Heavy-Ion Meeting (HIM2013-05)
Korea University, Seoul, Korea, May 24, 2013

Plan for Symmetry Energy Experiment at RAON

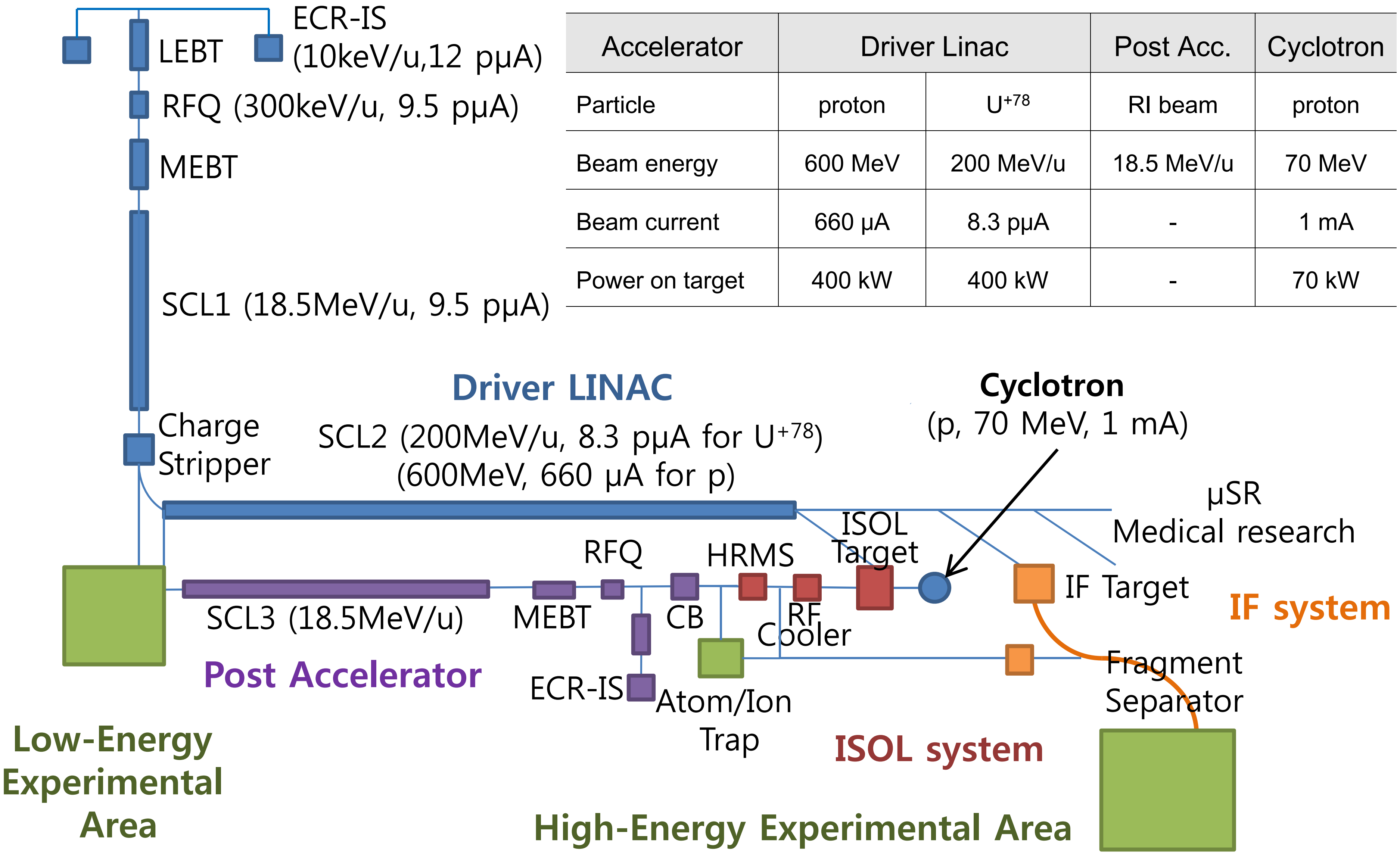
Byungsik Hong
(Korea University)

Outline

1. Brief introduction to RISP
    - Rare Isotope Science Project in Korea
        - RIB accelerator RAON
        - Various experimental facilities
2. KOBRA
    - Broad acceptance recoil spectrometer at low-energy experimental hall
3. LAMPS
    - Large-acceptance multipurpose spectrometer at low- & high-energy experimental halls
4. Summary

RAON

Accelerator	Driver Linac		Post Acc.	Cyclotron
Particle	proton	U^{+78}	RI beam	proton
Beam energy	600 MeV	200 MeV/u	18.5 MeV/u	70 MeV
Beam current	660 μA	8.3 pμA	-	1 mA
Power on target	400 kW	400 kW	-	70 kW

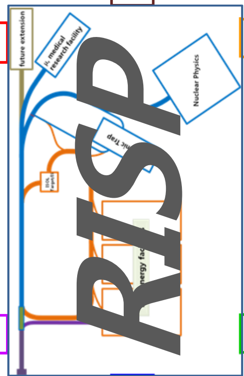


Research Topics

➢ **Nuclear Physics**
- Exotic nuclei near the neutron drip line
- Equation-of-state (EoS) of nuclear matter

➢ **Nuclear Astrophysics**
- Origin of nuclei
- Neutron stars and supernovae
- Nucleosynthesis Superheavies

➢ **Atomic/Particle Physics**
- Atomic trap
- Fundamental symmetries



➢ **Medical & Biosciences**
- Advanced therapy technology
- Mutation of DNA
- New isotopes for imaging

➢ **Nuclear data with fast neutrons**
- Basic nuclear reaction data for future nuclear energy
- Nuclear waste transmutation

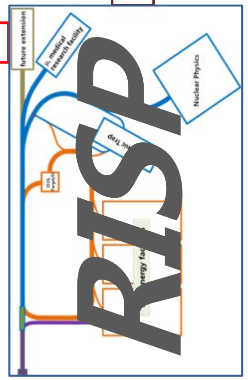
➢ **Material science**
- Production & Characterization of new materials
- β-NMR / μSR

