First experiments with Super-FRS

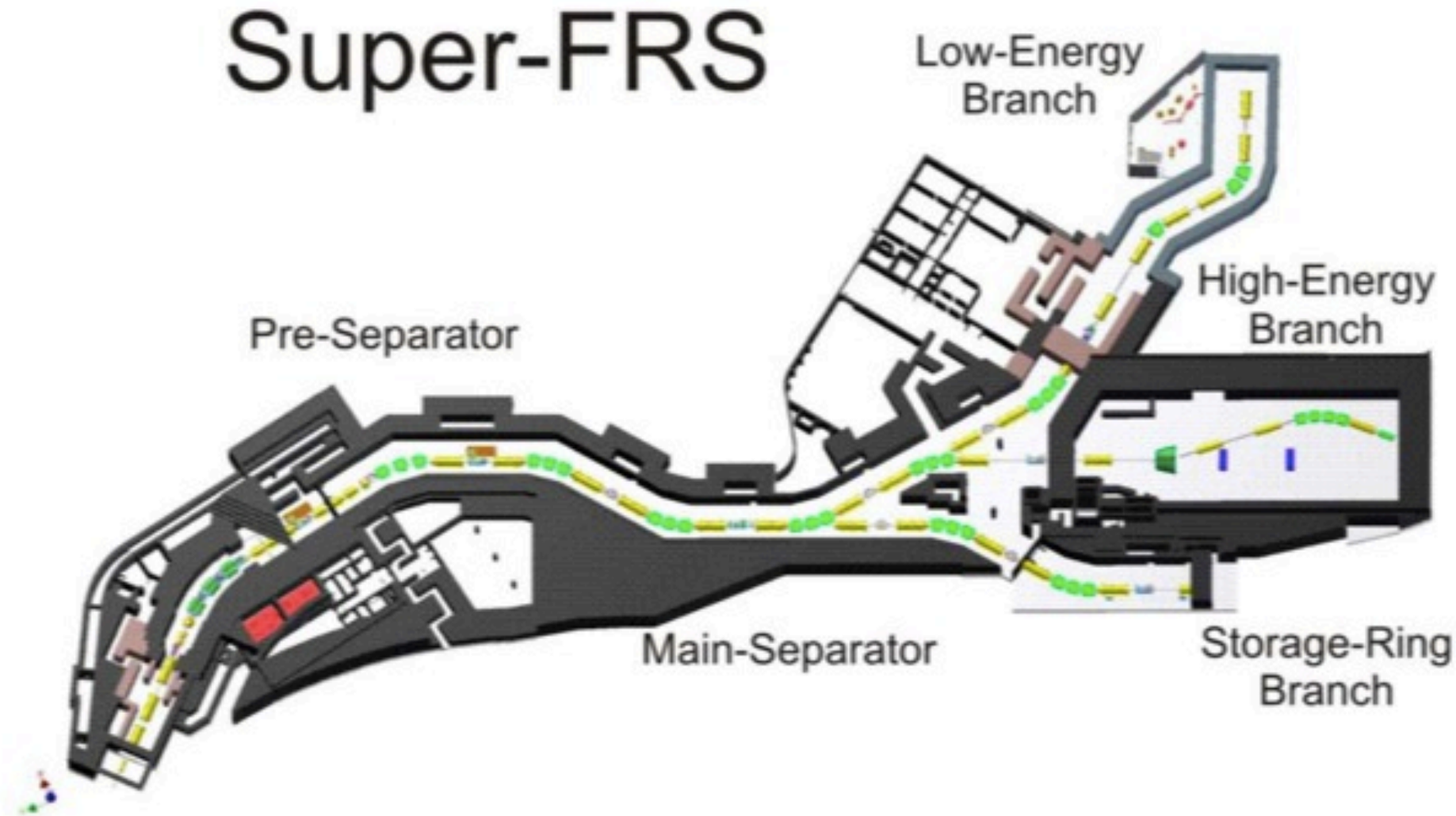
by Isao Tanihata as the spokesperson of the Super-FRS collaboration

International conference on Science and Technology for FAIR in Europe
17 October, 2014

Scientific Program of the Super-FRS Collaboration

GSI report 2014-4
DoI: 10.15120/GR-2014-4

t

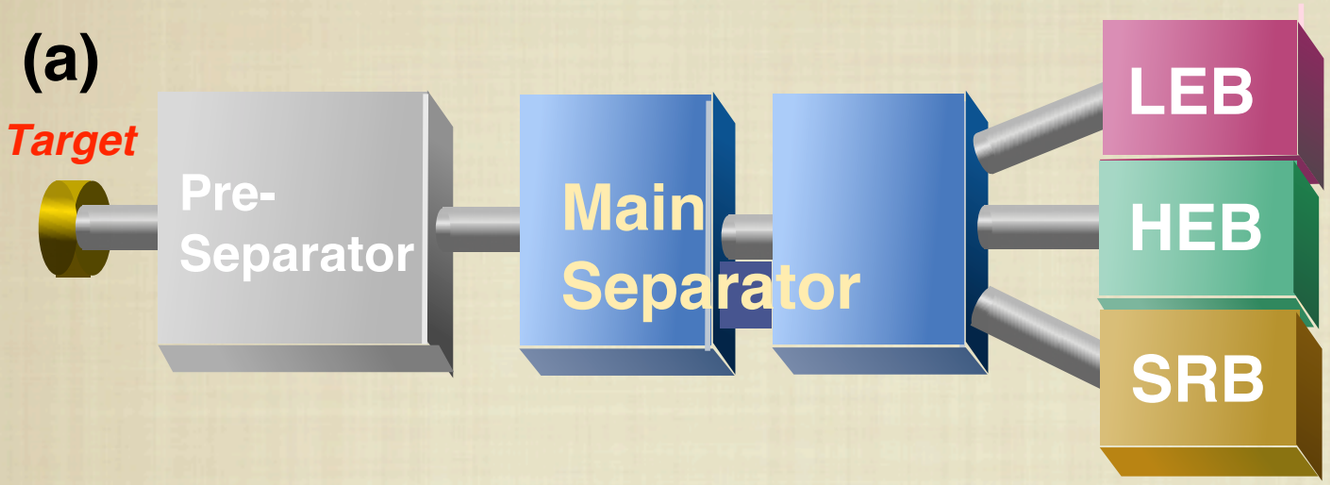


Uniqueness

- **FAIR Uniqueness:**
  - ***High-energy primary and secondary nuclear beams***
    - >400*A* MeV only at FAIR in the world.
    - Provides fully stripped ions of the heaviest elements.
  - ***High intensity***
    - The most exotic nuclei can be produced.
- **Super-FRS Uniqueness**
  - ***High separation power for exotic nuclei***
  - ***High momentum resolution (Δp/p)***
    - 10^{-4} or even better with dispersion matching modes.
  - ***Muti-staged spectrometer***
    - Combined use of a separator section and various spectrometer modes.

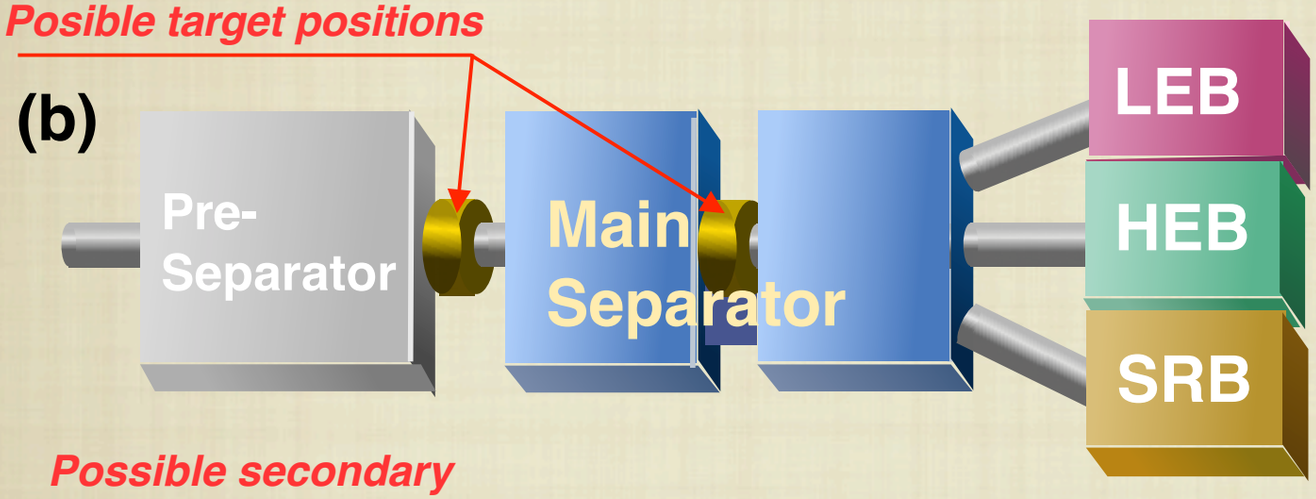
Various modes of Super-FRS

(a)

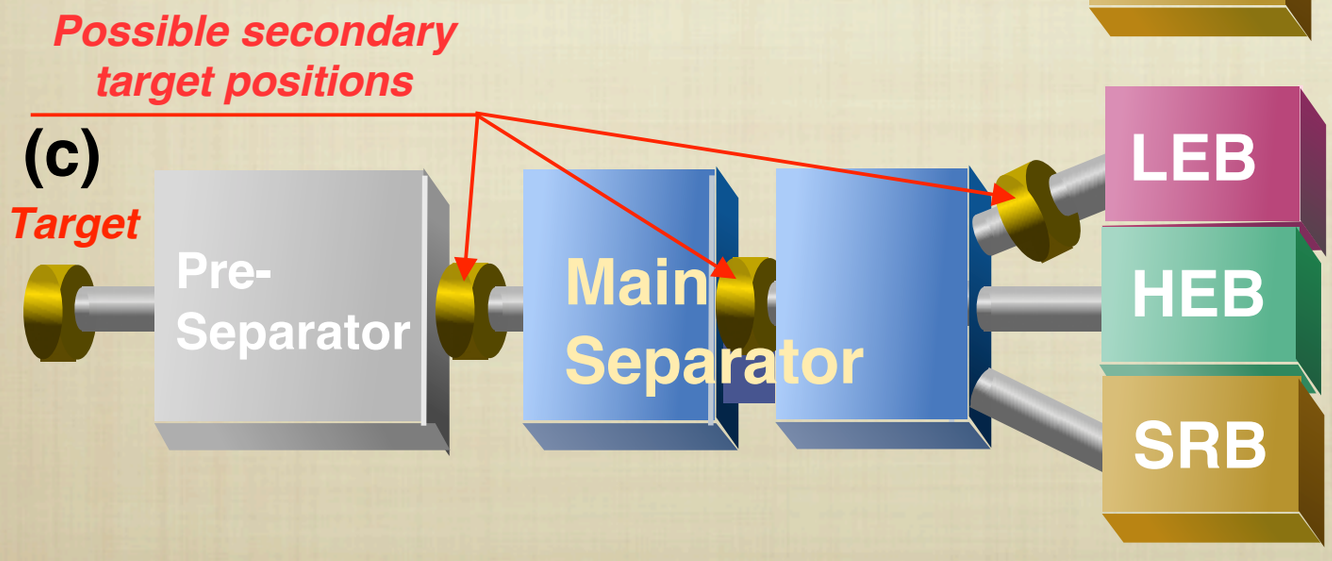


As high A and Q spectrometer
- Search for new isotopes
- Atomic physics

As high resolution 0º spectrometer
- η' bound nuclei and other mesonic atoms
- Tensor interactions



As high resolution 0º spectrometer
- Hyper nuclei
- Delta in nuclei



As RIbeam separator and spectrometer
- Low-q experiment with active target
- Interaction CC and charge changing CC
- Fragmentation of RIB
- LEB as despersion matching spectrometer.

