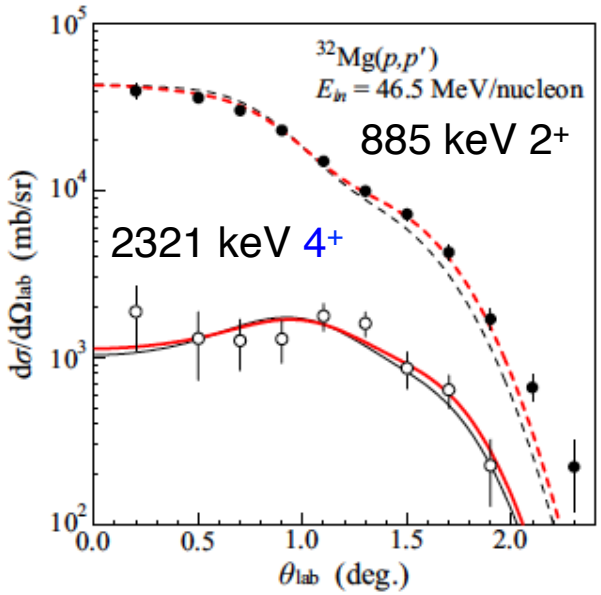
In 2009 -- ^{32}Mg again by (p,p') with a more sophisticated setup

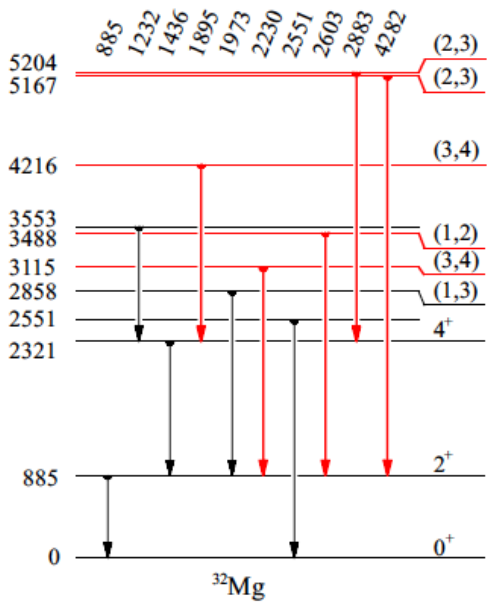
Identification of 4^+ / several new levels …

Takeuchi *et al.*, PRC 79 (2009) 054319









3 magnetic spectrometers at RIBF

~200 MeV/nucleon, heavier nuclei

ZDS (ZeroDegree) 2007-
RIKEN (Kubo, ….)

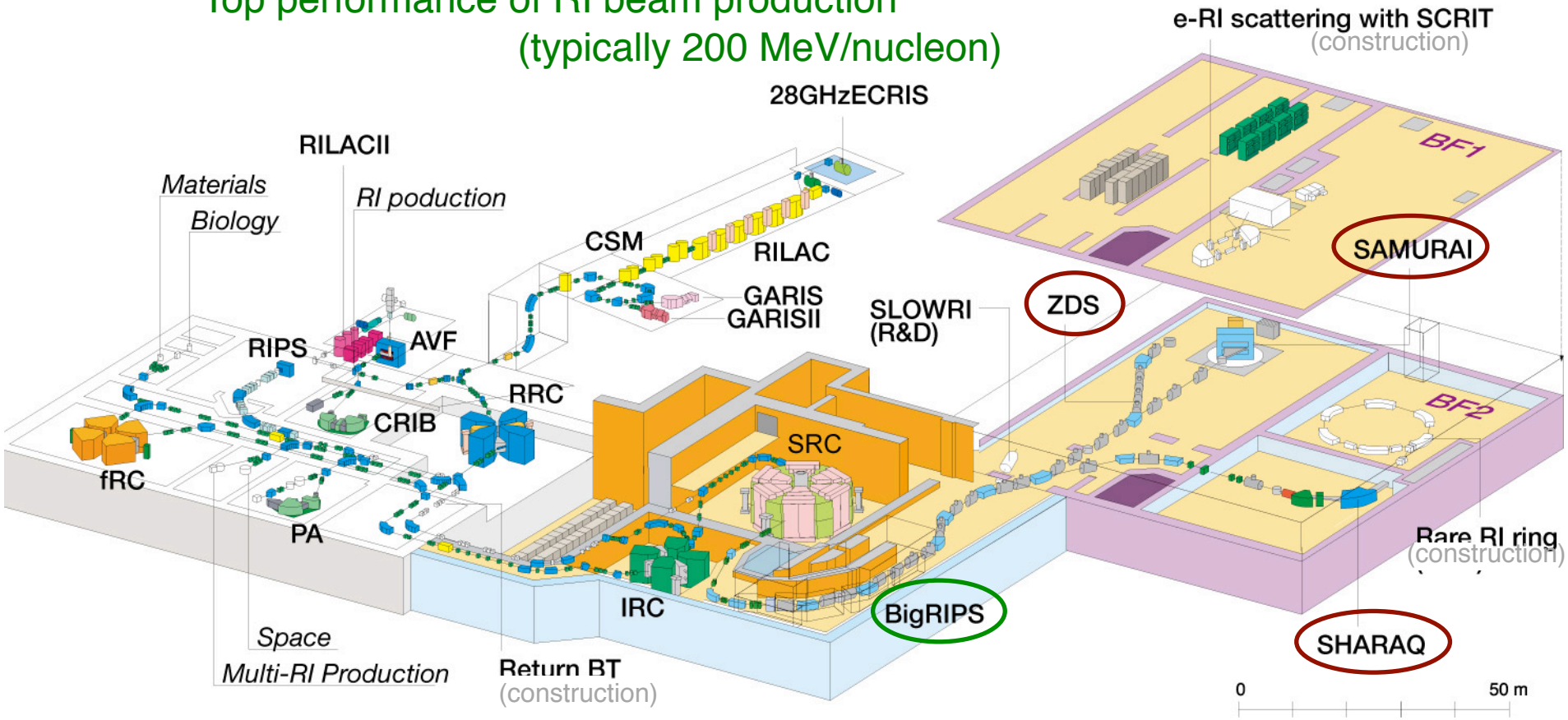
SAMURAI 2012-
Tohoku (Kobayashi), RIKEN, Tokyo Tech

SHARAQ 2009-
CNS (Shimoura, Sakai..), RIKEN

RIKEN RIBF (RI* Beam Factory)

* radioactive isotope

In operation since 2007
Top performance of RI beam production
(typically 200 MeV/nucleon)



3 magnetic spectrometers at RIBF

ZDS (ZeroDegree) 2007-

with elements of the BigRIPS designs

1) a part of the separator for new-isotope studies

decay studies *e.g.* with EURICA

2) analyzer (PID) for (two-body) secondary reaction products

coupled with DALI2 (γ detector) - Rikkyo-RIKEN

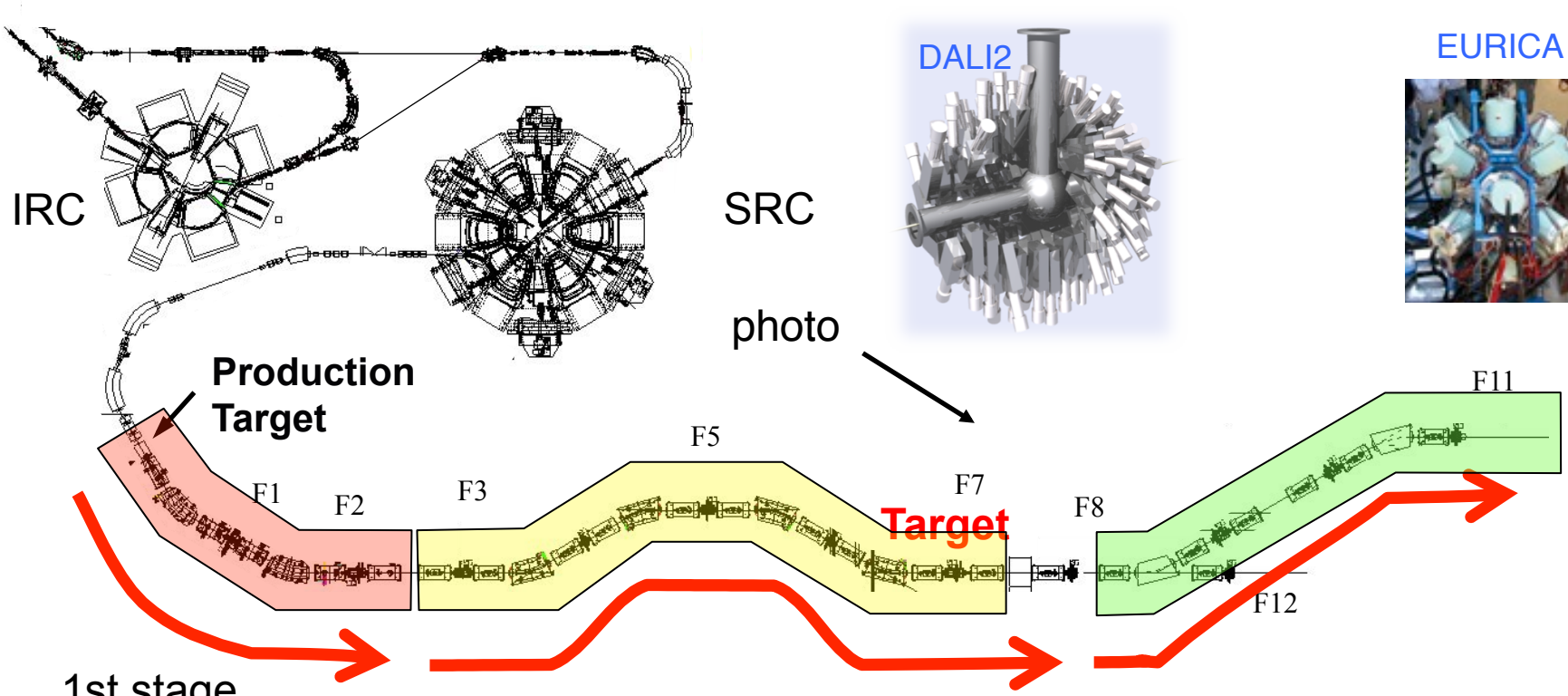
MINOS (vertex-sensitive liq. H_2 target) - Saclay