Research Topics

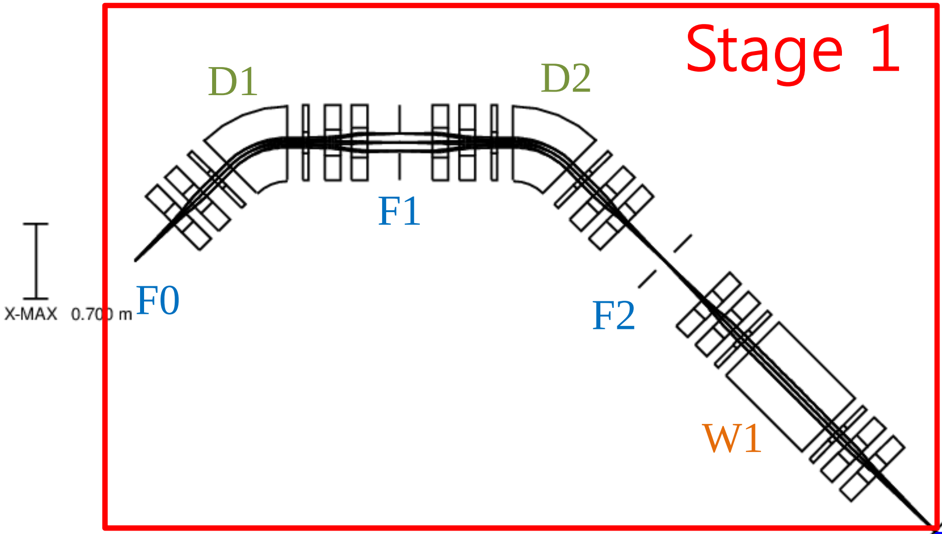
In this talk

- **Nuclear Physics**
  - Exotic nuclei near the neutron drip line
  - Equation-of-state (EoS) of nuclear matter

- **Nuclear Astrophysics**
  - Origin of nuclei
  - Neutron stars and supernovae
  - Nucleosynthesis Superheavies

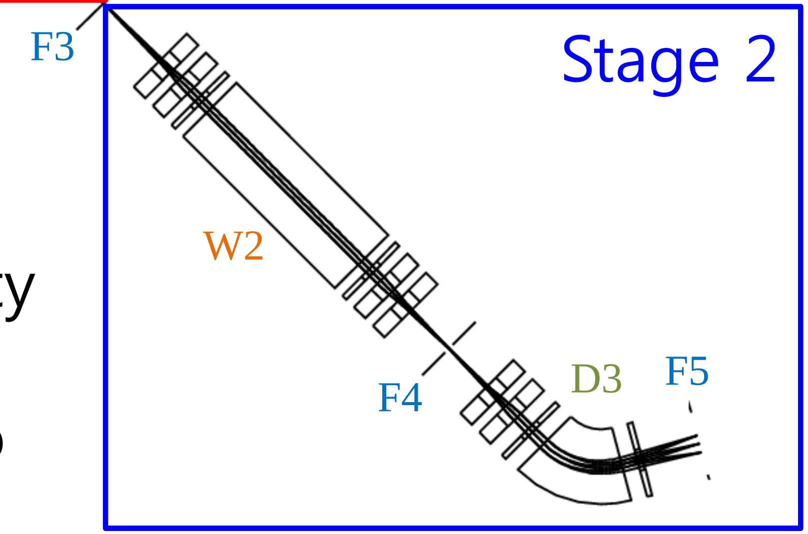


KOBRA

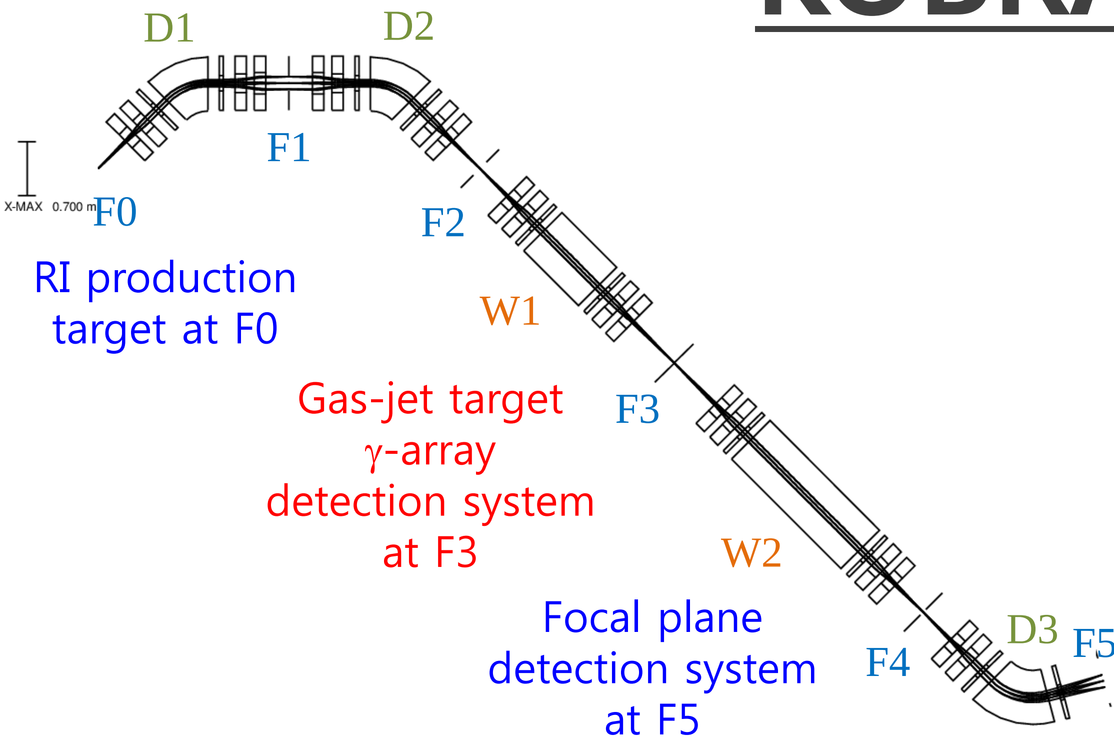


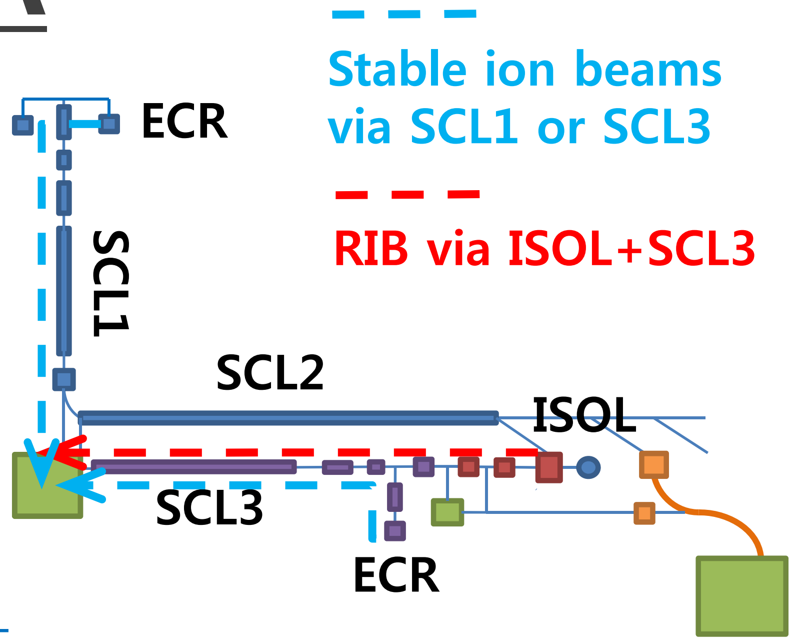
Korea Broad Acceptance Recoil Spectrometer and Apparatus at low-energy experimental area