Science Topics

- **Super-FRS for mass and charge separation**
  1. *Search for new isotopes and ground state properties*
  2. *Atomic collisions*
- **Super-FRS as high-resolution spectrometer**
  3. *Spectroscopy of meson-nucleus bound system (mesonic atoms)*
  4. *Exotic hypernuclei and their properties*
  5. *Importance of tensor forces in nuclear structure*
  6. *Delta resonances probing nuclear structure*
- **Super-FRS as multi-stage separator and high resolution reaction spectrometer**
  7. *Nuclear radii and momentum distributions*
  8. *Radioactive in-flight decays and continuum spectroscopy by particle emissions*
  9. *Low-q experiments with an active target*
  10. *Synthesis of new isotopes and nuclear reaction studies with RIBs*

Science Topics

- **Super-FRS for**
  1. *Search for new*
  2. *Atomic collisio*

Early execution of those experiments are not only giving the outstanding physics but also essential for success of other NUSTAR experiments.

- **Super-FRS as high-resolution spectrometer**
  3. *Spectroscopy of meson-nucleus bound system (mesonic atoms)*
  4. *Exotic hypernuclei and their properties*
  5. *Importance of tensor forces in nuclear structure*
  6. *Delta resonances probing nuclear structure*
- **Super-FRS as multi-stage separator and high resolution reaction spectrometer**
  7. *Nuclear radii and momentum distributions*
  8. *Radioactive in-flight decays and continuum spectroscopy by particle emissions*
  9. *Low-q experiments with an active target*
  10. *Synthesis of new isotopes and nuclear reaction studies with RIBs*

Science Topics

- **Super-FRS for**
  1. *Search for new*
  2. *Atomic collisio*

Early execution of those experiments are not only giving the outstanding physics but also essential for success of other NUSTAR experiments.

- **Super-FRS as high-resolution spectrometer**
  3. *Spectroscopy of meson-nucleus bound system (mesonic atoms)*
  4. *Exotic hypernuc*
  5. *Importance of tensor forces in nuclear structure*
  6. *Delta resonances probing nuclear structure*

Experiments that can be done only at Super-FRS.

- **Super-FRS as multi-stage separator and high resolution reaction spectrometer**
  7. *Nuclear radii and momentum distributions*
  8. *Radioactive in-flight decays and continuum spectroscopy by particle emissions*
  9. *Low-q experiments with an active target*
  10. *Synthesis of new isotopes and nuclear reaction studies with RIBs*

Science Topics

- **Super-FRS for**
  1. *Search for new*
  2. *Atomic collisio*

Early execution of those experiments are not only giving the outstanding physics but also essential for success of other NUSTAR experiments.

- **Super-FRS as high-resolution spectrometer**
  3. *Spectroscopy of meson-nucleus bound system (mesonic atoms)*
  4. *Exotic hypernuc*
  5. *Importance of tensor forces in nuclear structure*
  6. *Delta resonances probing nuclear structure*

Experiments that can be done only at Super-FRS.

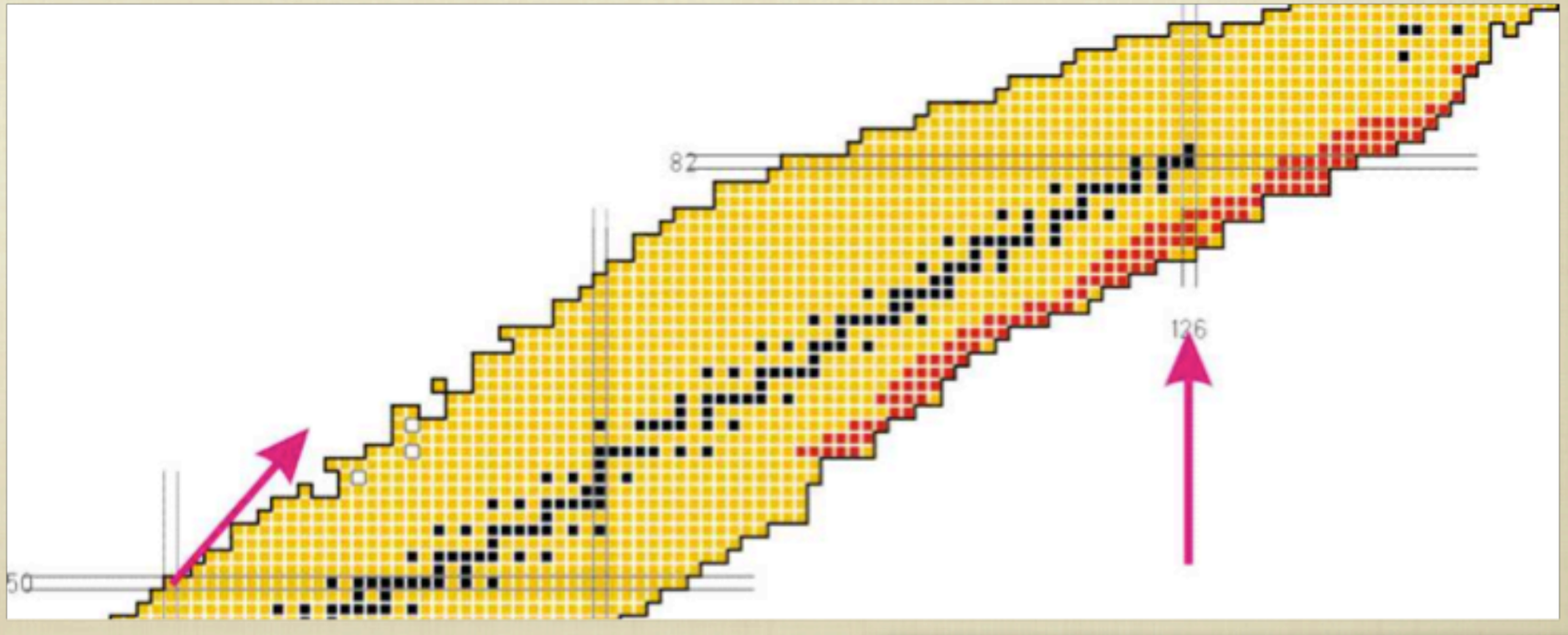
- **Super-FRS as multi-stage separator and high resolution reaction spectrometer**
  7. *Nuclear radii an*
  8. *Radioactive in-fl emissions*
  9. *Low-q experiments with an active target*
  10. *Synthesis of new isotopes and nuclear reaction studies with RIBs*

Experiments taking advantages of multi-stage spectrometer design of the Super-FRS.

1. Search for new isotopes and ground state properties

(Pietri, Jokinen, Plaβ et al.)

- Take advantage of E>500A MeV U or other beams, many new isotopes would be produced.
- The determinations of production cross sections and kinematics of unstable nuclei are imperative for Super-FRS operation.



Experience continues from FRS.

2. Atomic collisions

(Purushothaman, Geissel et al.)

- **Accurate knowledge of the atomic interaction of ions penetrating through a matter, such as charge-state distributions of ions of heavy elements, is essential.**
  - ***It is important also for delivering RIB from Super-FRS.***
- **New data for stopping power, energy and angular straggling will be obtained at high energies.**
  - ***Important also for gas stopping cells optimization.***
- **Resonant coherent excitation in crystals (nuclear Okorokov effect) will be measured for the first time.**

Experience continues from FRS.

3. Spectroscopy of meson-nuclus bound system (mesonic atoms)

(Itahashi, Weick et al.)

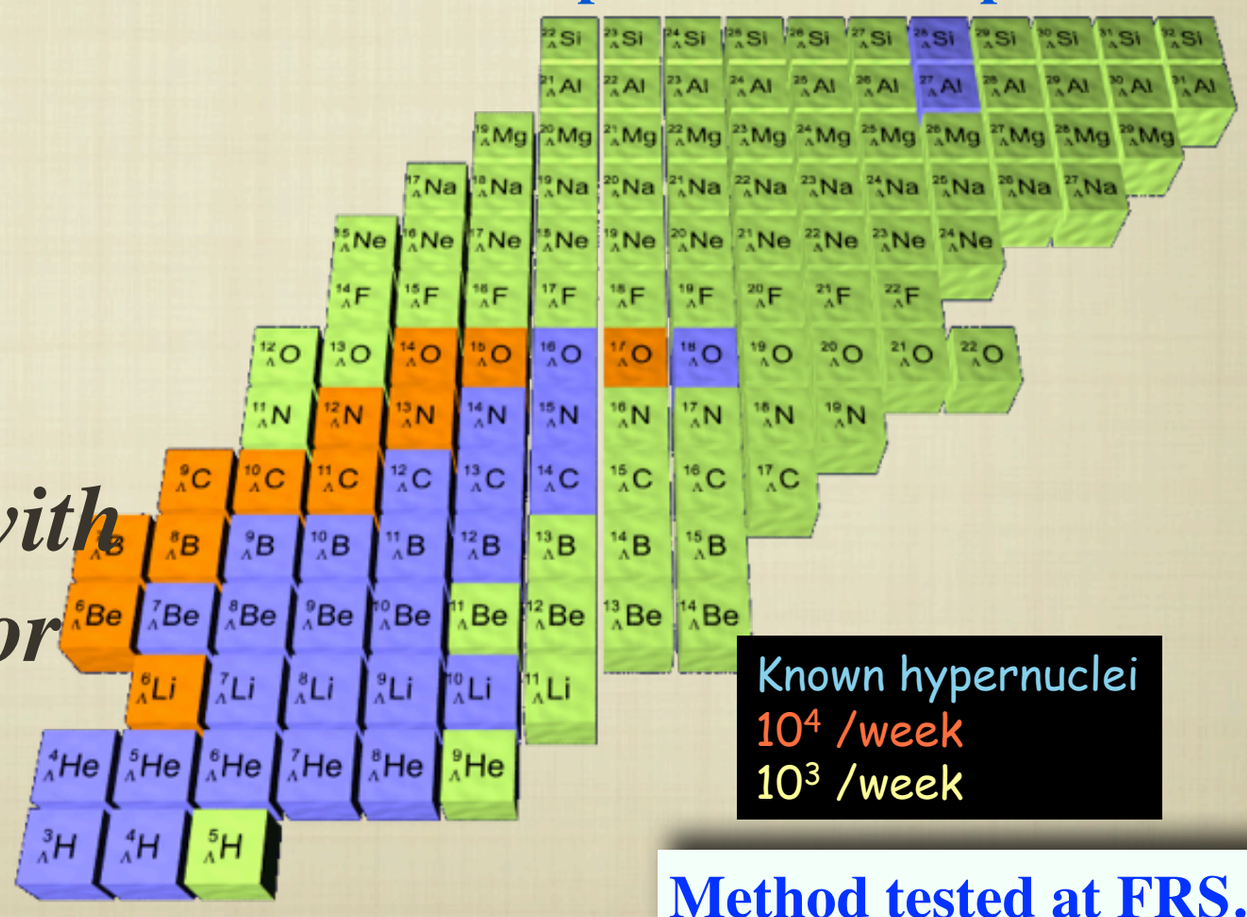
Later

4. Exotic hypernuclei and their properties

(Saito, Nociforo et al.)