SAMURAI 2012-

Tohoku (Kobayashi), RIKEN, Tokyo Tech

SHARAQ 2009-

CNS (Shimoura, Sakai..), RIKEN

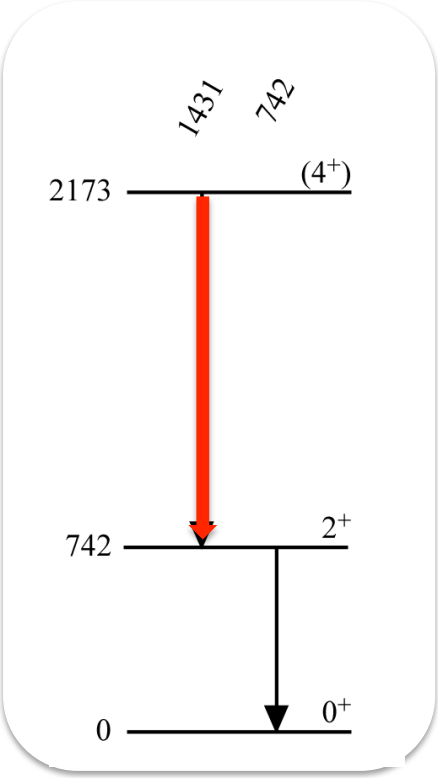

IRC
SRC
DALI2
EURICA
photo
Production
Target
F1
F2
F3
F5
F7
Target
F8
F11
F12
1st stage
separation
BigRIPS
2nd stage
analysis
ZeroDegree
analysis of 2ndary
reaction products

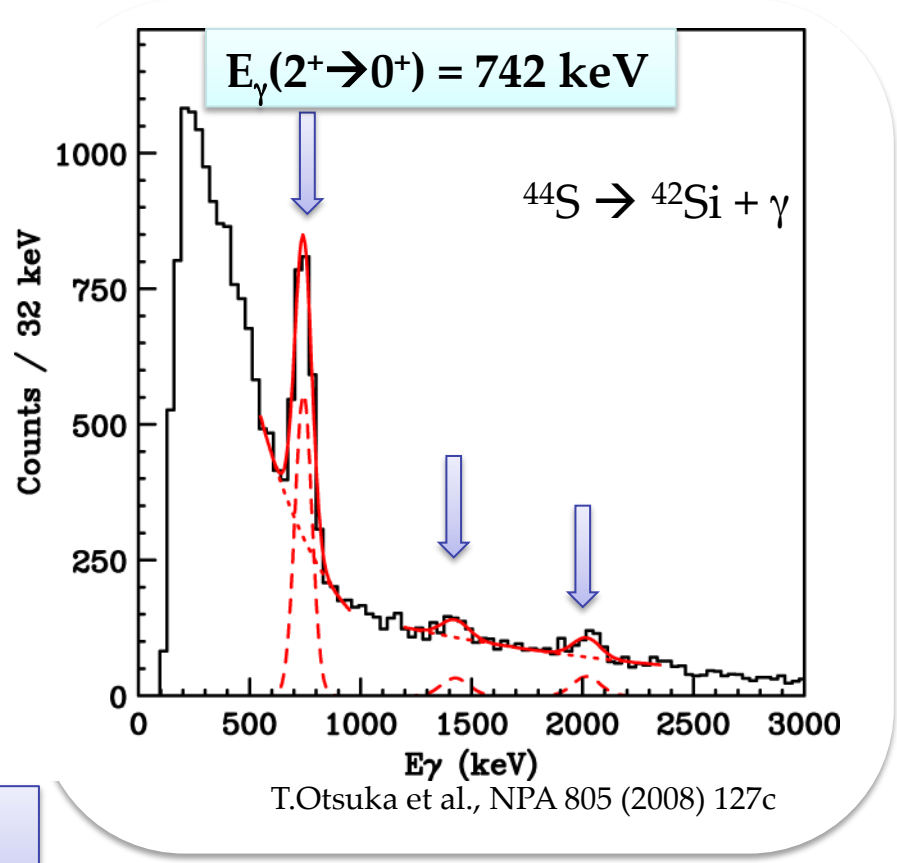
"doubly magic" ^{42}Si (Z=14, N=28) - confirmation of the low-lying 2^+ / higher states

Takeuchi et al., PRL 109 (2012) 182501

The state at **2173 (14) keV*** could be **4^+**

← systematics of 2N removal





T.Otsuka et al., NPA 805 (2008) 127c

$E_x(4^+)/E_x(2^+)$ = 2.93 (5)