- High-performance spectrometer with detection system
- Main experimental facility for nuclear science with low-energy beams up to 18.5 MeV/u



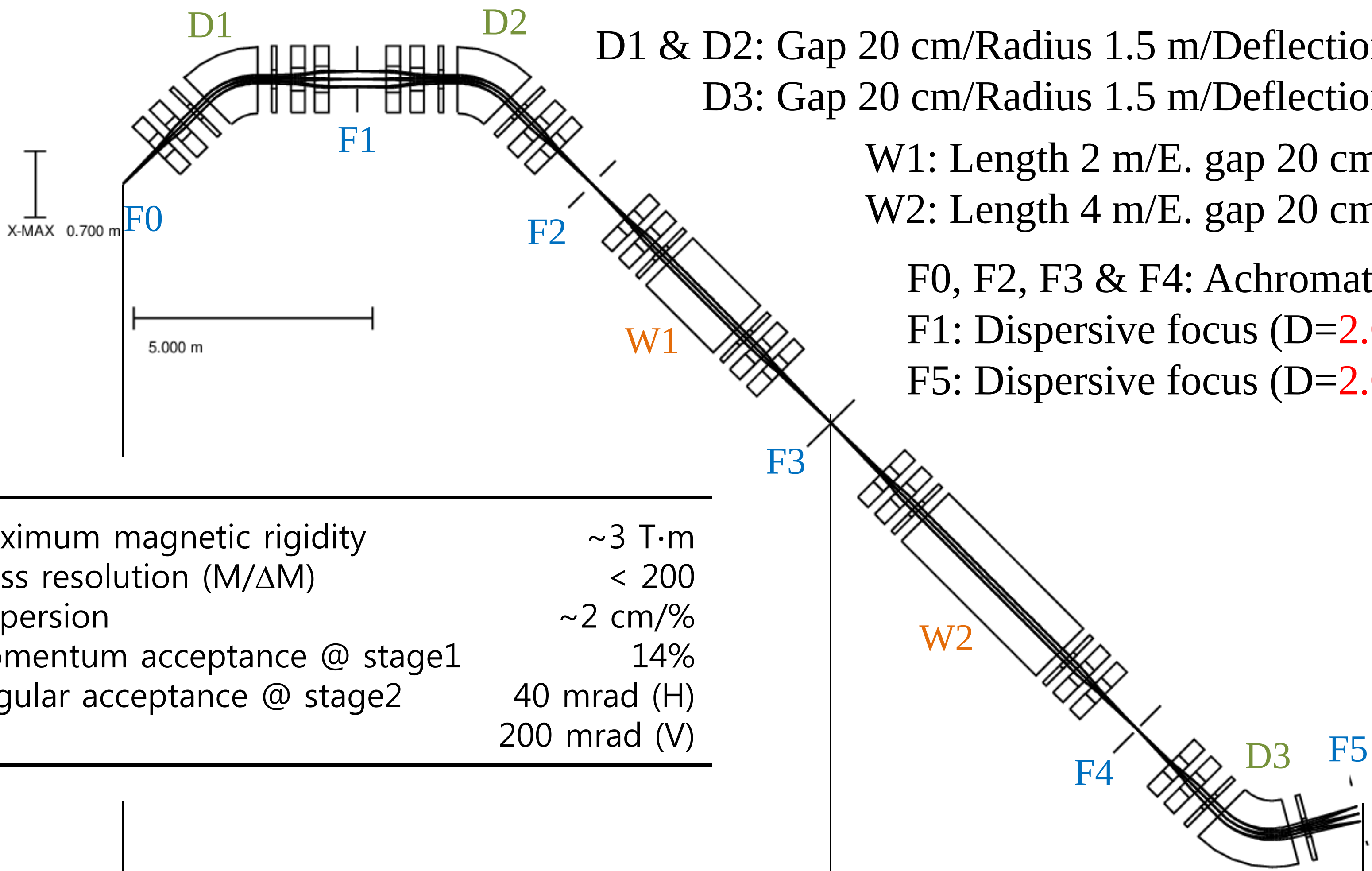
KOBRA





- Stage 1 (F0~F3): Production and separation of RIBs by in-flight method with high-intensity stable ion beams from ECR & LINAC
- Experimental target at F3 (enough space for ~3 m): In-beam γ-ray spectroscopy, Symmetry energy & charged particle spectroscopy, Super-heavy element, Spin dependence, etc.
- Stage 2 (F3~F5): Big-bite spectrometer with Wien filter

KOBRA



D1 & D2: Gap 20 cm/Radius 1.5 m/Deflection angle 45°
D3: Gap 20 cm/Radius 1.5 m/Deflection angle 60°

W1: Length 2 m/E. gap 20 cm/±300 kV
W2: Length 4 m/E. gap 20 cm/±300 kV

F0, F2, F3 & F4: Achromatic focusing
F1: Dispersive focus (D=2.03 cm/%)
F5: Dispersive focus (D=2.05 cm/%)

Maximum magnetic rigidity	~3 T·m
Mass resolution (M/ΔM)	< 200
Dispersion	~2 cm/%
Momentum acceptance @ stage1	14%
Angular acceptance @ stage2	40 mrad (H) 200 mrad (V)

Stage 1: In-flight Separator F0~F3 {QQDQQ-QQDQQ-QQWQQ}

Stage 2: Large-Acceptance Spectrometer F3~F5 {QQWQQ-QQD}

Available Beams for KOBRA

1. In-flight mode
   - p-rich RIB up to A~80 (cannot be produced via U fission)
   - Intensity > 10^6 pps, Purity ~100%
2. ISOL mode
   - p-rich RIB useful for radiative capture reactions
   - n-rich RIB with A=80~140 useful for the transfer reactions in r-process
3. Stable Ion Beams
   - ^{64}Ni & ^{58}Fe are useful for hot fusion reactions
   - Actinide target to produce Z=116~122
   - Examples: $^{58}Fe+^{232}Th \rightarrow {}^{290-x}\mathbf{116}$ + xn, $^{64}Ni+^{232}Th \rightarrow {}^{296-x}\mathbf{118}$ +xn, $^{58}Fe+^{244}Pu \rightarrow {}^{299}\mathbf{120}$ + 3n, $^{64}Ni+^{238}U \rightarrow {}^{299}\mathbf{120}$ + 3n
   - Gas-filled or vacuum mode