- **Production of hypernuclei by high-energy (>1.2*A* GeV) heavy-ions peripheral collision is expected to have large cross sections.**
- **Also this method is suitable for determination of lifetimes.**
- **Pilot experiment shows several new evidences of $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H**
  - ***The lifetime have also been determined.***
- ***$^{3}_{\Lambda}$n has been suggested.***
- ***Higher resolution of mass with FRS/Super-FRS will help for identifications.***

Land scape with FRS/Super-FRS



Method tested at FRS.

5. Importance of tensor forces in nuclear structure

(Ong, Terashima, Toki et al.)

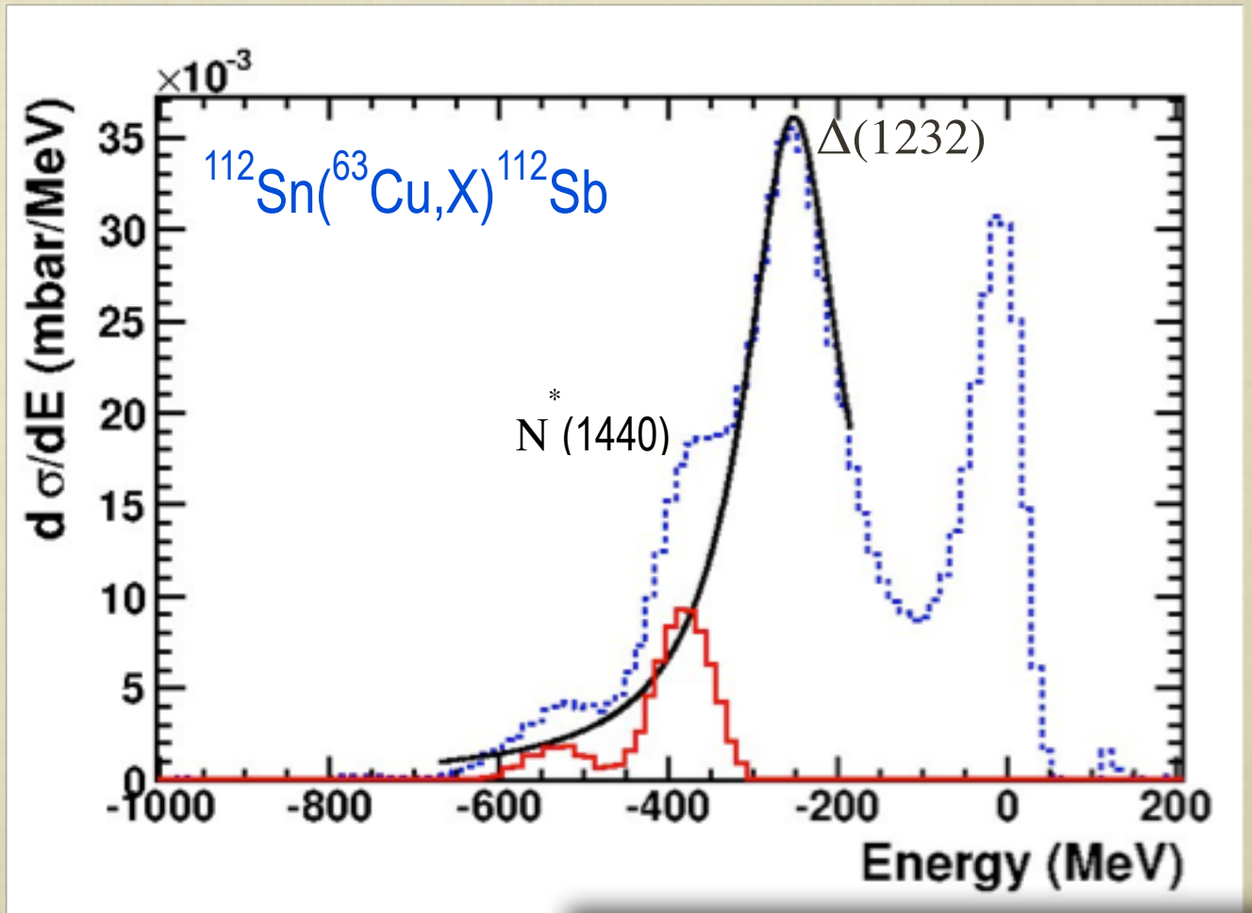
Later

6. Delta resonances probing nuclear structure

(Benlliure, Lenske et al.)

- **Charge changing reactions with high-energy heavy ions provide unique possibilities to study baryon resonances, including Δ-resonances in exotic nuclei.**
  - ***So far Δ-resonances in nuclei has been studied exclusively in stable or near stable nuclei***

- **Studying**
  - ***In-medium properties of baryon resonance in isospin asymmetric nuclear matter***
  - ***Gamow-Teller transition strength***
  - ***Radial distribution of neutrons and protons***
  - ***Nuclear matrix elements for inelastic neutrino interactions***



Some data obtained at FRS.

7. Nuclear Radii and momentum distribution

(Kanungo, Prochazka et al.)

- **Determinations of nuclear matter radii by the interaction cross sections and radii of proton distribution by the charge changing cross sections.**
- **Spectroscopy of exotic nuclei by momentum distribution measurement of the projectile fragments**
- **With Super-FRS measurements it can be extended to much heavier nuclei such as Sn isotopes.**

- ***More exclusive measurements of fragmentation could be better done in R3B.***
- ***Need continuous discussion for optimization for such cases.***

7. Nuclear Radii and momentum distribution

(Kanungo, Prochazka et al.)

- **Determinations of nuclear matter radii by the interaction cross sections and radii of proton distribution by the charge changing cross sections.**
- **Spectroscopy of exotic nuclei by momentum distribution measurement of the projectile fragments**
- **With Super-FRS measurements it can be extended to much heavier nuclei such as Sn isotopes.**

Experiments developed at FRS lead the world study of exotic nuclei.

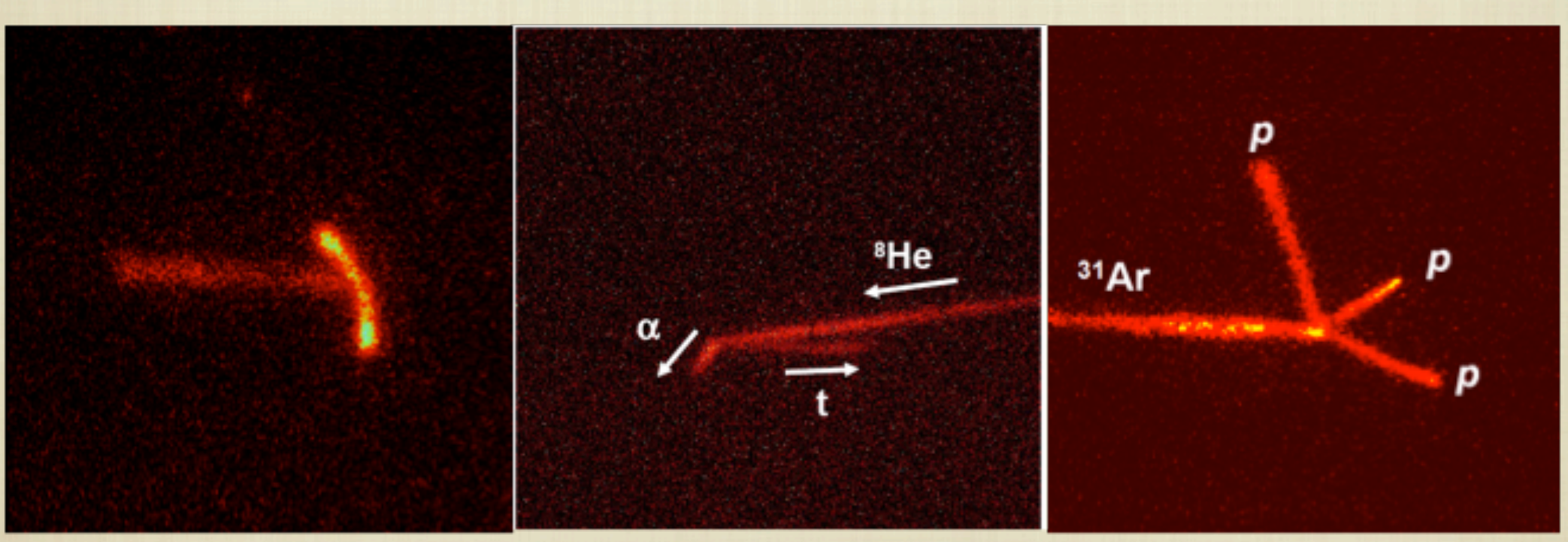
Halos, neutron skins, new magic numbers, and spectroscopy of drip line nuclei.

- *More exclusive meas*
  done in R3B.
- *Need continuous discussion for optimization for such cases.*

8. Radioactive in-flight decays and continuum spectroscopy by particle emission

(Fomichev, Pfützner, Mukha et al.)