→ well-developed deformation

LETTER

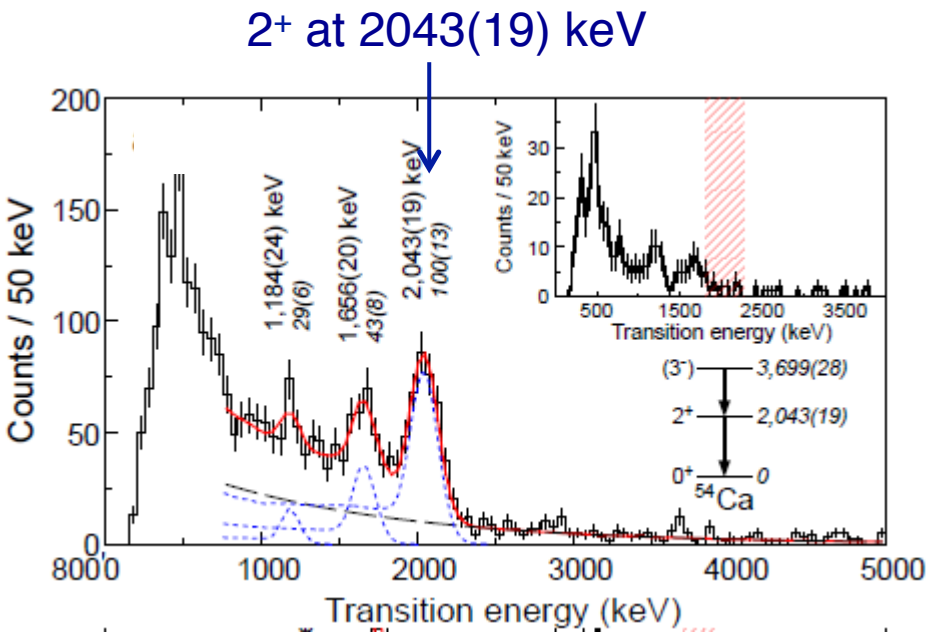
Nature, **502** (2013) 207

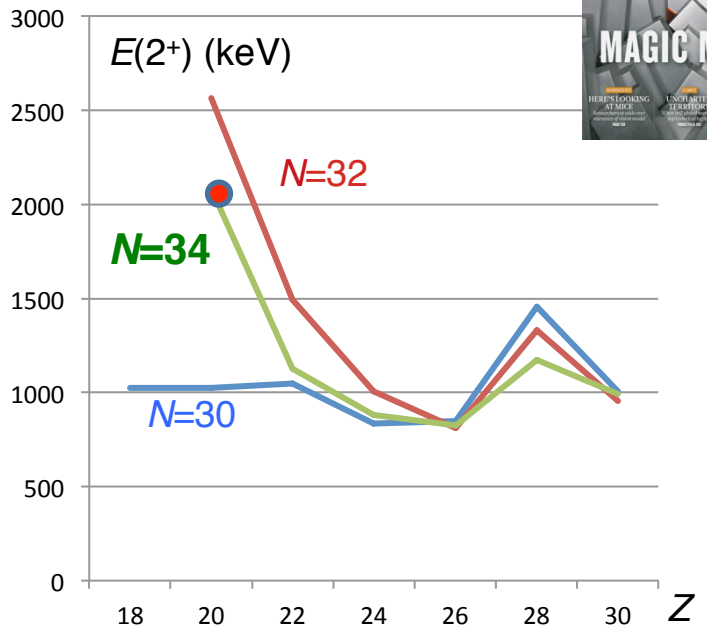
doi:10.1038/nature12522

Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

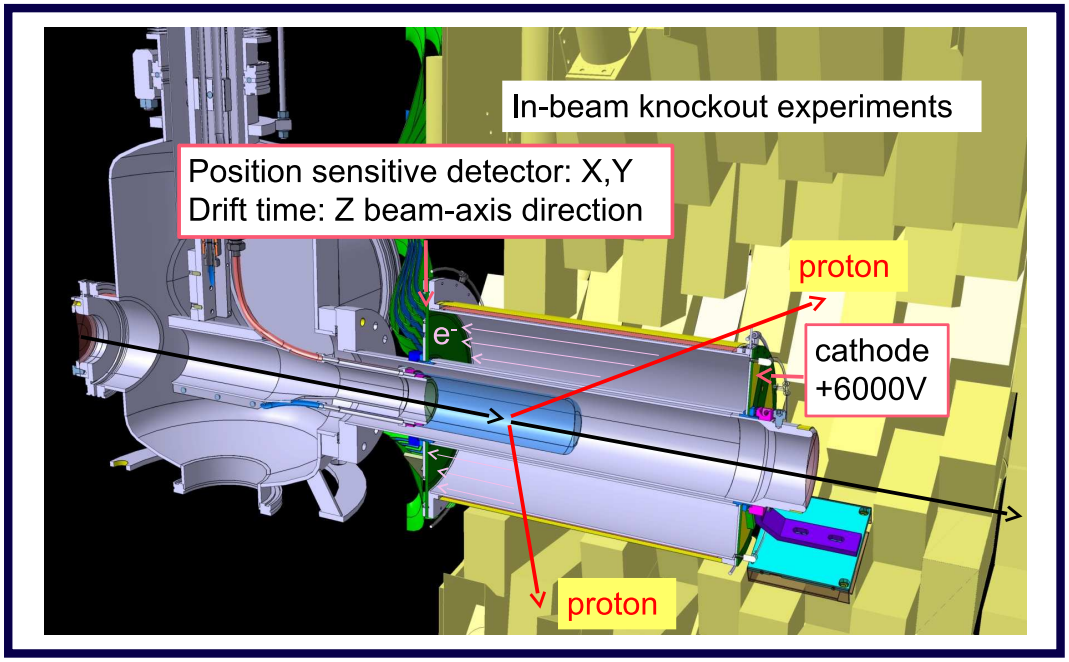
D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

N=34 shell gap large in ^{54}Ca? ➔ Yes

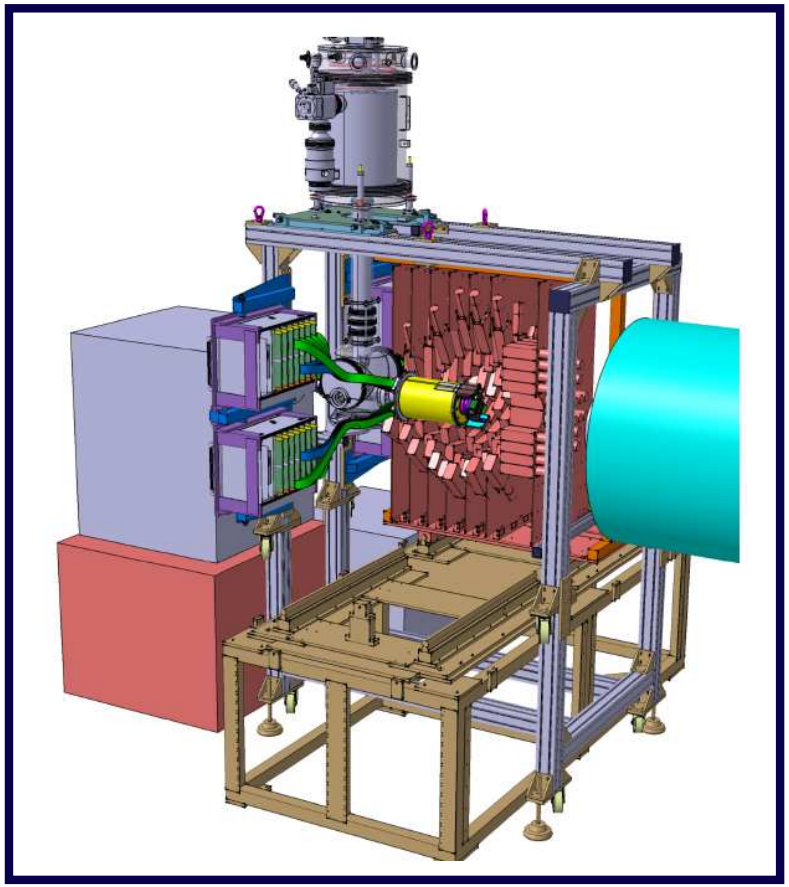




SEASTER* campaign
with MINOS (a liq. H_2 target + a TPC) + DALI2
- spectroscopy of (p,2p)# residues -



efficient and useful



MagIc Numbers Off Stability

`http://minos.cea.fr`

- ☐ Up to 1 g/cm^2 liquid hydrogen target
- ☐ Position sensitive TPC
  - Driftime → Z-beam axis
  - Vertex position reconstruction
  - Achieved ≈5 mm (FWHM)

A. Obertelli *et al.*, Eur. Phys. J. A 50, 8 (2014).

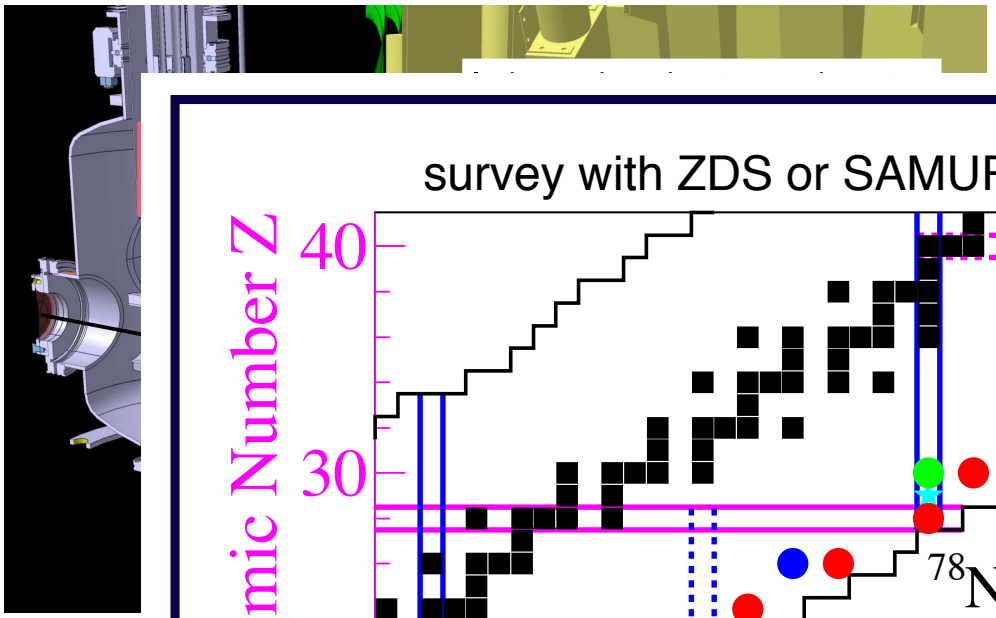
- Shell Evolution And Search for Two-plus energies At RIBF