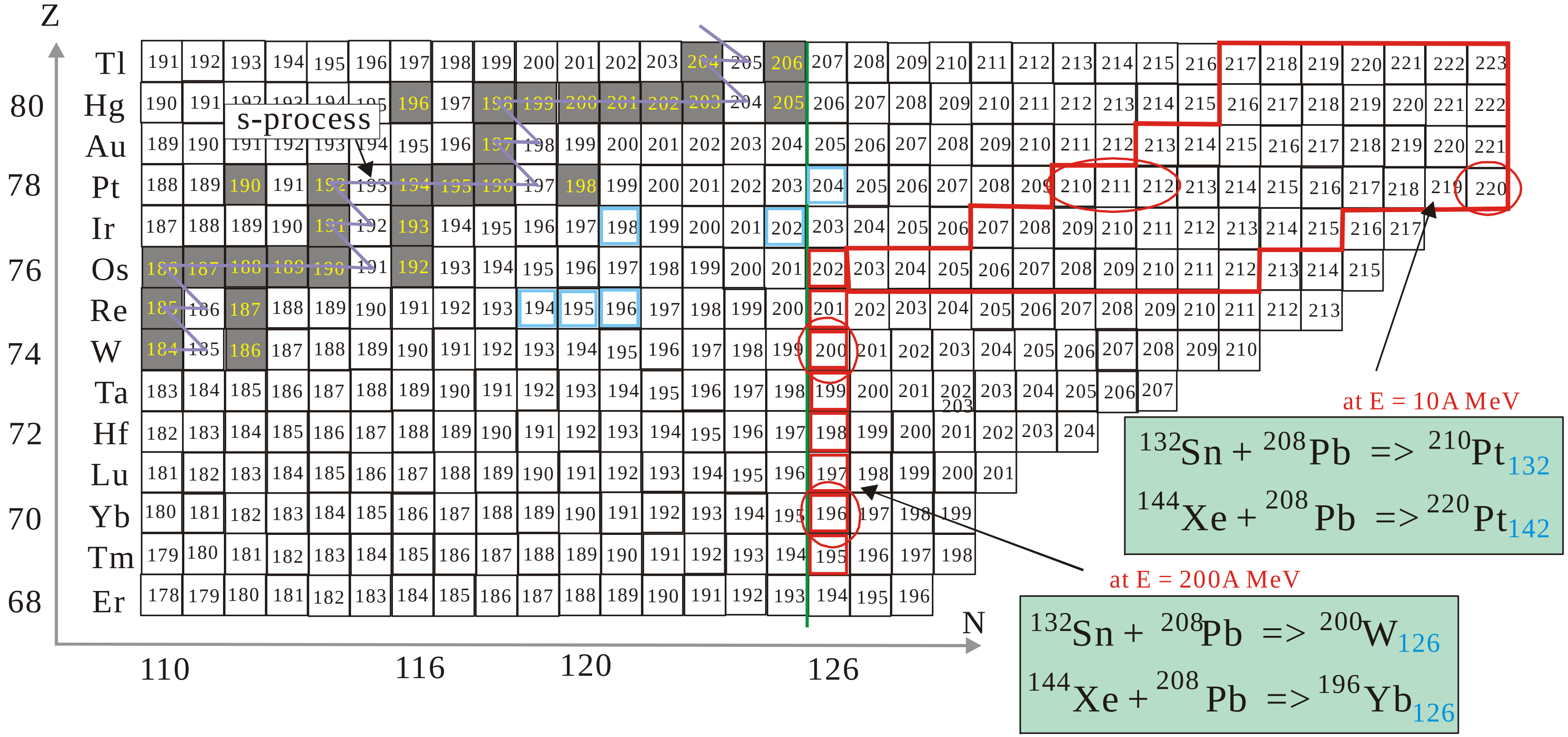
KOBRA: Science Program

1. Nuclear structure
   – Comparison of the nuclear structures for the isobaric mirror nuclei at drip lines (charge symmetry and independence)
   – Resonant conditions of unbound nuclear states
   – Spin dependence of basic properties
2. Nuclear astrophysics
   – Capture reactions: (p,γ), (α,γ), (n,γ)
   – Resonant scattering: p and α resonant elastic scattering
   – Transfer reactions: (d,p), (α,p), etc.
3. Rare events
   – Super-heavy elements
   – Decay spectroscopy
4. Nuclear symmetry energy
   – Pygmy dipole resonance (PDR)/Giant dipole resonance(GDR)
   – Charged particle and neutron production in central collisions

KOBRA: Science Program

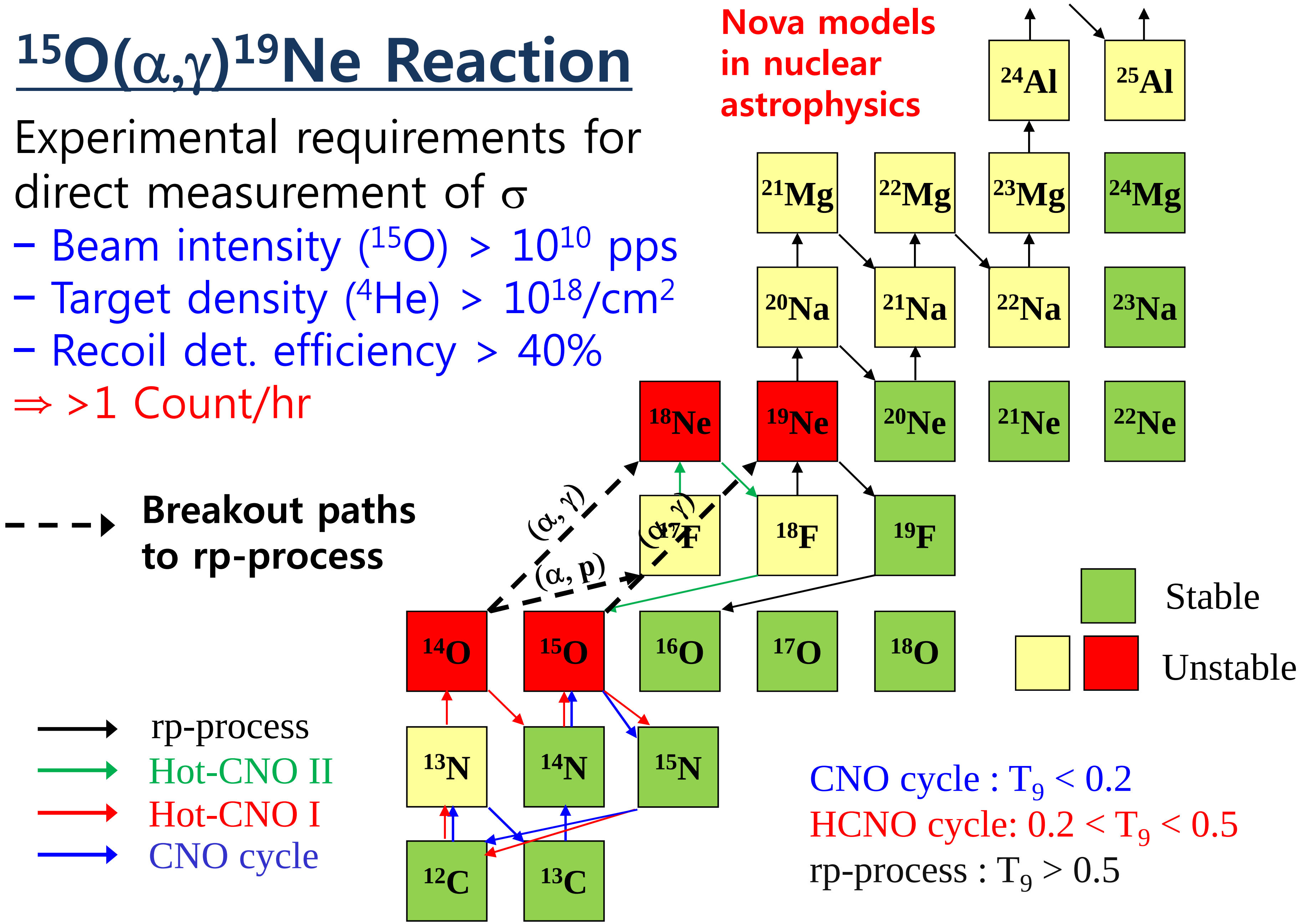
- New neutron-rich heavy nuclei

"High Intensity Stable Beams in Europe"
NUPECC Report (July 2007)