- **Study decays (particle emission) of nuclear beyond the drip line and other resonances.**
  - ***One-, two- four- proton decays, two-proton decay***
  - ***Neutron radioactivity***



- ***Complementary with missing mass, invariant mass measurements.***

EXPERT:

EXotic Particle Emission and Radioactivity by Tracking

VERY THICK secondary target for one- or two-nucleon knockout

Identification of heavy fragment excitations by target area g array

GADAST

4

Last achromatic stage of fragment separator is **Hi-res spectrometer** for heavy decay fragment

Degrade the heavy fragment energy

$^{A-1}(Z-2)$

5

$^{A-2}(Z-1)$

Warsaw OTPC

Radioactive particle emission for stopped reaction and decay products

Beam

^{A}Z

^{A-1}Z

$^{A}(Z-1)$

p

n

1

2

3

Radiation--hard SSDs

for beam diagnostics

mSi tracking

detector system for light charged particles

NeuRad

High-angular resolution neutron detector

FRS, SuperFRS one of the middle focal planes

Particle unstable systems beyond proton or neutron driplines

Hi-res angular measurements both for proton and neutron dripline nuclei populated on secondary target

6

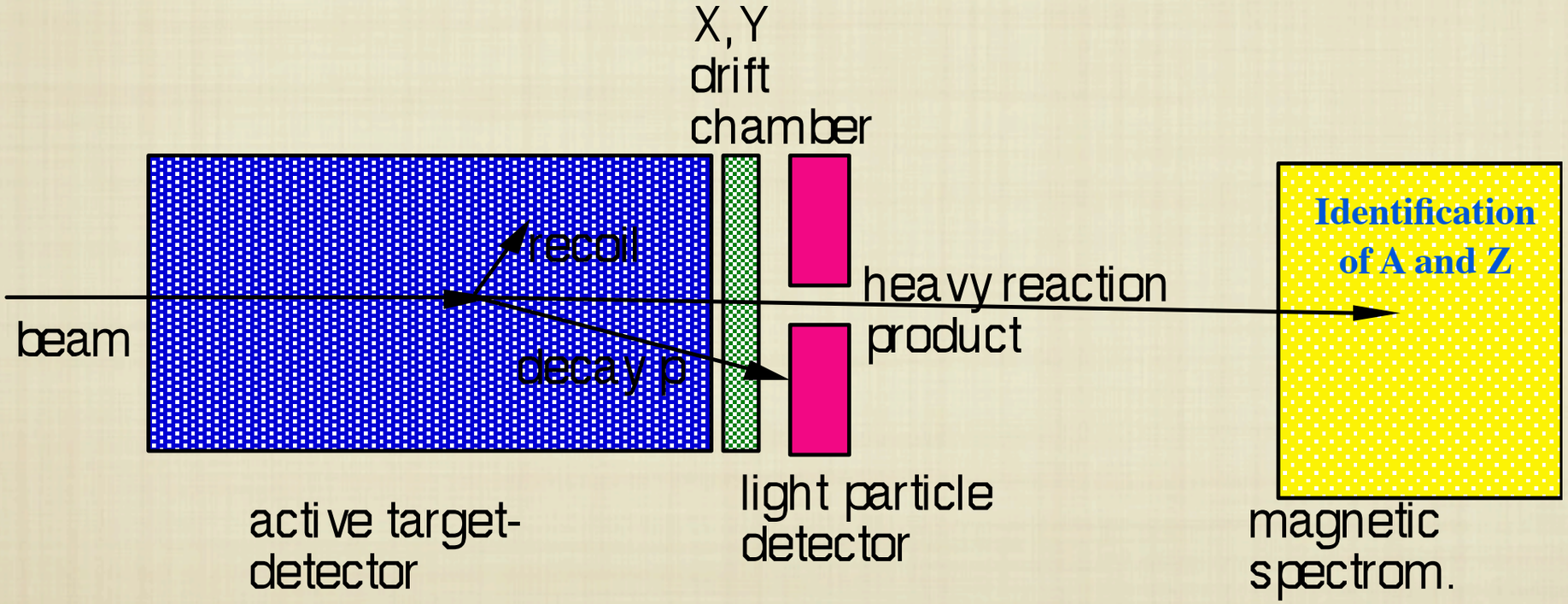
MC simulation framework

to interpret the correlation data with incomplete kinematics

9. Low-q experiment with an active target

(Egelhof, Kalantar et al.)

- **Elastic scattering of heavy neutron rich nuclei for study of nuclear distribution and neutron skin.**
- **Such systematic studies provide the information on EOS of asymmetric nuclear matter.**

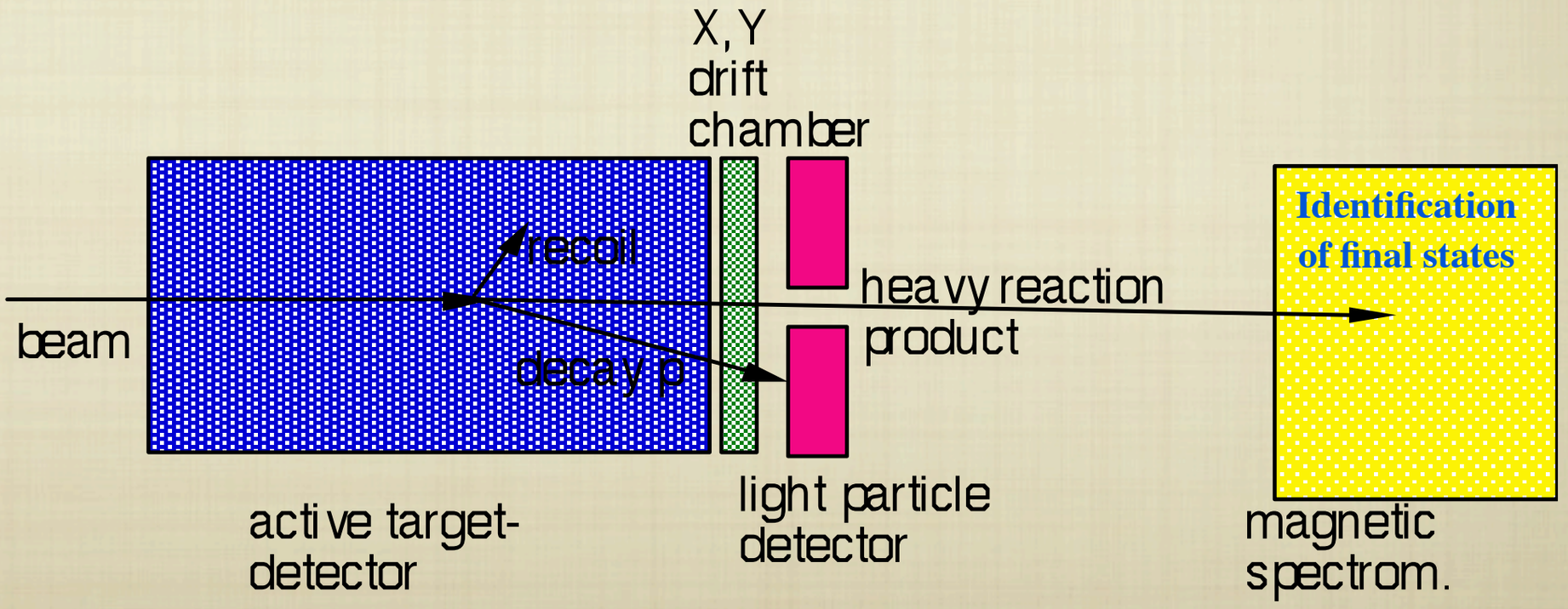


- ***Some overlap with usage of other facility (R3B) has to be discussed continuously for mutual improvement.***

Experience of IKAR at FRS.

9. Low-q experiment with and active target (II)

- **When heavy nuclei such as Sn isotopes are concerned.**
  - ***Recoil proton energies for the first bump exceed the range of active target. Therefore the inelastic scattering would not be separated by the active target itself.***
  - ***A forward high-resolution spectrometer can resolve excited states but need better than $8x10^{-5}$ momentum resolution.***



10. Nuclear reaction studies and synthesis of isotopes with low-energy RIBs

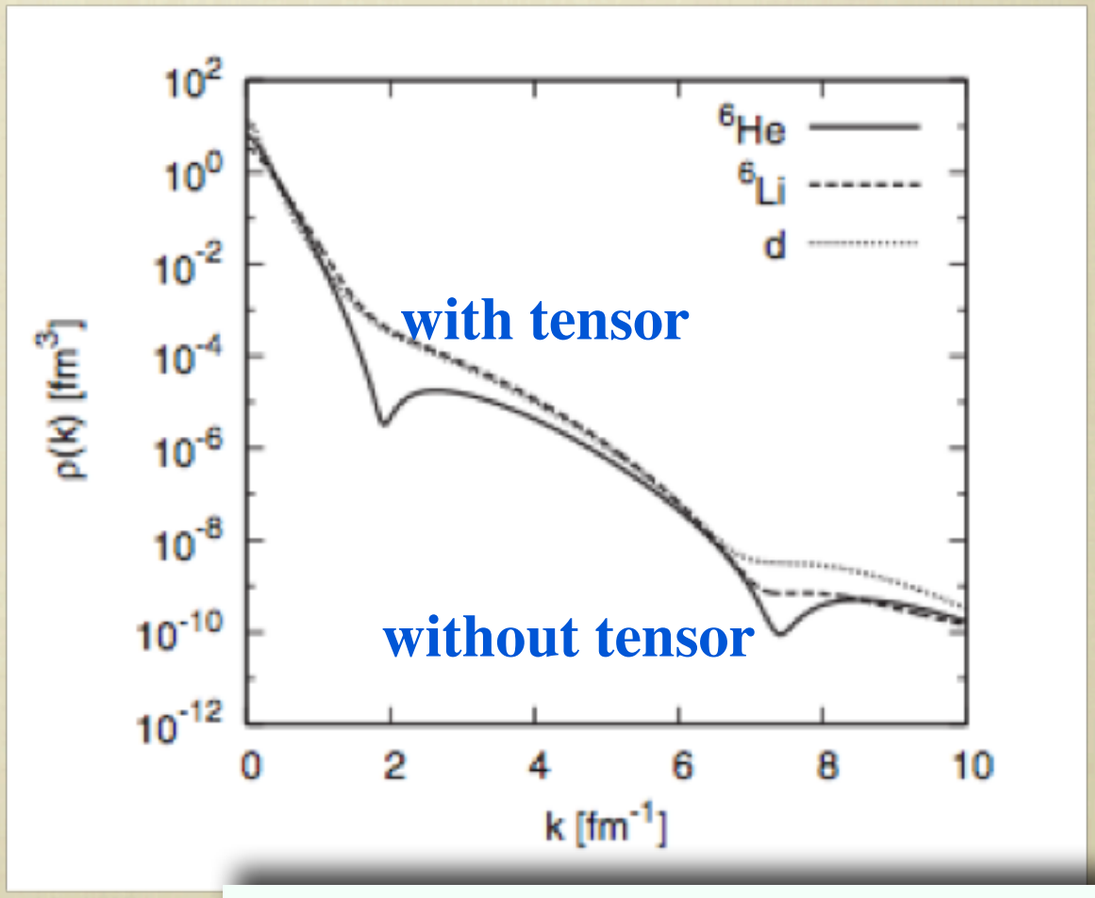
(Heinz, Winfield et al.)

- **At Low Energy beam line.**
- Experiments with RIB at Coulomb-barrier energies challenge a new field for reaction studies.
  - *Which will contribute to a better understanding of deep inelastic, fusion-fission and complete fusion reactions*.
- This knowledge is essential for the extension of the nuclear chart towards superheavy elements beyond the existing limit. They will possibly give access to new neutron-rich isotopes beyond uranium, and also below uranium, both regions are not accessible in fusion reactions with stable beams nor in fragmentation reactions.

5. Importance of tensor forces in nuclear structure

(Ong, Terashima, Toki et al.)

- **Although it is important for binding nuclei, tensor forces have not been treated explicitly in most of successful nuclear structure models such as mean field models and shell models.**
- **Those important contributions are through nucleons with high momentum.**
- **Studies of such high-momentum nucleons (P~2 fm^{-1}) will be done by high-energy pick-up reactions.**
  - ***(p,d), (d,^{3}He), (d,t), (p,pd), (p,nd) reactions***
  - ***In some complementary cases***
  - ***(p,pd), (p,nd) reactions may be better at R3B***
  - ***It has to be carefully evaluated.***



Pilot experiment planned at FRS.