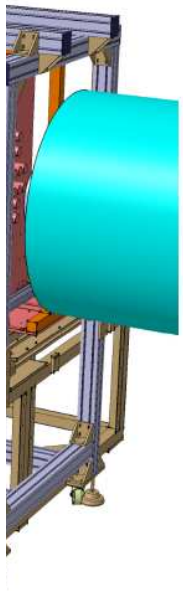
SEASTER* campaign

with MINOS (a liq. H_2 target + a TPC) + DALI2

- spectroscopy of (p,2p)# residues -

efficient and useful



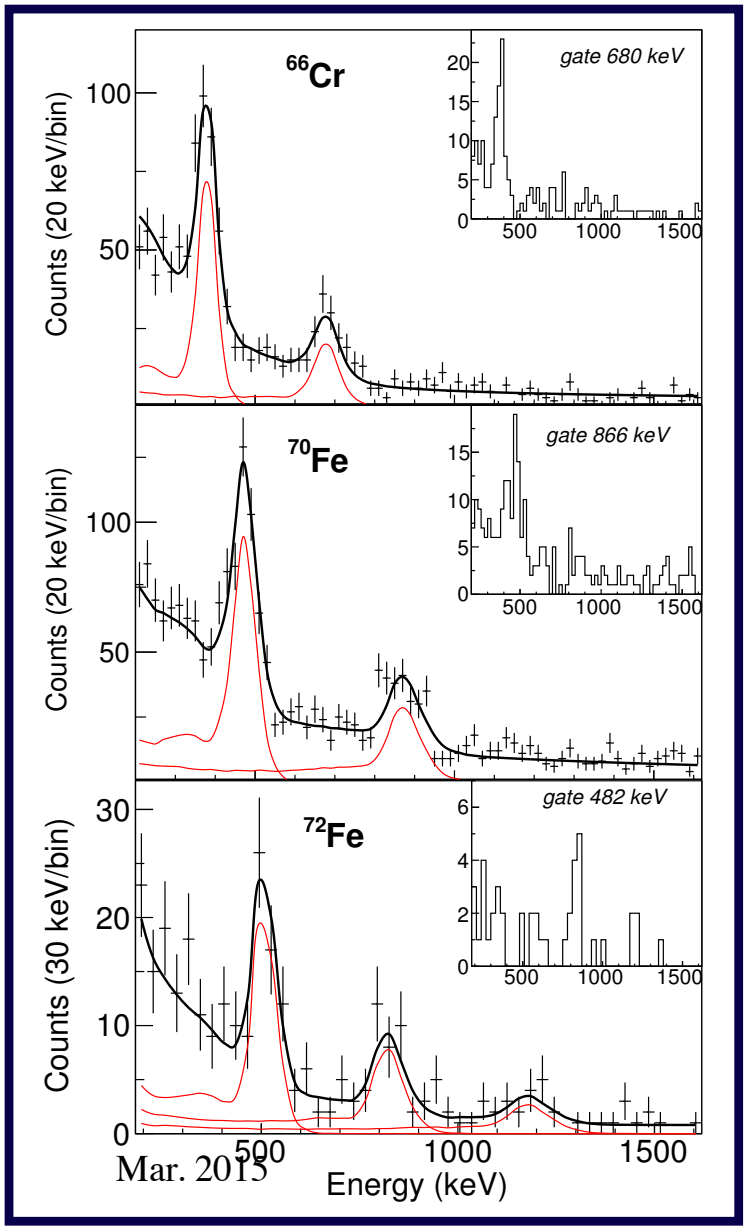


Ma

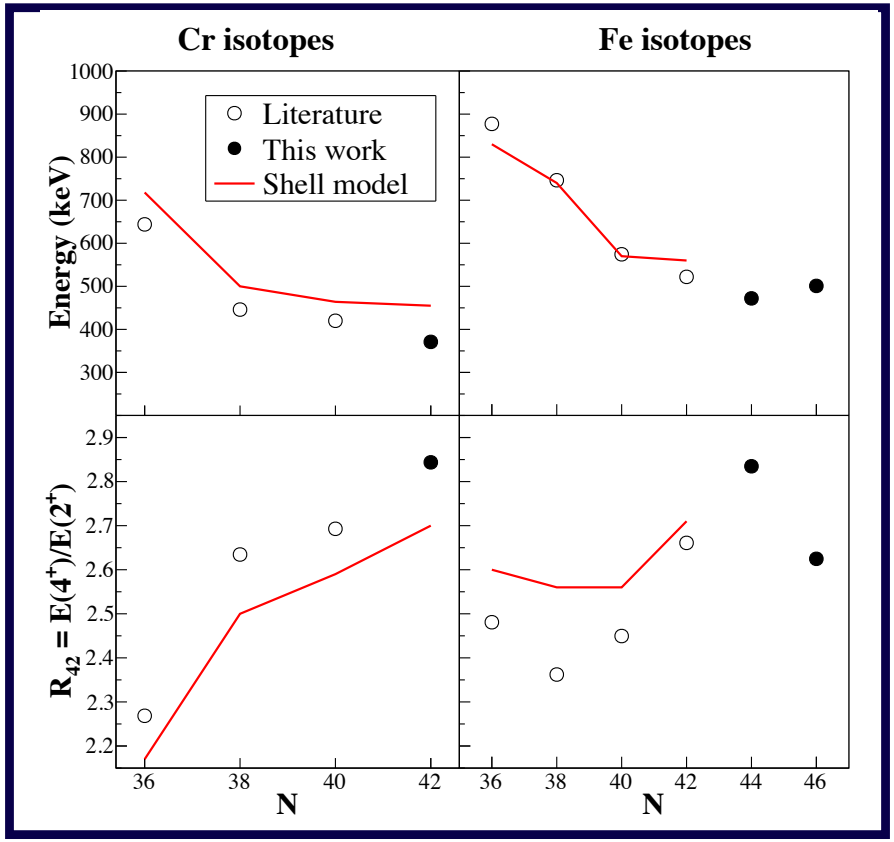
http

A. Obertelli *et al.*, Eur. Phys. J. A 50, 8 (2014).

Maximum of Collectivity Beyond $N = 40$



n-rich Cr and Fe isotopes



- ^{73}Co rate: 0.49 pps/pnA, expected 0.86 pps/pnA
- Collaboration with F. Nowacki, IPHC, $fp - fpg_9d_5$ valence space
- D. Santamaria (CEA Saclay), C. Louchart (TU Darmstadt)

3 magnetic spectrometers at RIBF

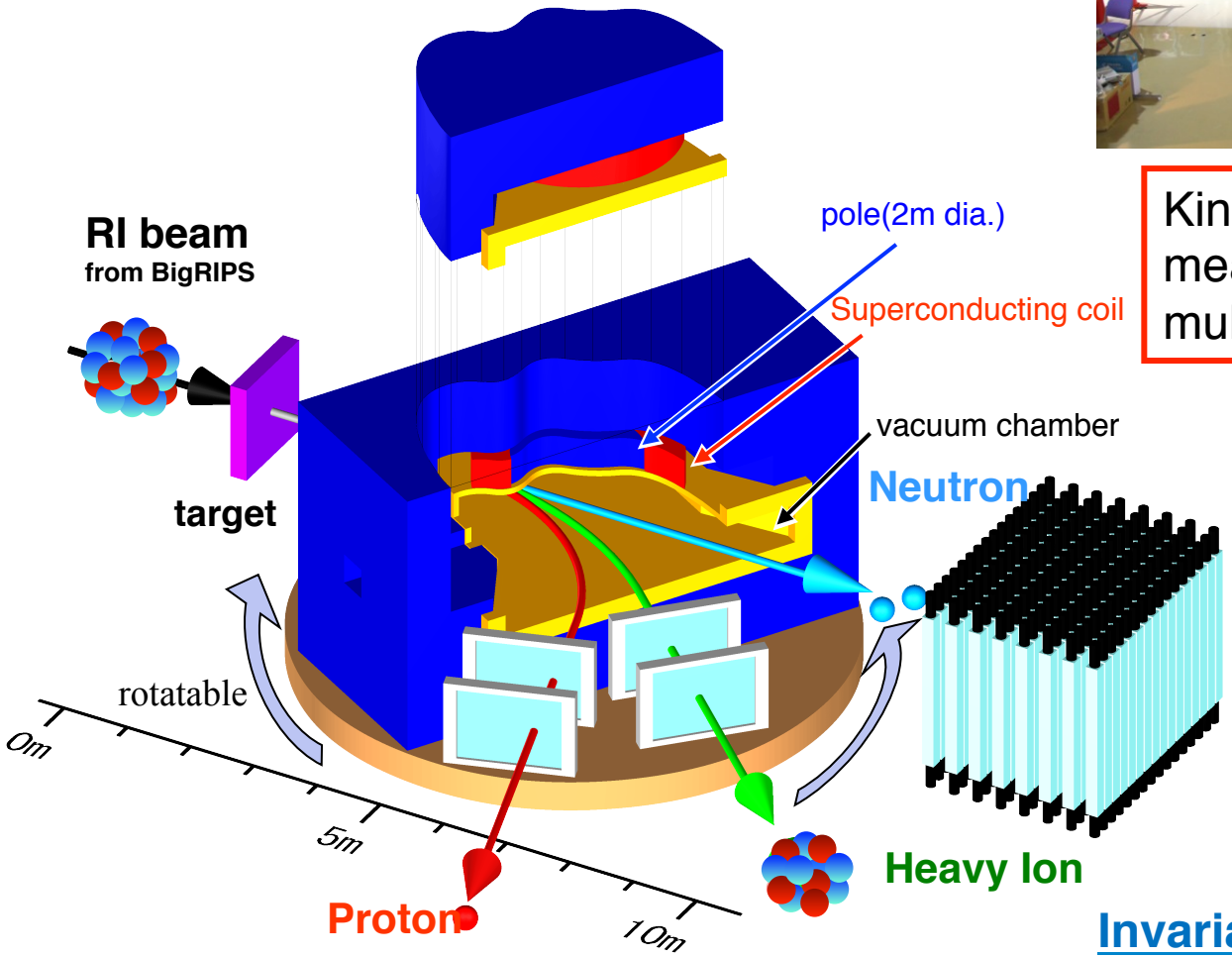
ZDS (ZeroDegree) 2007-
RIKEN (Kubo, ….)