$^{15}O(\alpha,\gamma)^{19}Ne$ Reaction

- Experimental requirements for direct measurement of σ
  - Beam intensity (^{15}O) > 10^{10} pps
  - Target density (^{4}He) > $10^{18}/cm^2$
  - Recoil det. efficiency > 40%
  - ⇒ >1 Count/hr



CNO cycle : $T_9 < 0.2$

HCNO cycle: $0.2 < T_9 < 0.5$

rp-process : $T_9 > 0.5$

^{44}Ti(α,p)^{47}V Reaction

INTEGRAL

Gamma Ray Emission from Cassiopeia A

29 Sep 2006

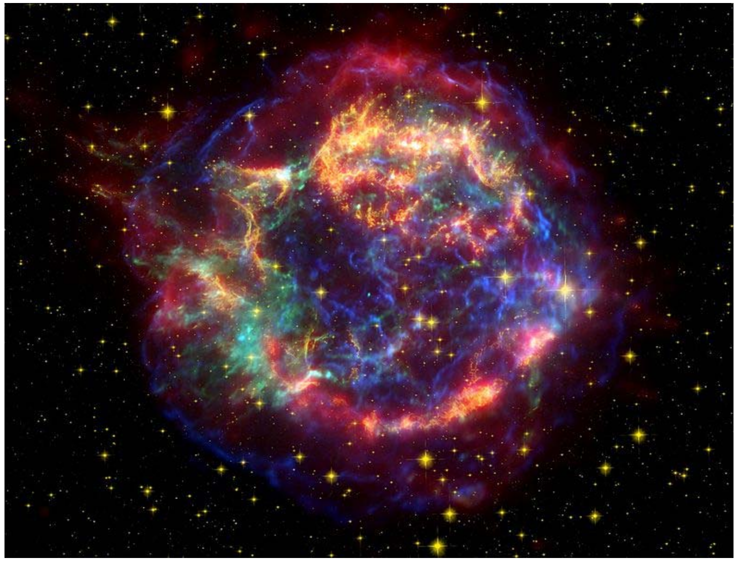
Supernovae and their remnants are the main galactic nucleosynthesis sites. Few radioactive isotopes are accessible to gamma-ray astronomy for probing these stellar explosions. Among them, ^{44}Ti is a key isotope for the investigation of the inner regions of supernovae and their young remnants.

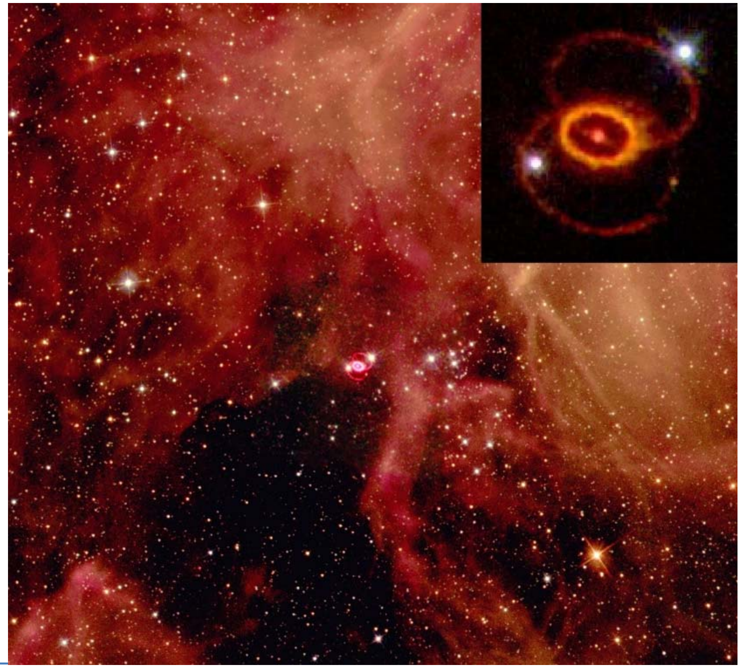
INTEGRAL

INTEGRAL finds titanium in supernova remnant 1987A

17 Oct 2012

Astronomers using INTEGRAL have detected the first direct signature of titanium-44 in the remnant of the nearby supernova 1987A. The discovery reveals a large amount of this key isotope in the remnant, equivalent to 0.03 per cent the mass of the Sun. This value is close to upper bounds from theoretical predictions and exceeds the amount of titanium-44 observed in Cassiopeia A - the only other supernova remnant where this isotope has been found. The amount of titanium-44 found in SNR 1987A demonstrates that its radioactive decay has been powering the source for the past 22 years.