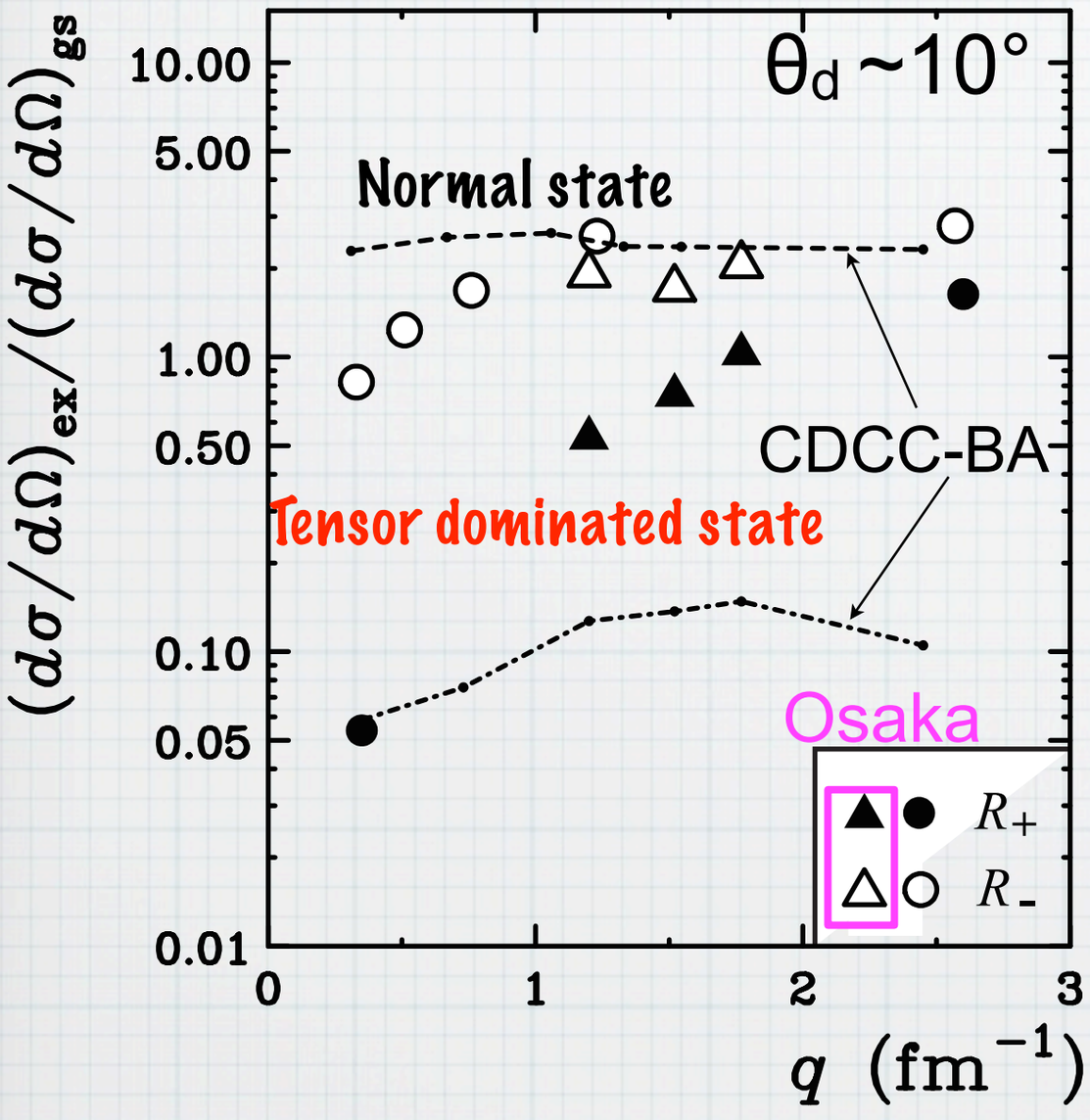
Super-FRS Collaboration Pilot Experiment (S436):

Understanding Effect of Tensor Forces in ^{16}O

-- probing high-momentum components via ^{16}O(p,d)

Finite-angle measurements (in Osaka)

HJO, IT *et al.*, PLB 725, 277(2013)

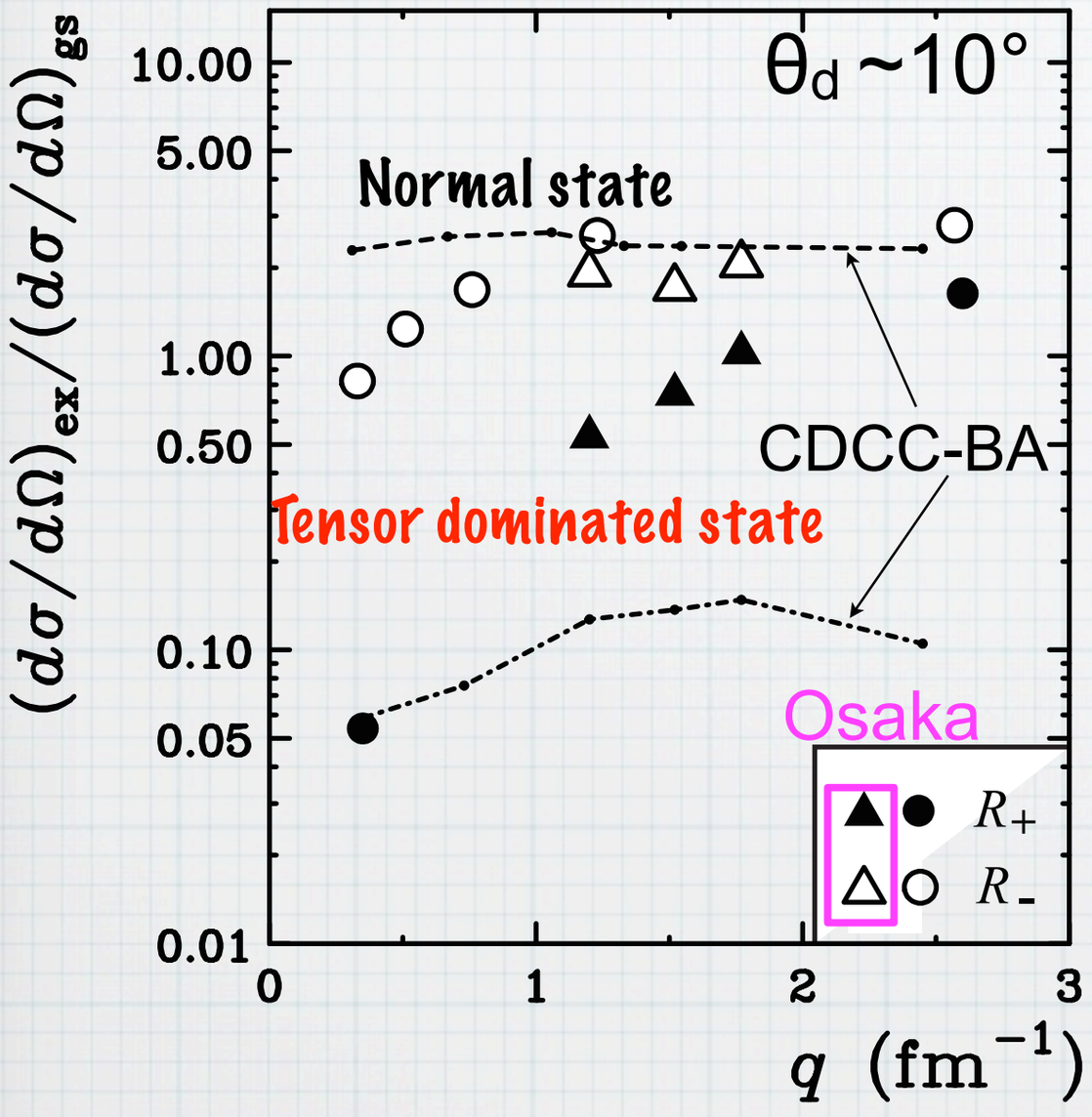


Super-FRS Collaboration Pilot Experiment (S436):

Understanding Effect of Tensor Forces in ^{16}O

-- probing high-momentum components via ^{16}O(p,d)

HJO, IT *et al.*, PLB 725, 277(2013)



Finite-angle measurements (in Osaka)

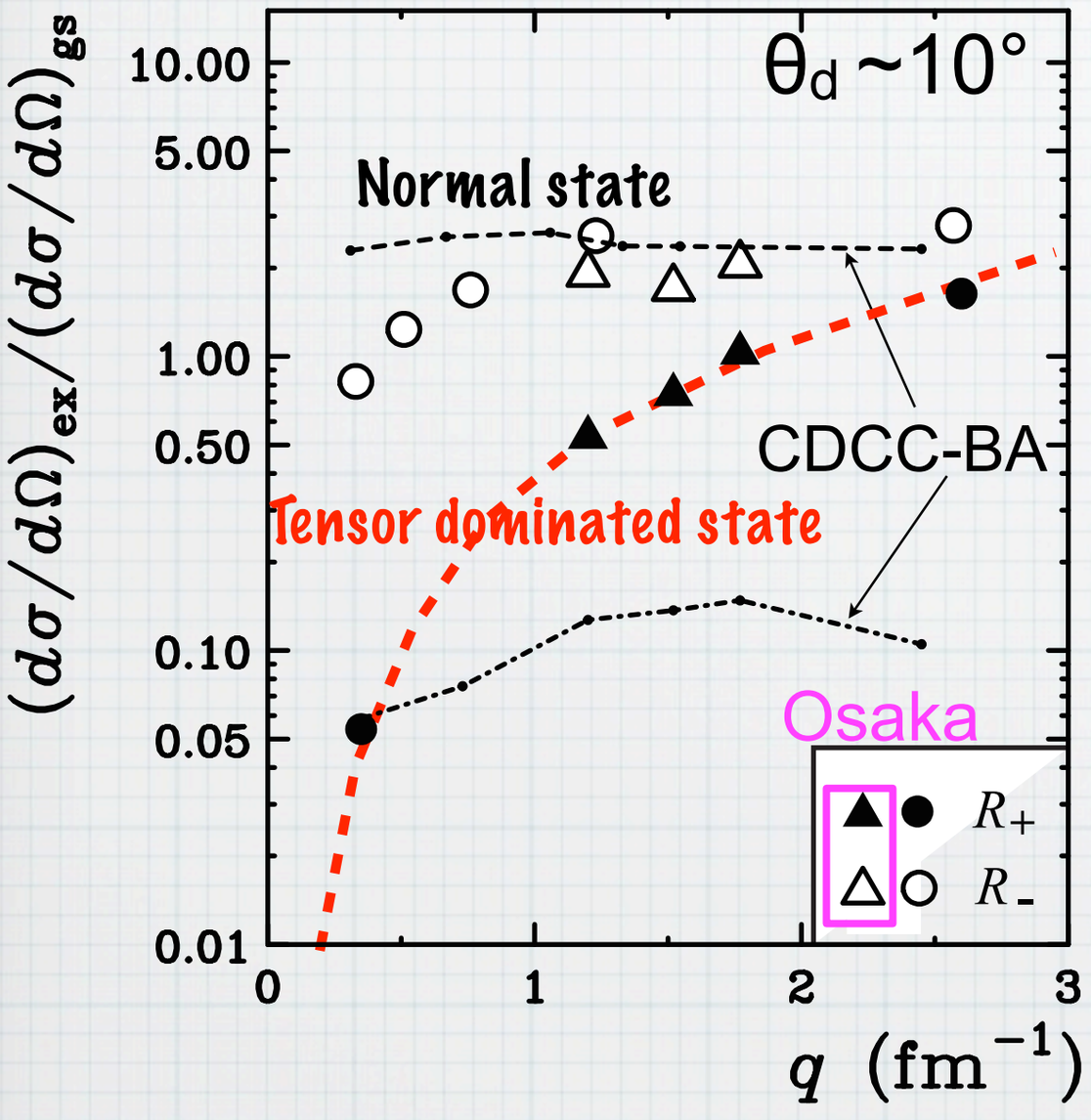
- ✓ drastic increase in cross section ratios for 5/2+ and 1/2- (ground state)
- ✓ reaction theory qualitatively agrees with ratios for the neutron-hole state 3/2- but underestimate those for the 5/2+ state
- ✓ **TOSCOM-type momentum wave functions** (red dashed curve) that include high-momentum components “fit” the data well