SAMURAI 2012-
large acceptance for momentum and angle
for particle correlation (invariant masss, …)

SHARAQ 2009-
CNS (Shimoura, Sakai..), RIKEN

SAMURAI

Superconducting **A**nalyzer for **MU**lti-particle from **RA**dio **I**sotope Beam with 7Tm of bending power



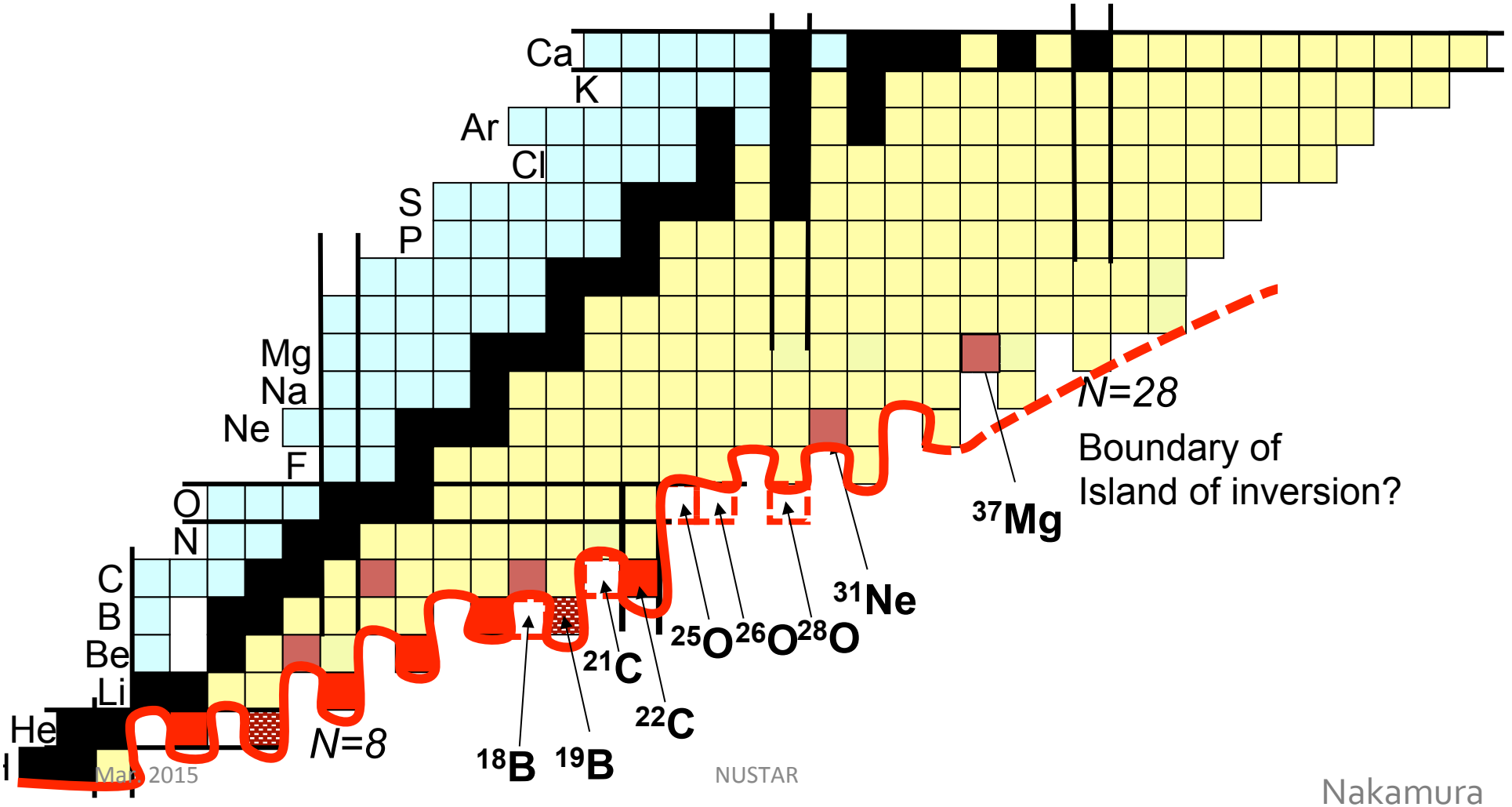
Kinematically complete measurements by detecting multiple particles in coincidence

- Superconducting Magnet
  3T with 2m dia. pole
  (designed resolution 1/700)
  80cm gap (vertical)
- Heavy Ion Detectors
- Proton Detectors
- Neutron Detectors
- Large Vacuum Chamber
- Rotational Stage

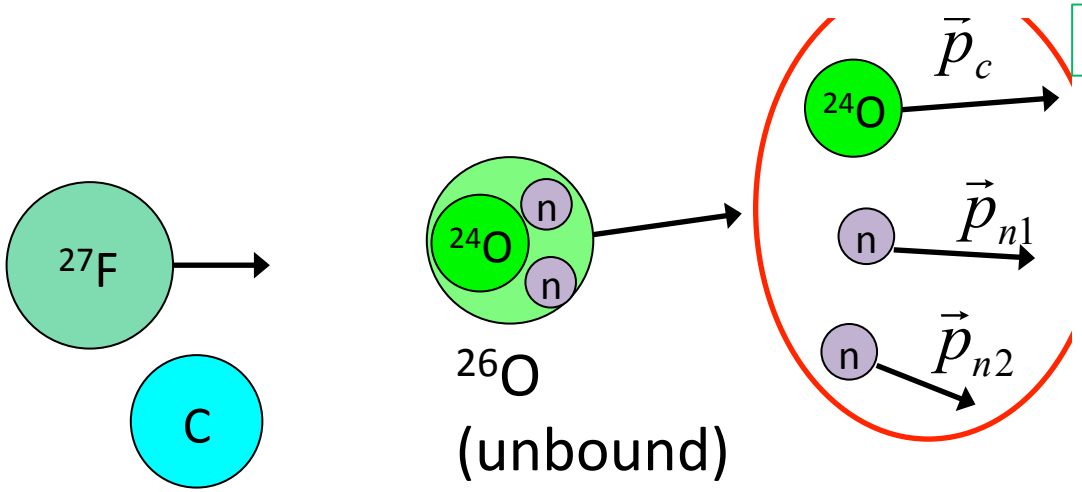
Invariant Mass Measurement
Missing Mass Measurement

SAMURAI

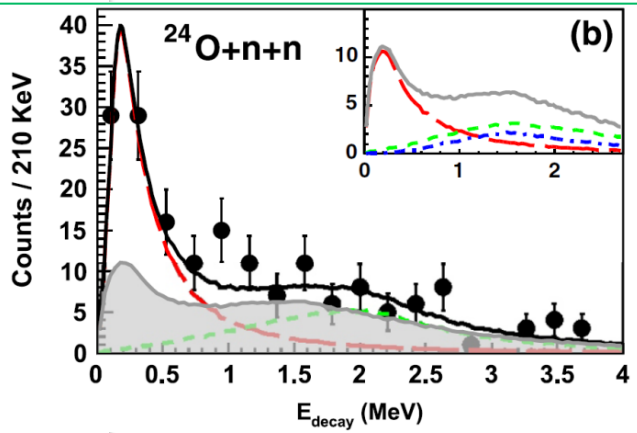
unbound states in nuclei at/around the neutron drip line
shell structure / deformation / n-halo, skin / …



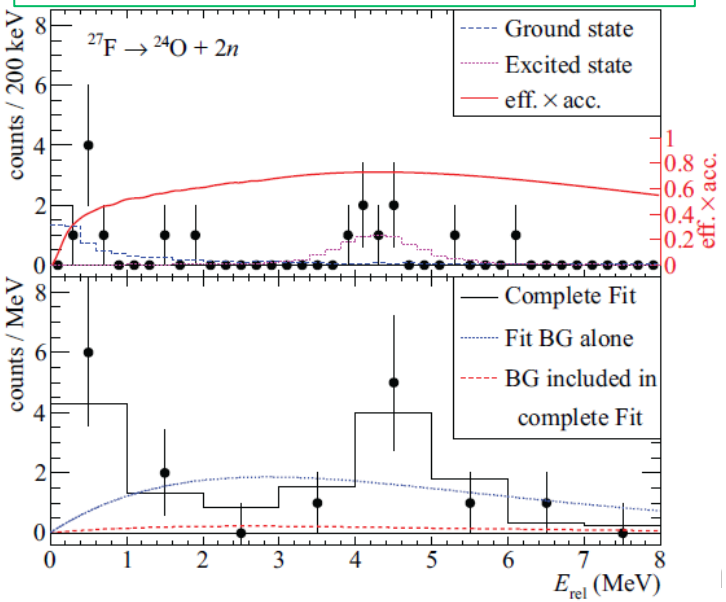
decay energy (invariant mass)
- for $^{27}F+C \rightarrow ^{26}O \rightarrow ^{24}O+2n$