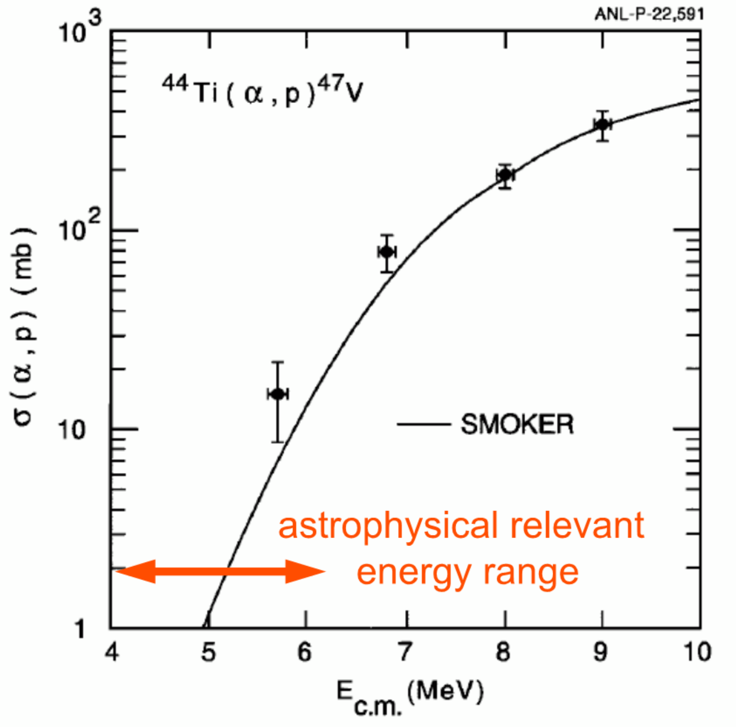
$^{44}Ti(\alpha,p)^{47}V$ Reaction

Order of Importance of Reactions Producing ^{44}Ti at $\eta = 0$

Reaction Rate Multiplied by 1/100		Reaction Rate Multiplied by 100	
Reaction	^{44}Ti Change (percent)	Reaction	^{44}Ti Change (percent)
$^{44}Ti(\alpha, p)^{47}V$	+173	$^{45}V(p, \gamma)^{46}Cr$	−98
$\alpha(2\alpha, \gamma)^{12}C$	−100	$\alpha(2\alpha, \gamma)^{12}C$	+67
$^{40}Ca(\alpha, \gamma)^{44}Ti$	−72	$^{44}Ti(\alpha, p)^{47}V$	−89
$^{45}V(p, \gamma)^{46}Cr$	+57	$^{44}Ti(\alpha, \gamma)^{48}Cr$	−61
$^{57}Ni(p, \gamma)^{58}Cu$	−47	$^{57}Co(p, n)^{57}Ni$	+25
$^{57}Co(p, n)^{57}Ni$	−33	$^{40}Ca(\alpha, \gamma)^{44}Ti$	+22
$^{13}N(p, \gamma)^{14}O$	−16	$^{57}Ni(n, \gamma)^{58}Ni$	+10
$^{58}Cu(p, \gamma)^{59}Zn$	−14	$^{54}Fe(\alpha, n)^{57}Ni$	+9.4
$^{36}Ar(\alpha, p)^{39}K$	−11	$^{36}Ar(\alpha, p)^{39}K$	+5.5
$^{12}C(\alpha, \gamma)^{16}O$	+3.5	$^{36}Ar(\alpha, \gamma)^{40}Ca$	+5.3

The *et al*., *Astrophys. J.* 504 (1998)

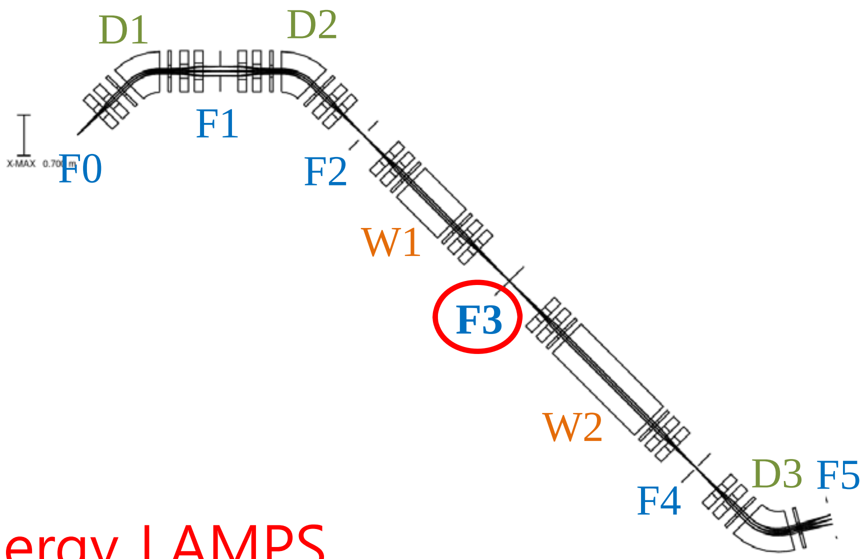
Measurement at FMA at Argonne Nat. Lab.
^{44}Ti intensity of ~5 x 10^5 s^{-1}



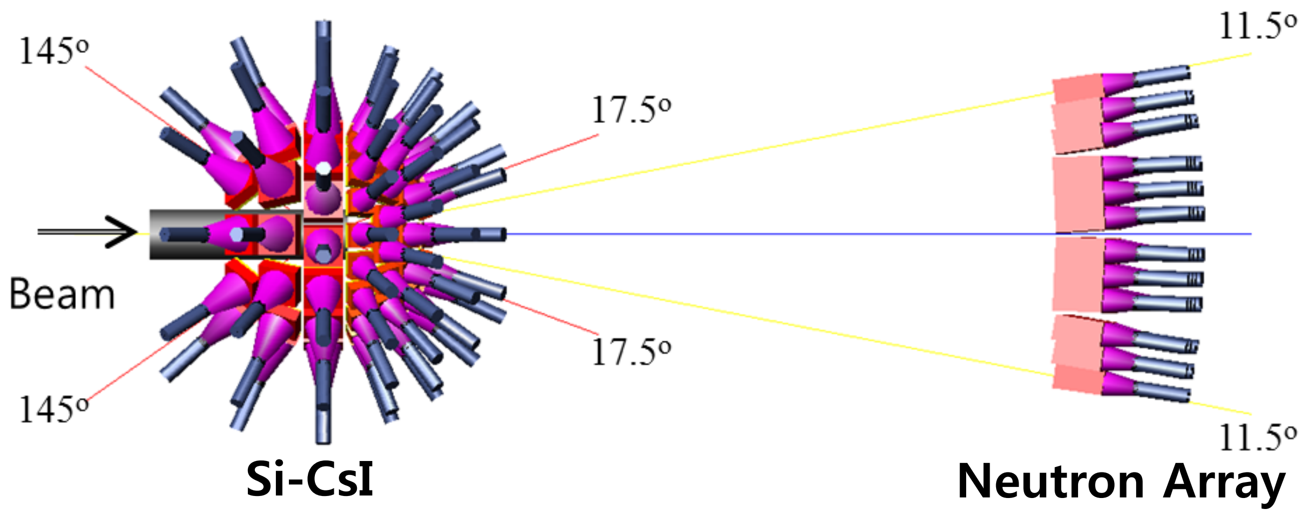
Sonzogni *et al*., *Phys. Rev. Lett.* 84 (2000)

- Presently, TRIUMF, CERN, CNS CRIB are working on this reaction.
- At RISP, the direct measurement will be possible with an active target in the IF mode of KOBRA.