Super-FRS Collaboration Pilot Experiment (S436):

Understanding Effect of Tensor Forces in ^{16}O

-- probing high-momentum components via ^{16}O(p,d)

HJO, IT *et al.*, PLB 725, 277(2013)



Finite-angle measurements (in Osaka)

- ✓ drastic increase in cross section ratios for 5/2+ and 1/2- (ground state)
- ✓ reaction theory qualitatively agrees with ratios for the neutron-hole state 3/2- but underestimate those for the 5/2+ state
- ✓ **TOSCOM-type momentum wave functions** (red dashed curve) that include high-momentum components “fit” the data well

T. Myo, PTP 117 (2007) 257.

⇩

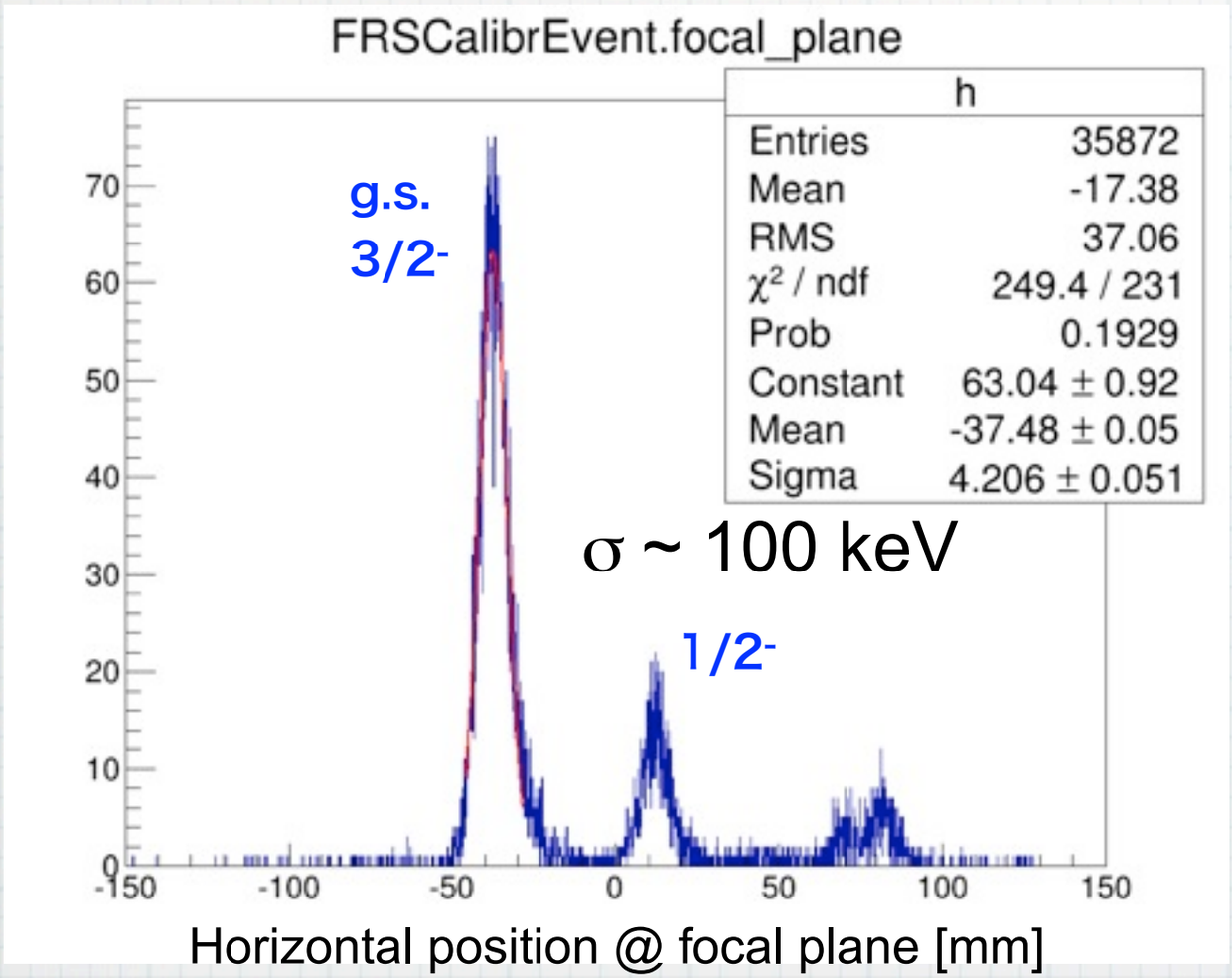
Possible evidence of tensor forces

S436: Online spectra (performance of FRS)

Proton beam @400 MeV/u,
with 107 mg/cm^2 ^{nat}C target

^{12}C(p,d)

Measurements have been made for
400, 600, 900, 1200 MeV/u
in August 2014

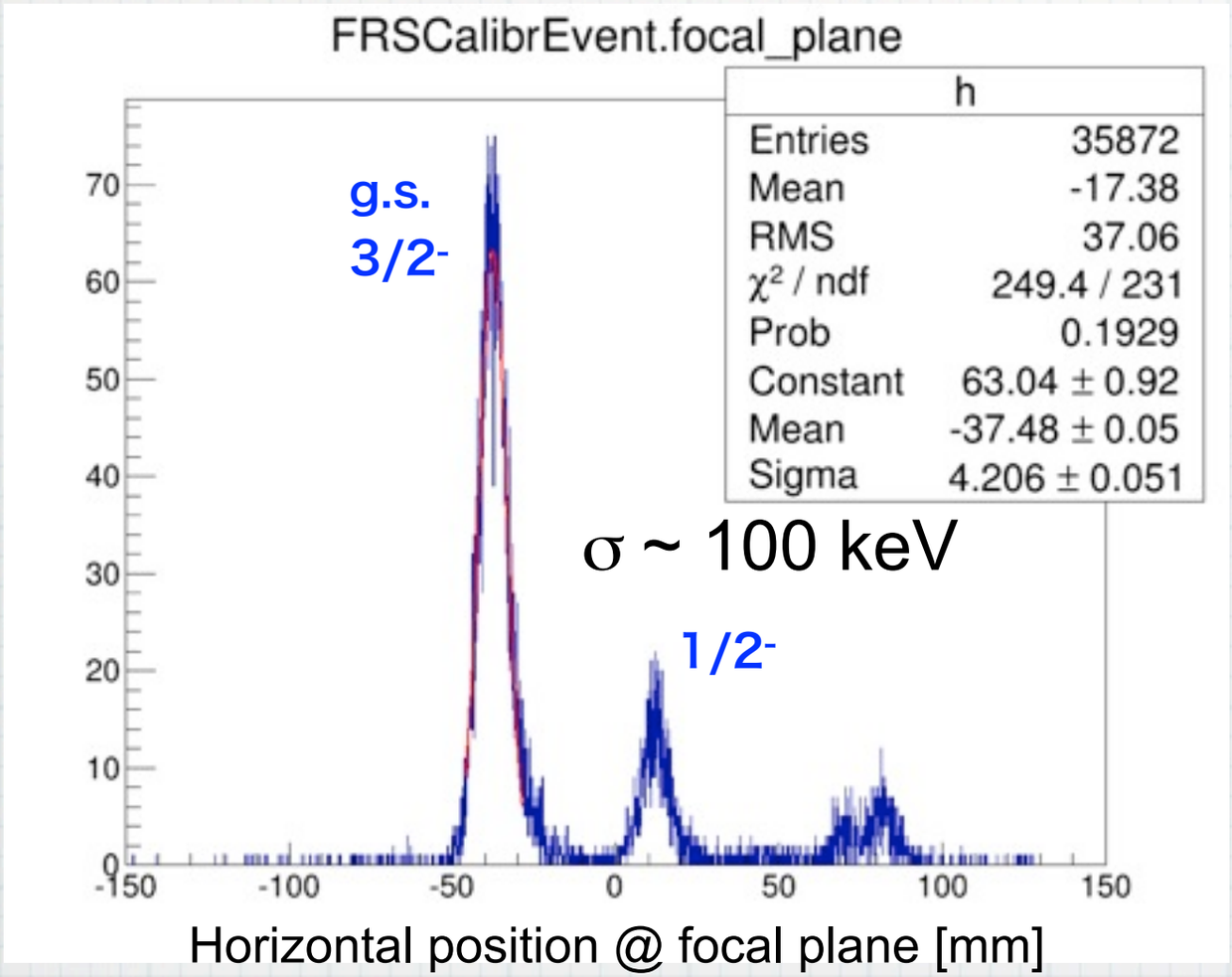


S436: Online spectra (performance of FRS)