E. Lunderberg et al.PRL108, 142503 (2012)



C. Caesar et al.PRC88, 034313 (2013)



Ground state
- 5 times higher statistics
- →better determination of energy

Excited state at ~1.3MeV
- First observation
- Most probably 2^+

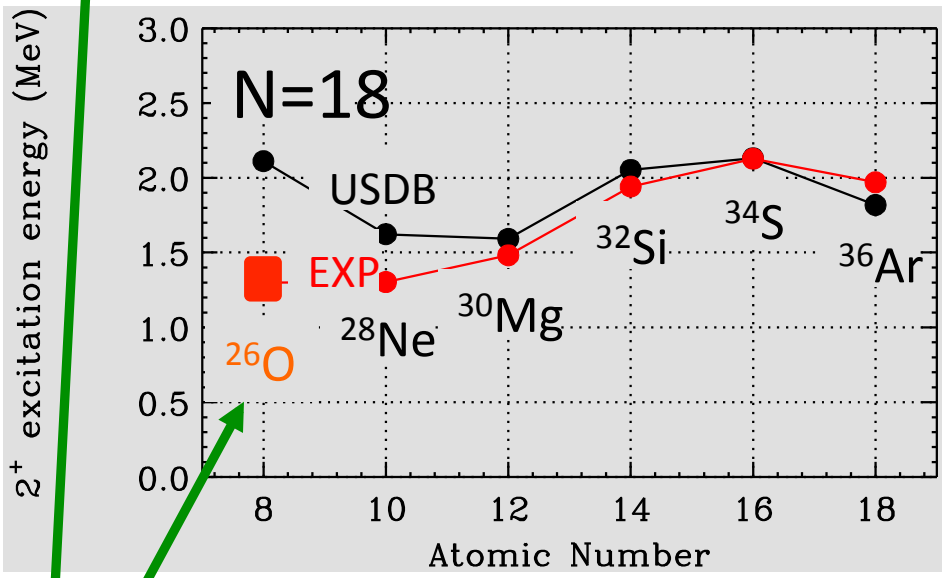
No peak at ~4.2MeV

decay energy (invariant mass) for $^{27}F+C \rightarrow ^{26}O \rightarrow ^{24}O+2n$

Being analyzed.

$E_r(^{26}O_{gs}) \lesssim 50keV$ (preliminary)

A lower limit will also be obtained.



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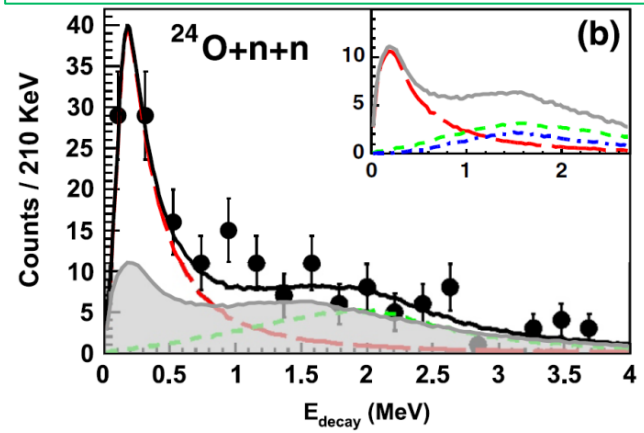
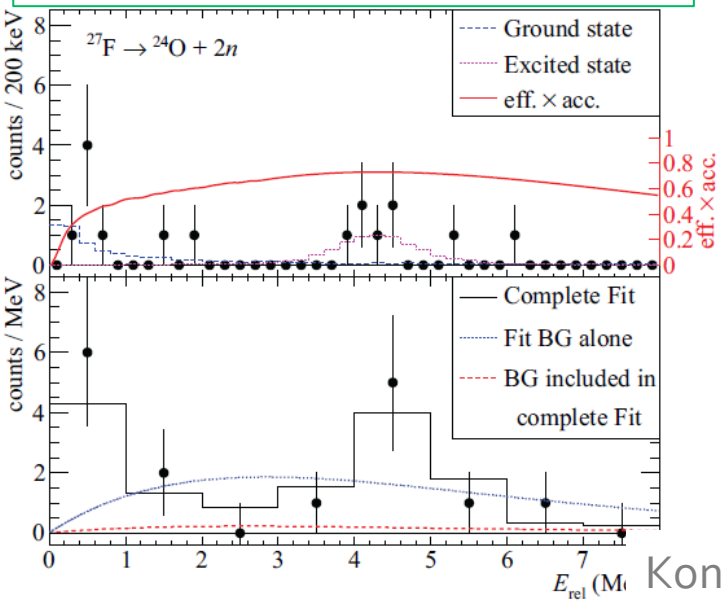
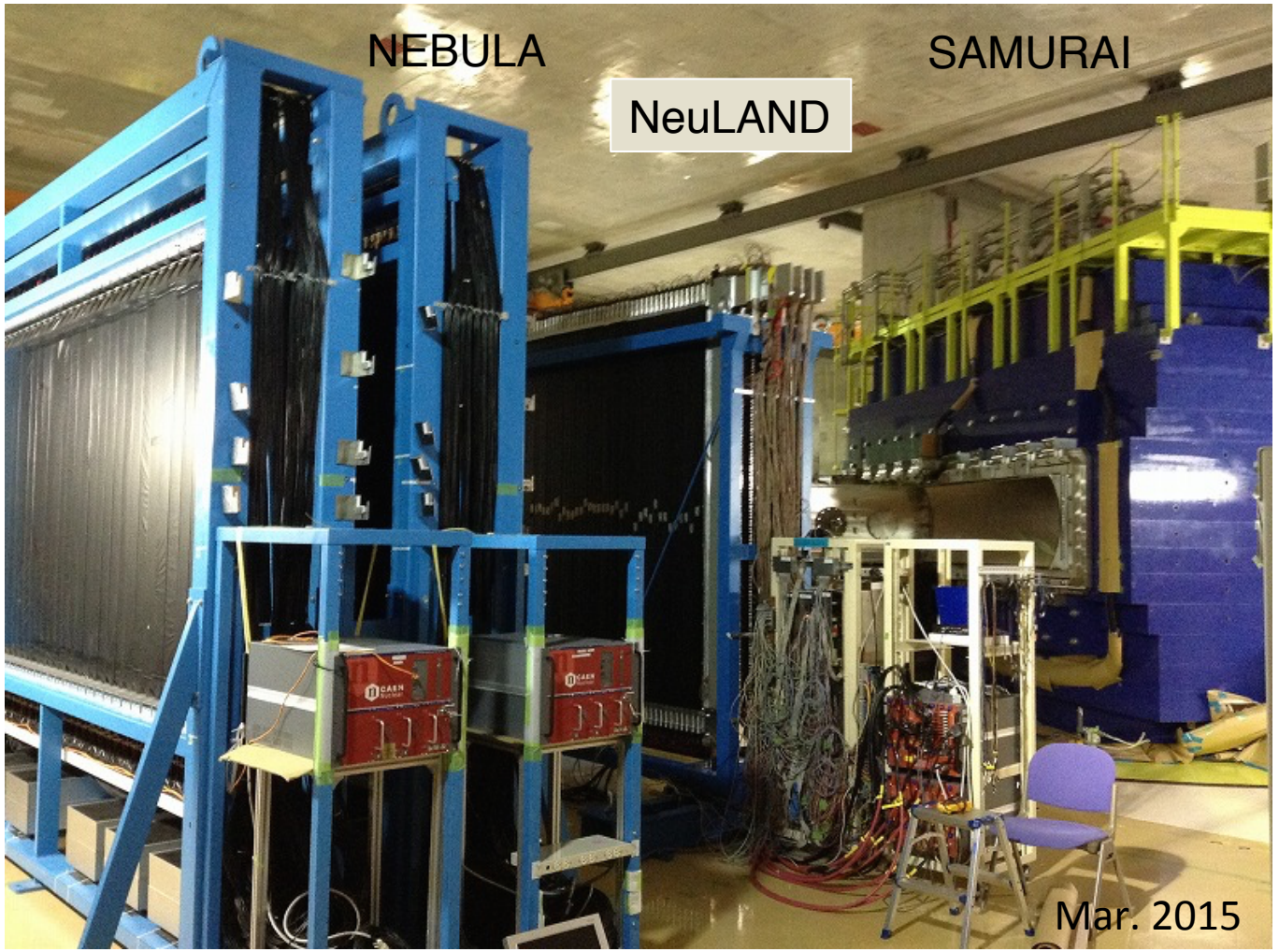
E. Lunderberg et al.PRL108, 142503 (2012)