Symmetry Energy at KOBRA



Low-energy LAMPS



Equation of State (EoS) and Symmetry Energy

- Energy of nuclear matter

$$E(\rho,\delta)\,/A = E(\rho,\delta=0) + E_{sym}(\rho)\delta^2 + \mathcal{O}(\delta^4) + \cdots$$

where $\rho = \rho_n + \rho_p$ and $\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$

- Useful expansion of $E_{sym}(\rho)$ around ρ_0

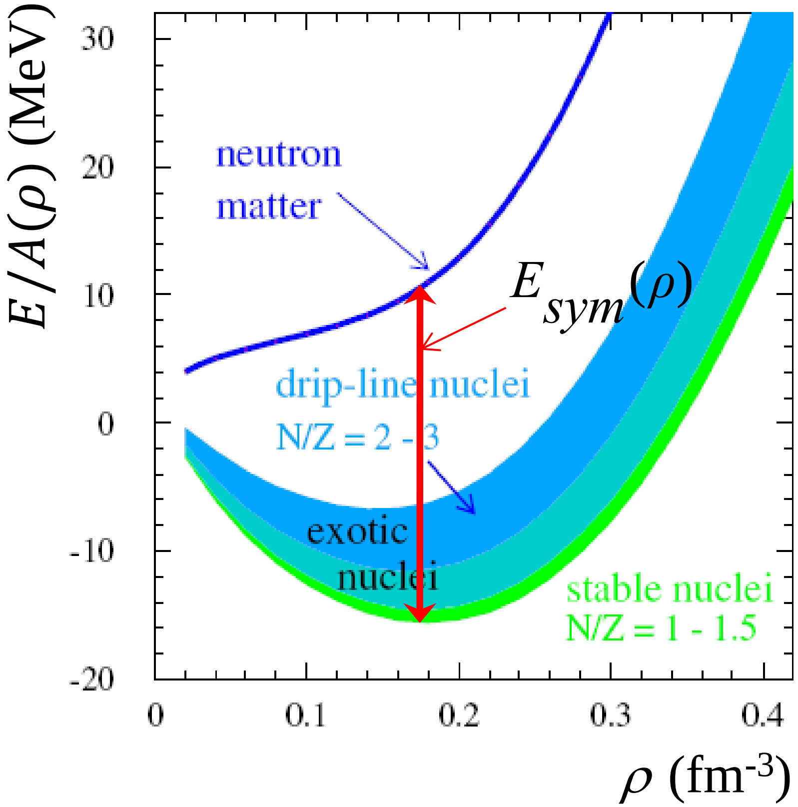
$$E_{sym}(\rho) = J + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2$$

where

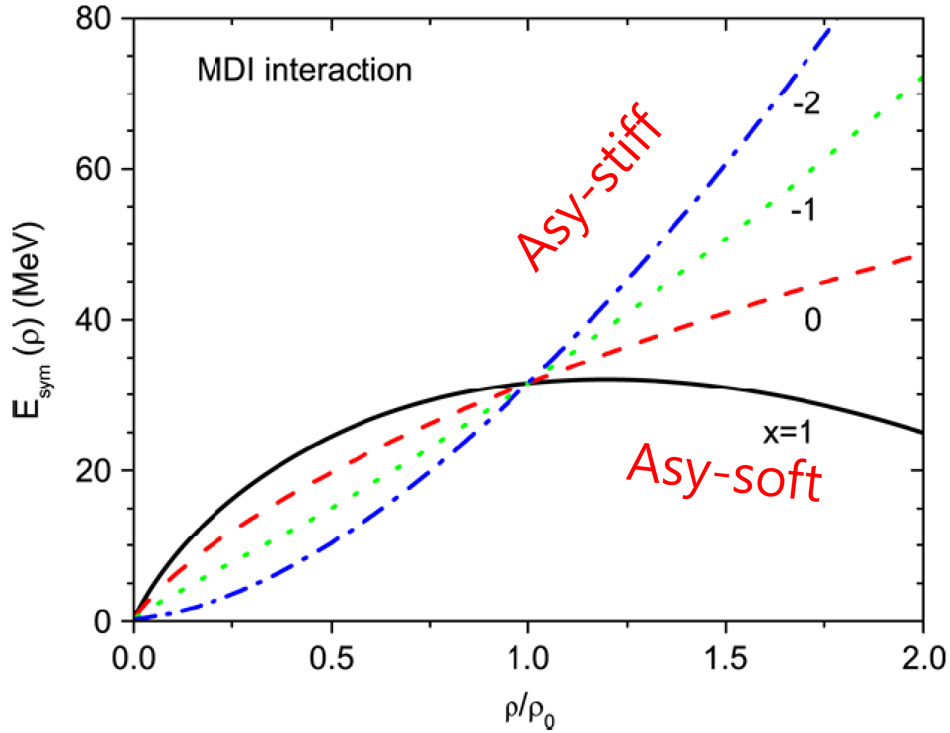
$$L = \frac{3}{\rho_0} P_{sym} = 3\rho_0 \left.\frac{\partial E_{sym}(\rho)}{\partial \rho}\right|_{\rho=\rho_0} \quad \text{(slope)}$$

$$K_{sym} = 9{\rho_0}^2 \left.\frac{\partial^2 E_{sym}(\rho)}{\partial \rho^2}\right|_{\rho=\rho_0} \quad \text{(curvature)}$$