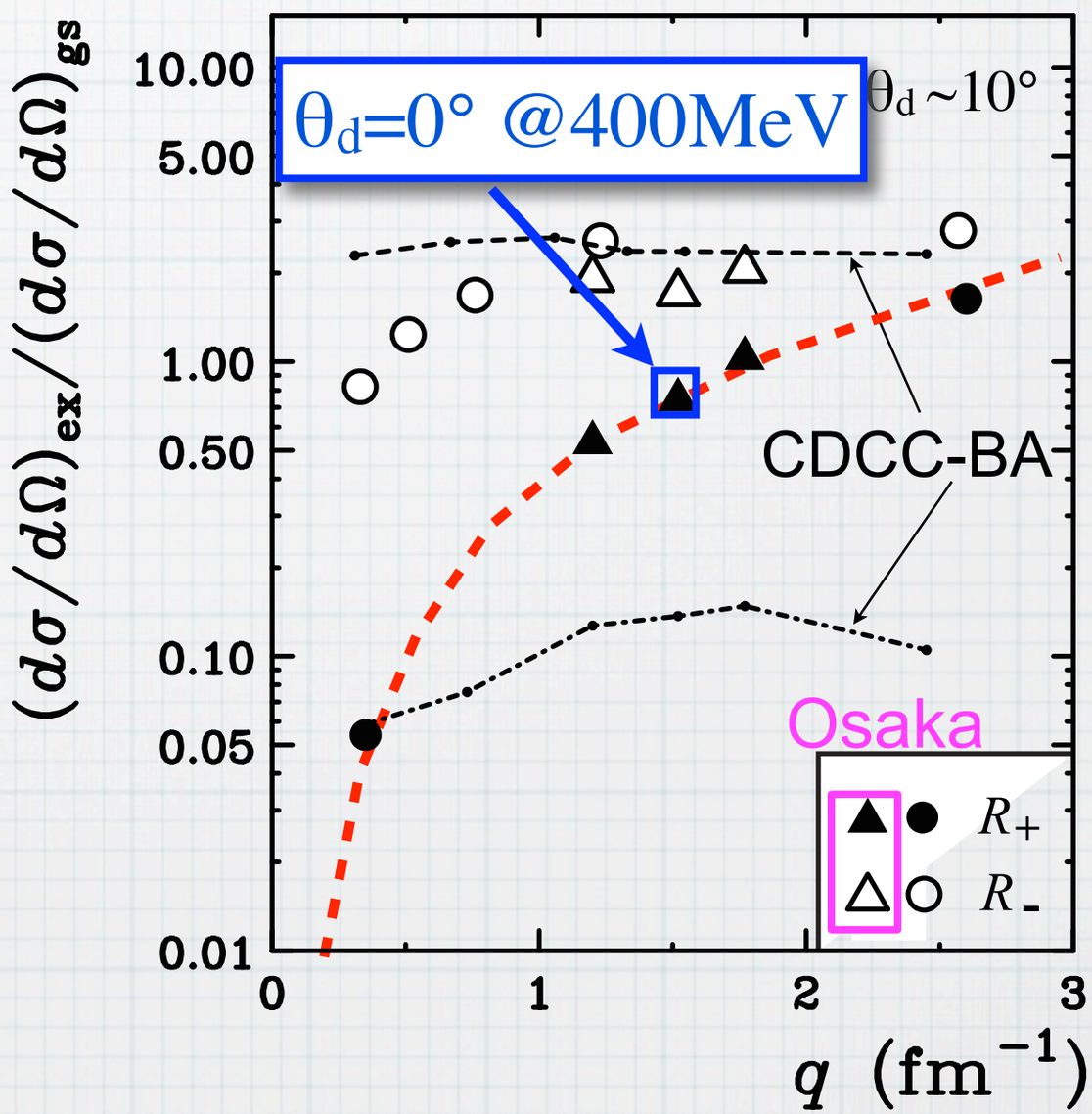
Proton beam @400 MeV/u,
with 107 mg/cm^2 ^{nat}C target

^{12}C(p,d)

Measurements have been made for
400, 600, 900, 1200 MeV/u
in August 2014

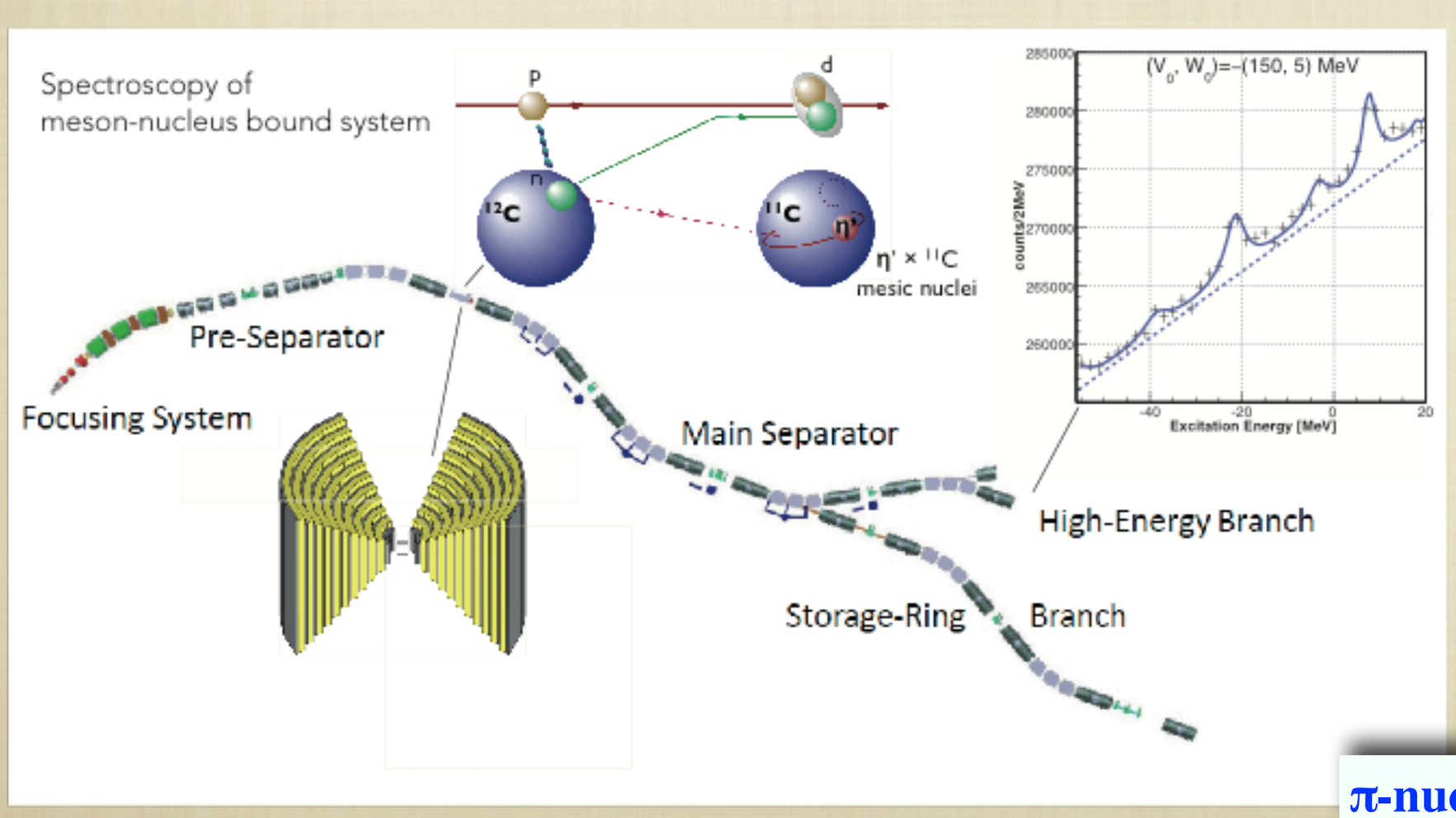


HJO, IT *et al.*, PLB 725, 277(2013)



3. Spectroscopy of meson-nuclus bound system (mesonic atoms) (Itahashi, Weick et al.)

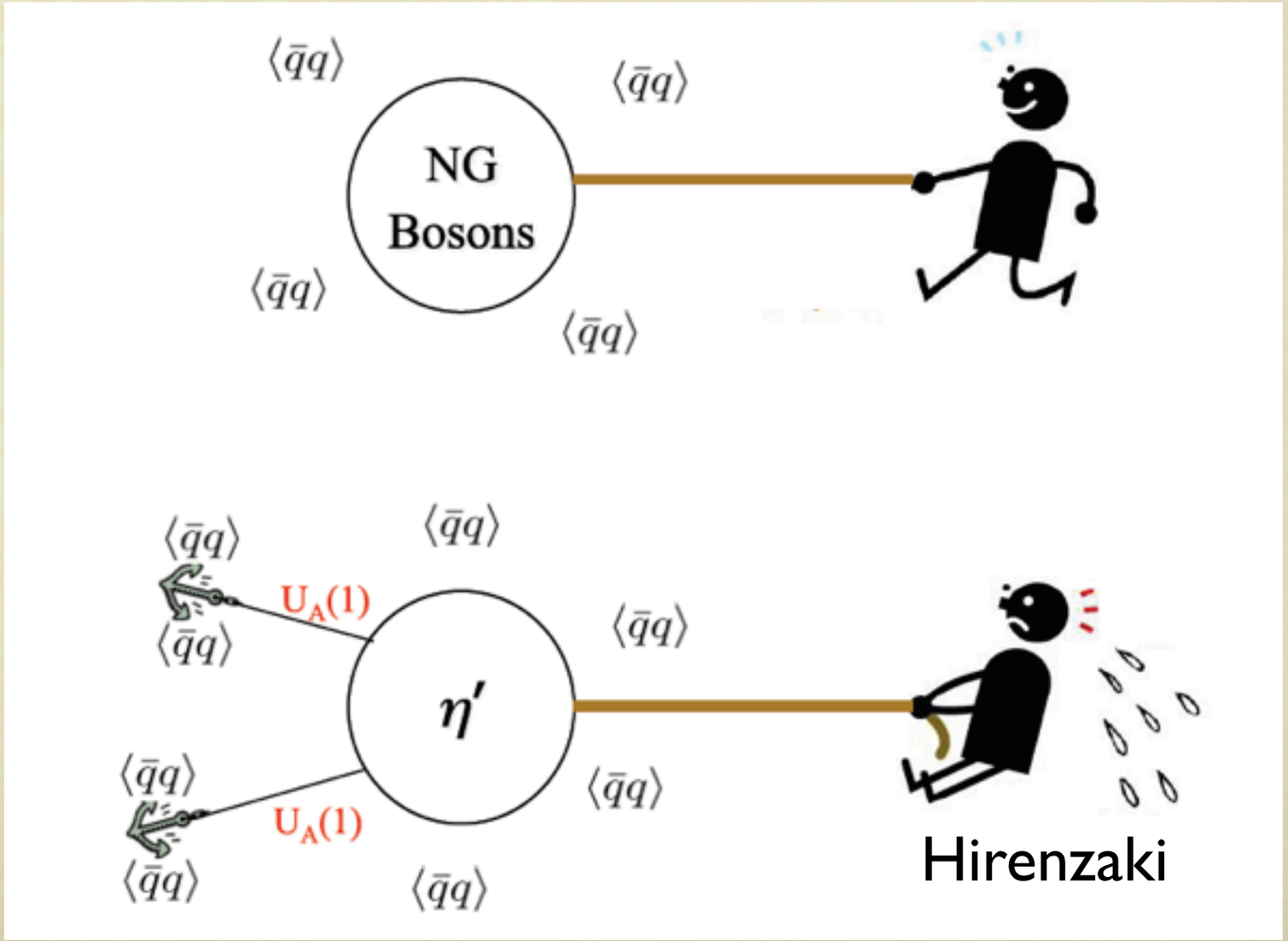
- **The discovery of deeply-bound pionic state in heavy atoms with FRS opened a new field of fundamental studies of the meson-nucleus interactions, which contributes to the understanding of the non-trivial structure of the vacuum of QCD.**
- **Observation of η'-bound nuclei with (p, d) reaction is the first aim of the experiment.**



π-nucleus discovered at FRS.