C. Caesar et al.PRC88, 034313 (2013)

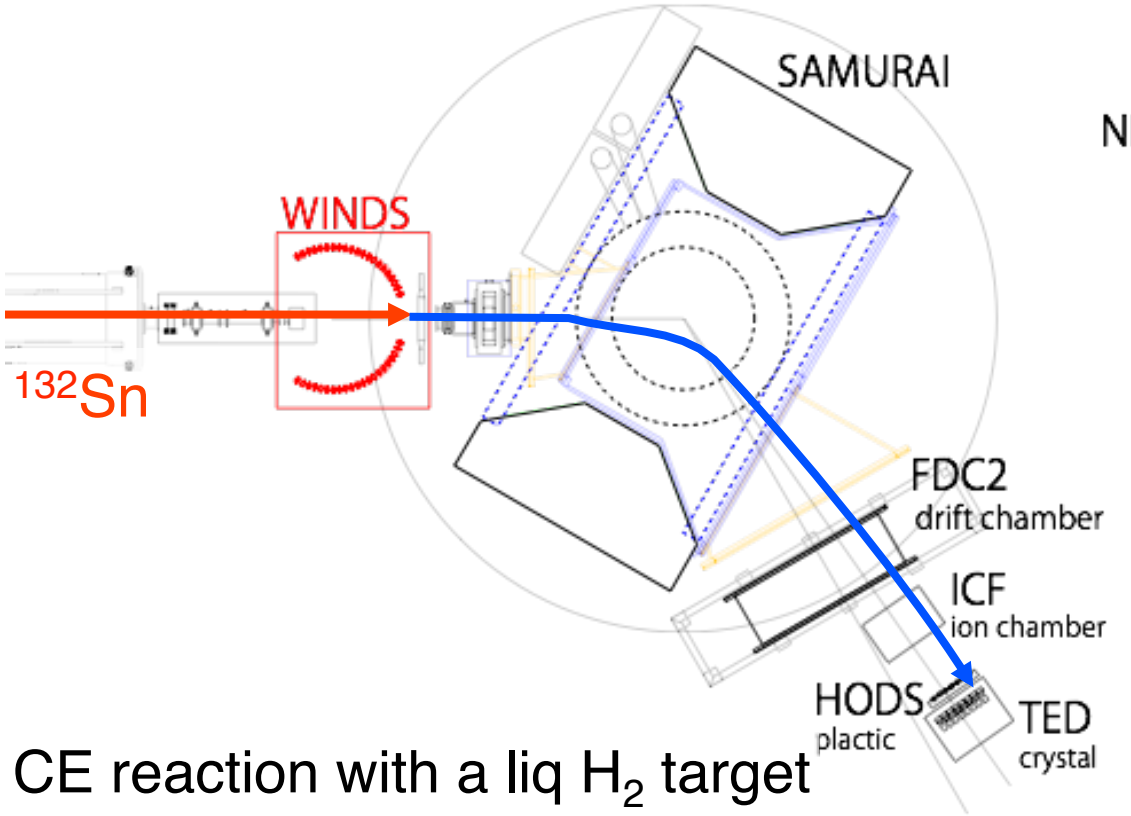


SAMURAI next: ^{28}O (N=20) → ^{24}O+4n ?



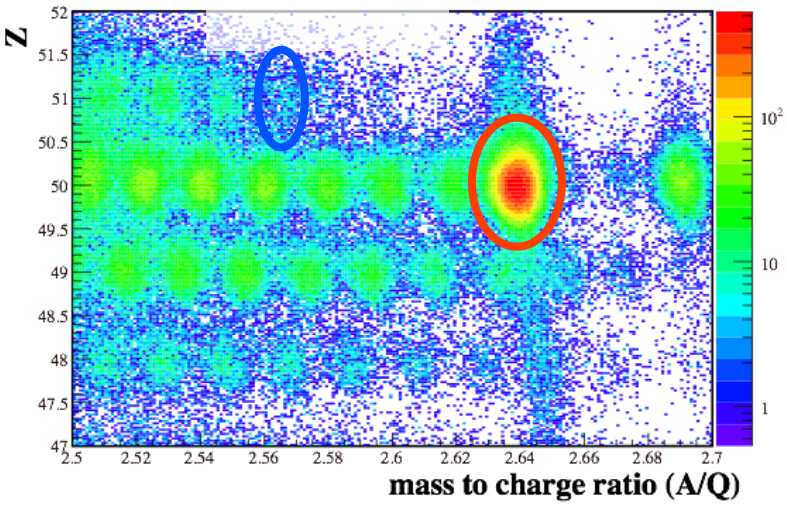
SAMURAI - various applications

ID of the reaction (particle decay) channel
in missing mass measurements (by neutron detection) for ^{132}Sn(p,n)^{132}Sn*



CE reaction with a liq H_2 target

good PID
$\sigma(Z)$=4.5, $\sigma(A)$=6.1



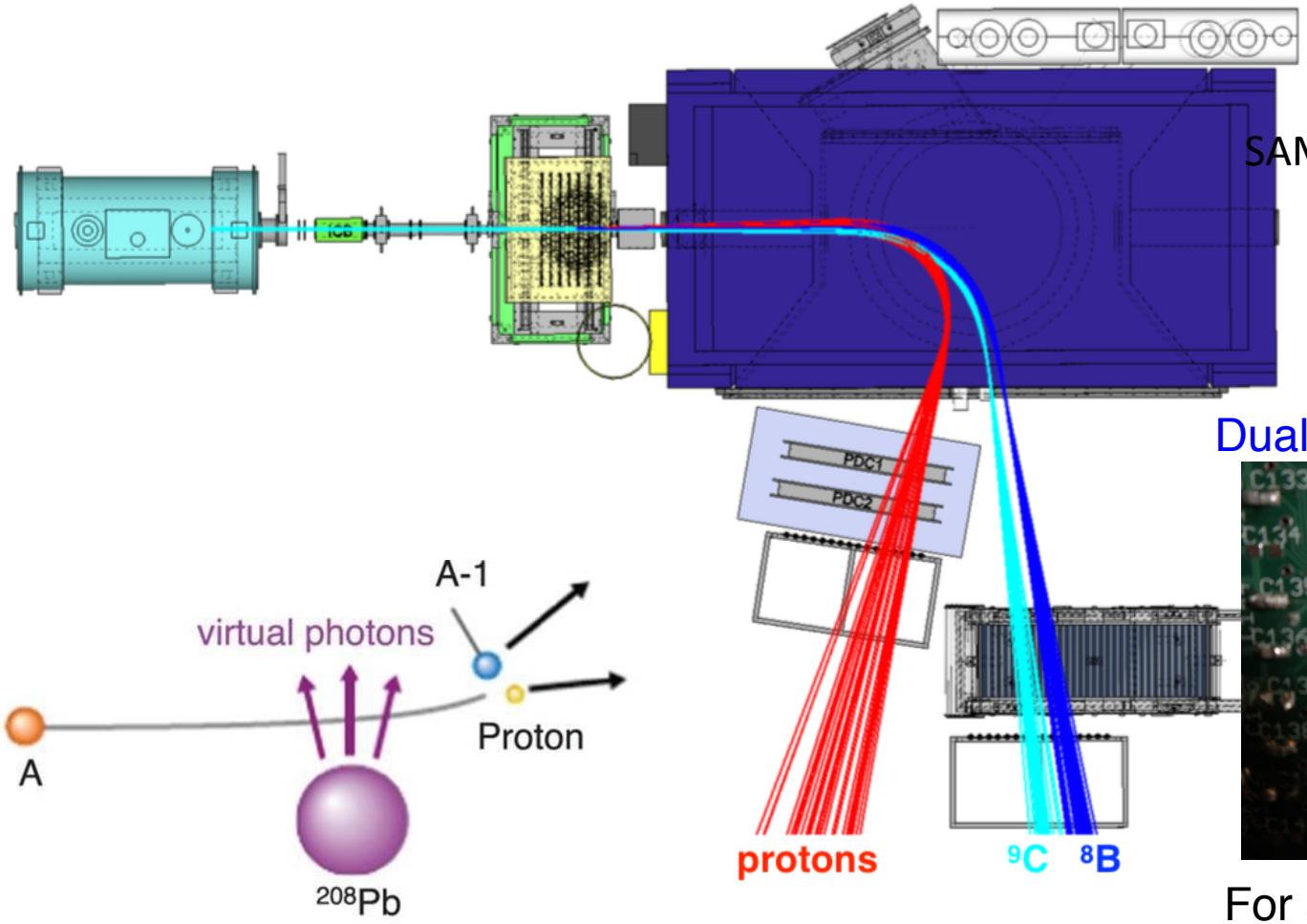
SAMURAI - various applications

TPC (Time Projection Chamber) in the SAMURAI magnet for EOS studies

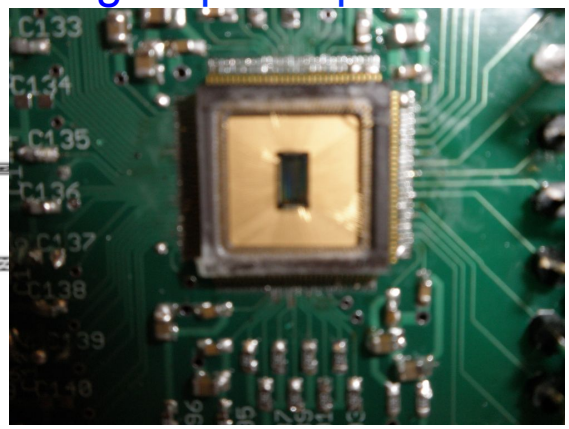
collaboration with MSU, Kyoto U., ..