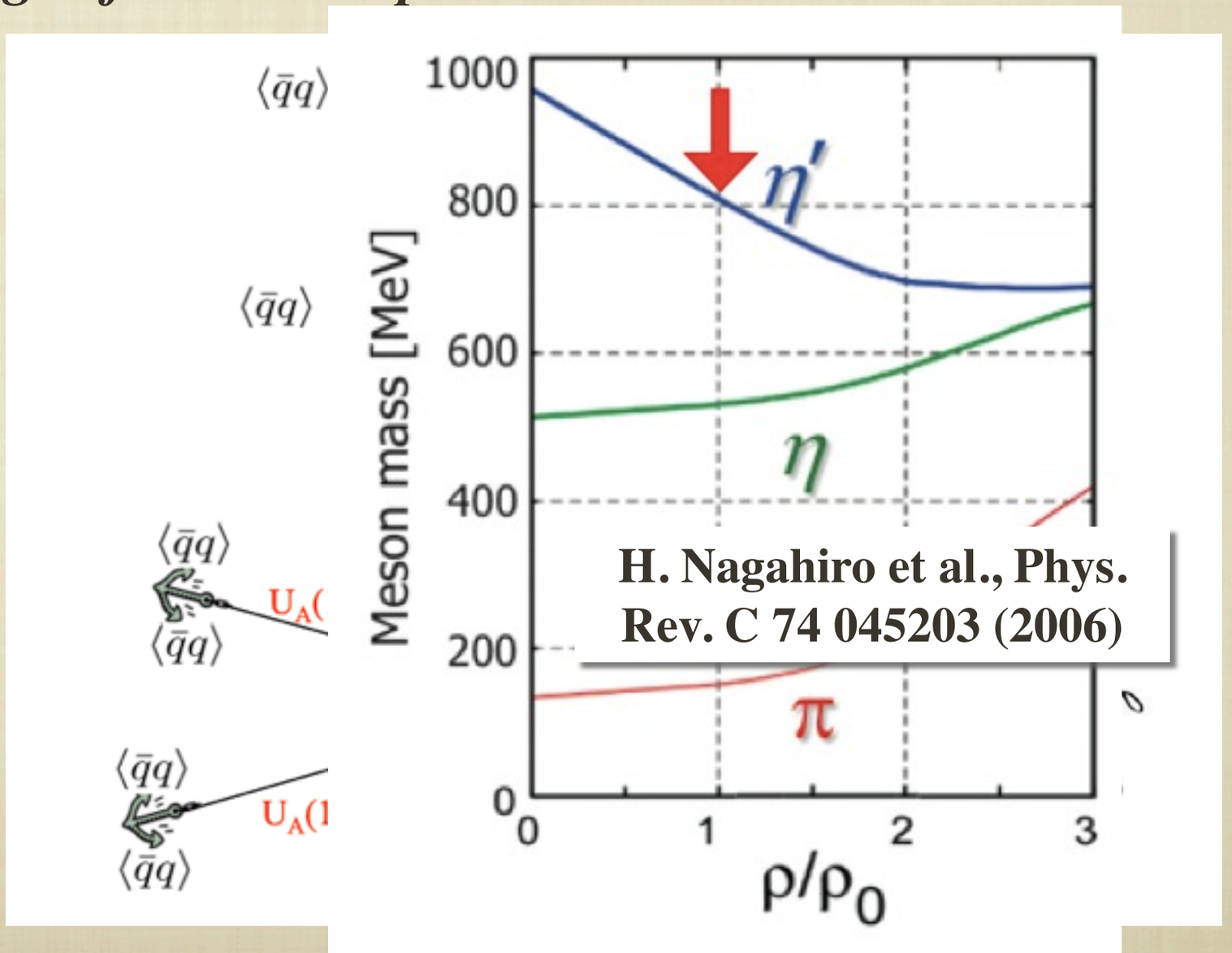
Why η' Meson

- **η' meson is a singlet among SU3 pseudo-scalar mesons but has an unexpectedly heavy mass.**
  - ***It is considered to be due to the coupling to QCD vacuum.***
  - ***Therefore a change of mass is expected in nuclei.***



Why η' Meson

- **η' meson is a singlet among SU3 pseudo-scalar mesons but has an unexpectedly heavy mass.**
  - ***It is considered to be due to the coupling to QCD vacuum.***
  - ***Therefore a change of mass is expected in nuclei.***

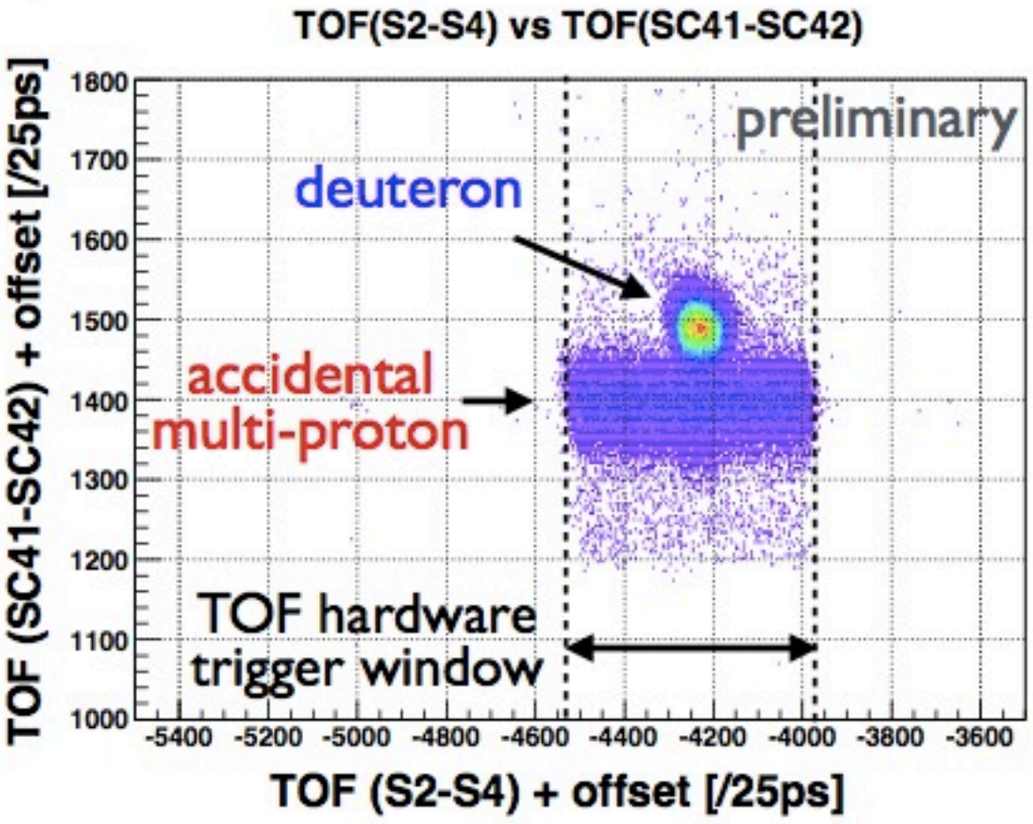


H. Nagahiro et al., Phys. Rev. C 74 045203 (2006)

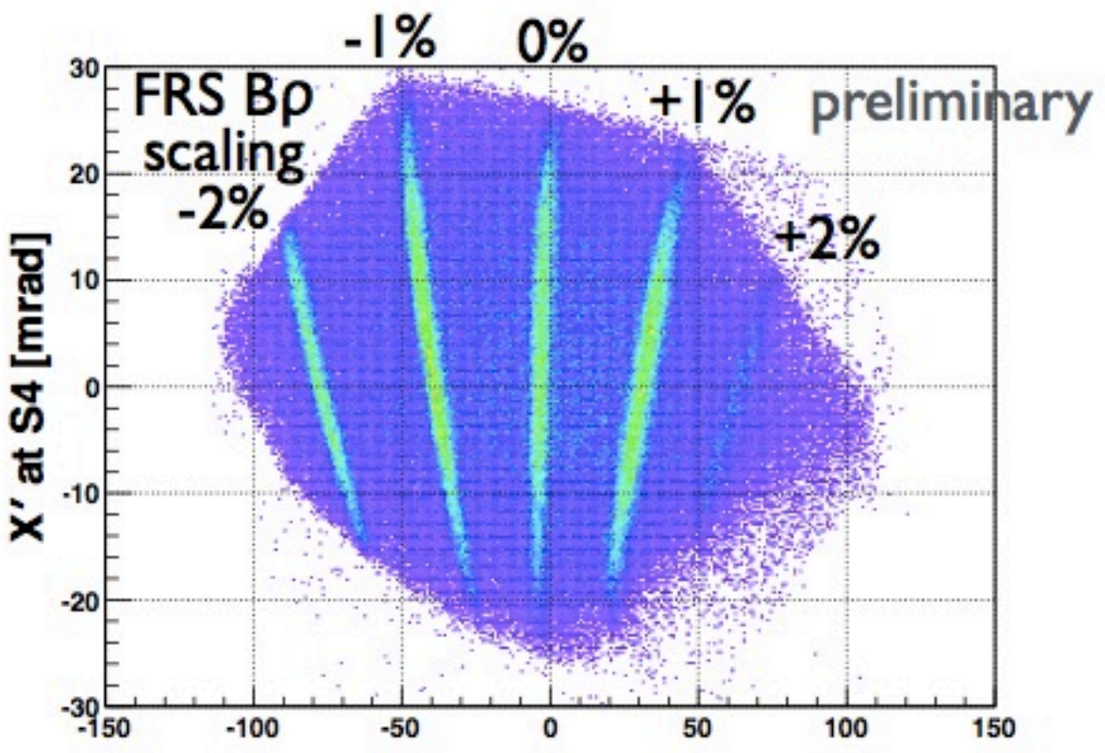
With 2.5 GeV proton on ^{12}C target $^{12}C(p,d)$

Online status of experiment in 2014 August

Deuteron PID



FRS spectrometer calibration



- using d(p,d)p elastic scattering at T_p=1.6GeV
- FRS ion-optical properties were measured.

Production run

- η′ excitation energy from -90 MeV to +40 MeV was measured.
- In total, O(10^7) deuterons were accumulated.

Good quality and high statistics data were successfully obtained

Super-FRS experiments are good candidates of day-one experiment at FAIR

- **Super-FRS collaboration is not only the plan of the experiments at FAIR.**
- **It also contain on-going physics experiments (so called pilot experiment) using SIS/FRS.**
- **These experiments provide important physics result and developments for experiments at FAIR Super-FRS.**
- **Recent experimental runs in the last summer.**
  - ***Tensor forces***
  - ***η' bound nuclei***

Super-FRS experiments are good candidates of day-one experiment at FAIR

- Super-FRS collaboration is not only the plan of the experiments at FAIR.
- It also contain on-going physics experiments (so called pilot experiment) using SIS/FRS.
- These experiments provide important physics result and developments for experiments at FAIR Super-FRS.
- Recent experimental runs in the last summer.
  - *Tensor forces*
  - *η' bound nuclei*

Efficient and continuing effort.

Hoping great outcome of NUSTAR and Super-FRS collaborations

Thank you very much for your attention.