SAMURAI - various applications

Proton-nucleus invariant mass measurements for processes of astrophysical interest
development of a silicon tracker (with electronics)



Dual-gain preamplifier ASIC



For a dynamic range >3000
. -- p+Sn(Z=50)

collaboration with Texas, Bucharest, Debrecen, Seoul..

3 magnetic spectrometers at RIBF

ZDS (ZeroDegree) 2007-
RIKEN (Kubo, ….)

SAMURAI 2012-
Tohoku (Kobayashi), RIKEN, Tokyo Tech

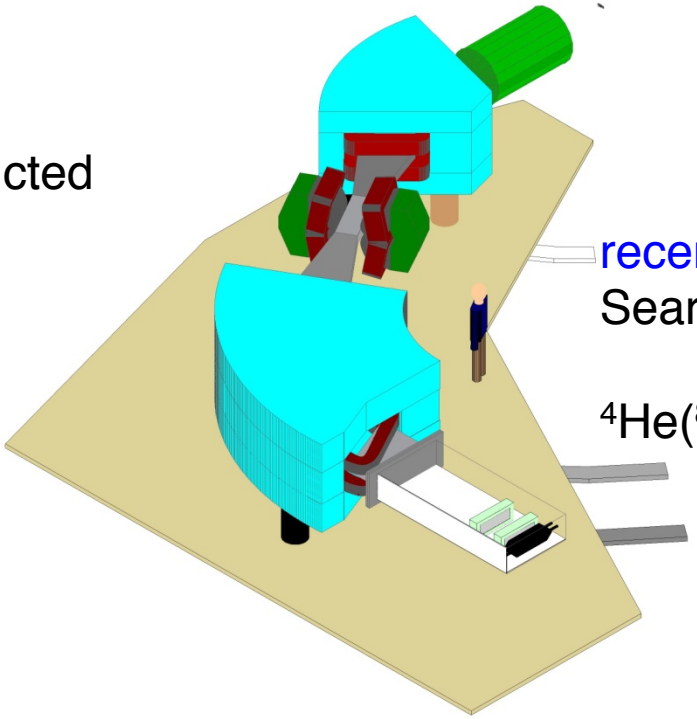
SHARAQ 2009-
high momentum resolution (dispersion matching)
for missing mass measurements

SHARAQ

Spectroscopy with
High-resolution **A**nalyzer of
Radio**A**ctive **Q**uantum beams

Designed and constructed
by CNS, Univ. Tokyo.
Beam line by RIKEN.

Q-D-Q-D



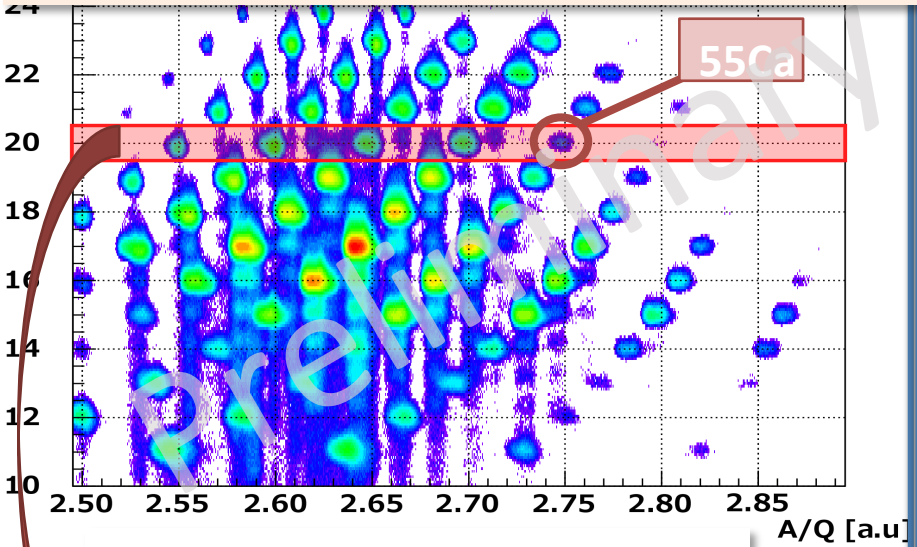
recent highlight
Search for Tetra-neutron resonance

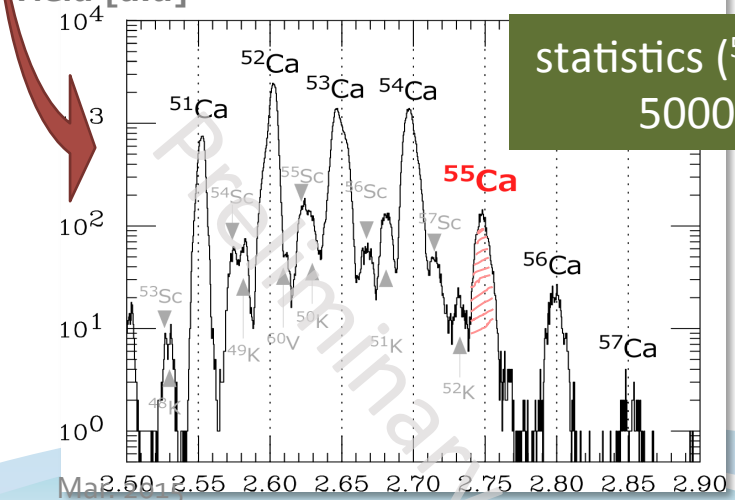
^{4}He(^{8}He,^{8}Be)4n

Mar. 2015

SHARAQ: Experiments

Direct mass measurement of neutron-rich Ca isotope at N~34

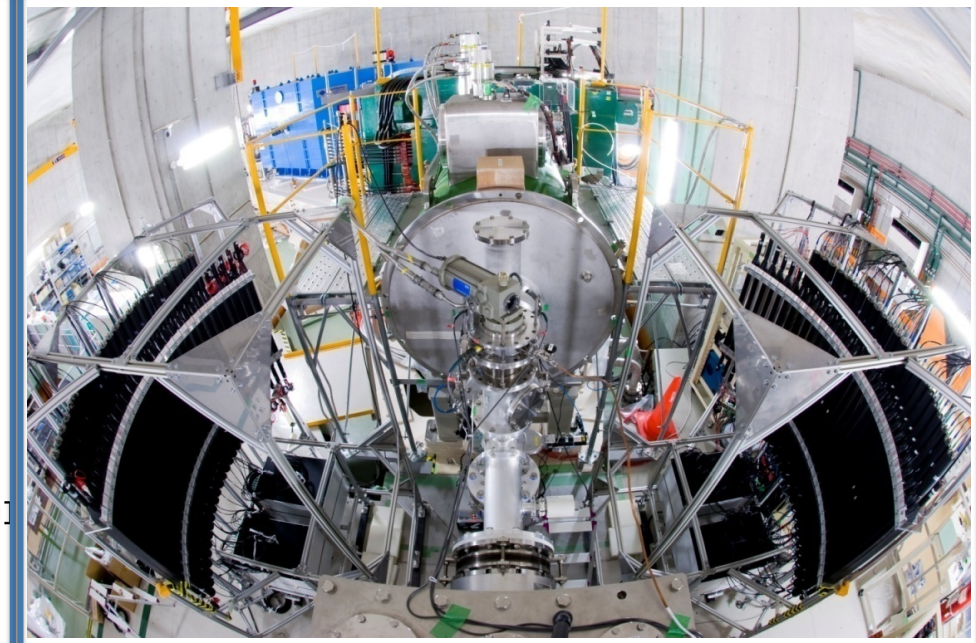


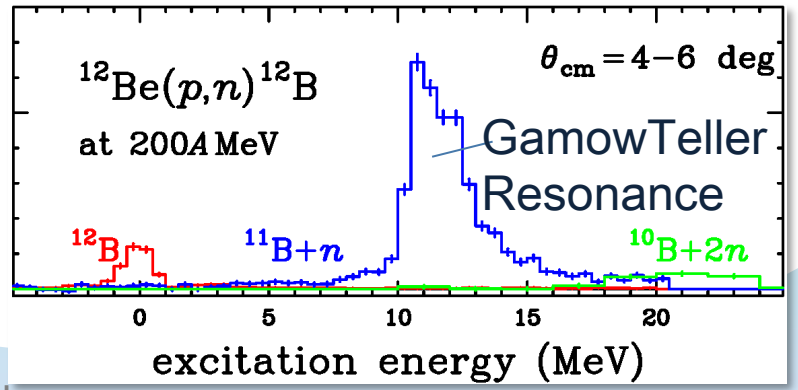


statistics (^{55}Ca): 5000

Preliminary

(p,n) reaction in inverse kinematics: WINDS





3 magnetic spectrometers at RIBF

ZDS (ZeroDegree) 2007-

evolution of shell closure / collectivity in n-rich nuclei

SAMURAI 2012-

neutron unbound states

various subjects: GT strength, EOS, explosive H burning,…

SHARAQ 2009-

4n scattering states, mass, GT resonances