Equation of State and Symmetry Energy

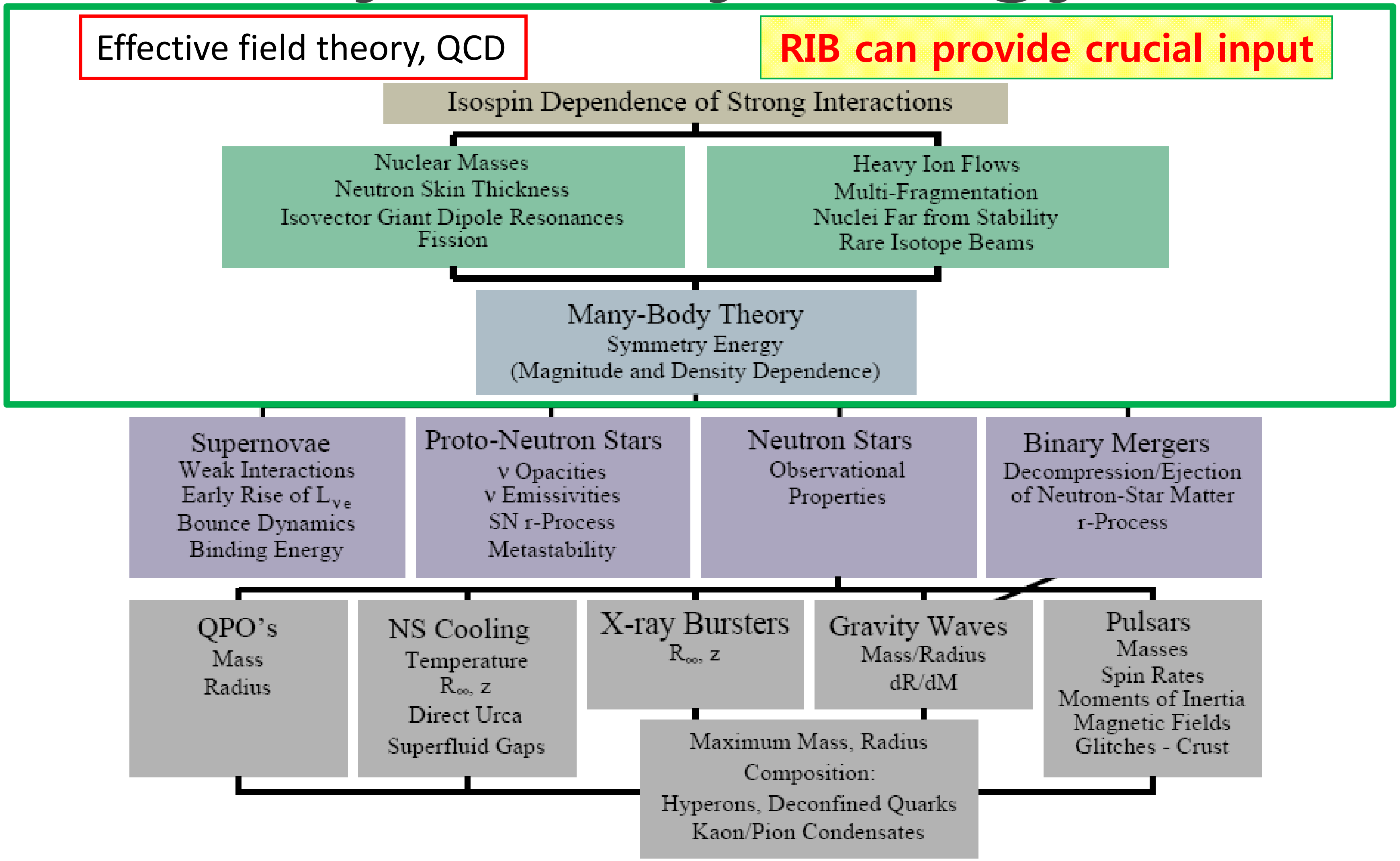


CDR, FAIR (2001)



L.W. Chen, C.M. Ko, B.A. Li,
Phys. Rev. Lett. 94, 032701 (2005)

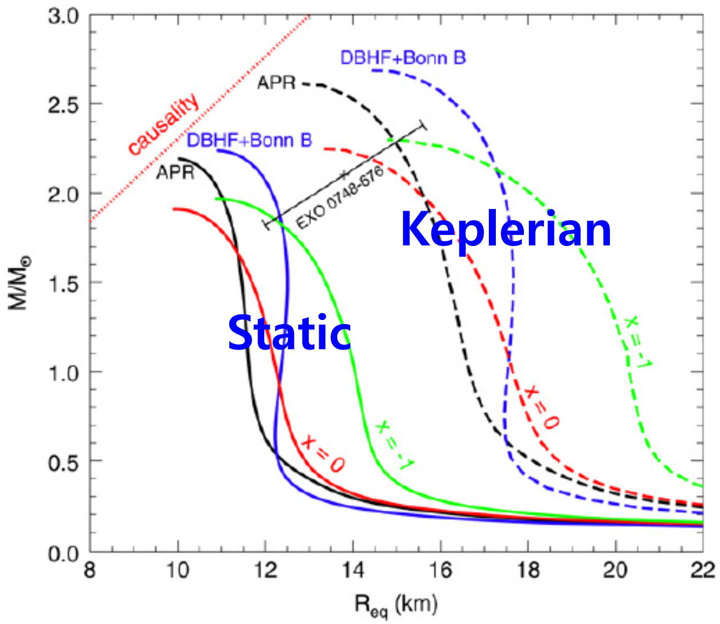
Symmetry Energy



- A.W. Steiner, M. Prakash, J.M. Lattimer and P.J. Ellis, Physics Report 411, 325 (2005)

Symmetry Energy & Neutron Stars

- Neutron star stability against gravitational collapse
- Determine stellar density profile and internal structure
- Observational consequences
  - Cooling rates of proto-neutron stars
  - Stellar masses, radii & moment of inertia from temperatures & luminosities of X-ray bursters
- M vs. R relationship
  - Uncertainty of softness of EOS and influence of E_{sym}
- Important to provide complementary laboratory constraints at specific densities



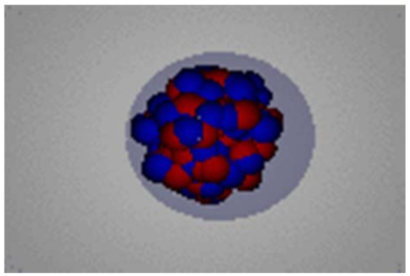
P. Krastev, B.A. Li, and A. Worley, Astrophys. J. 676, 1170 (2008)

Experimental Observables

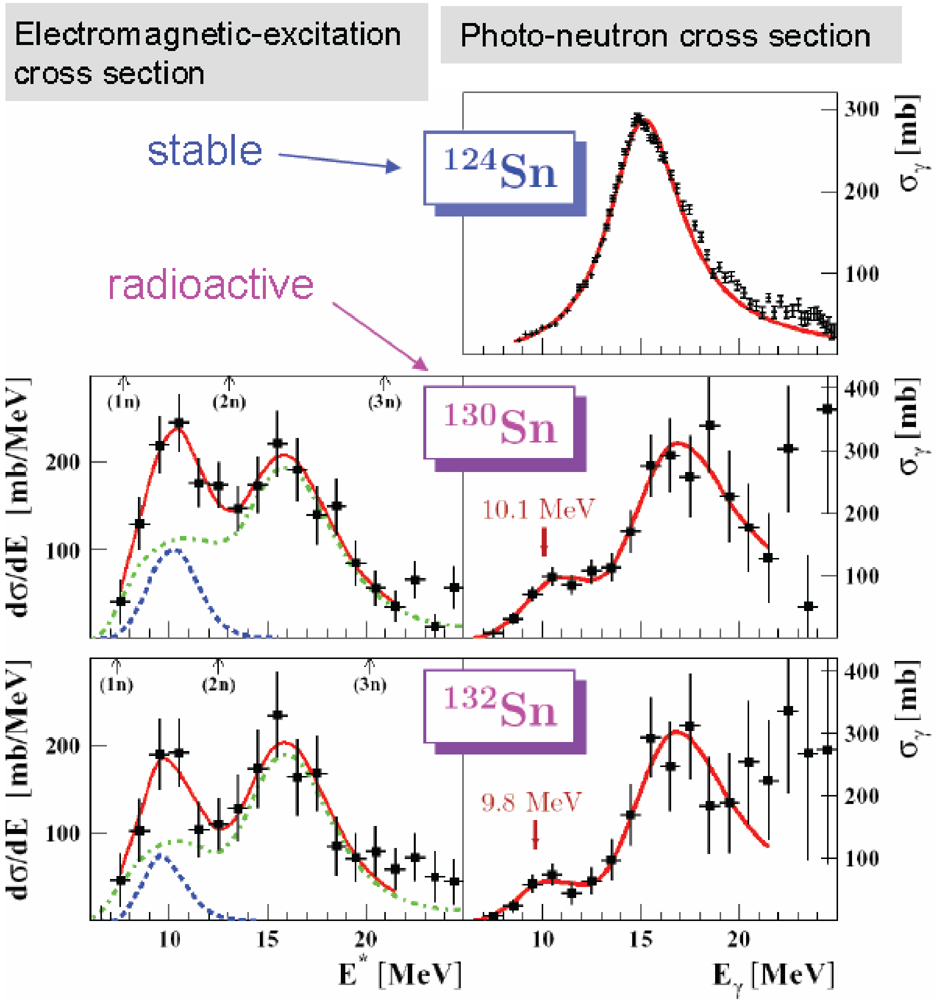
1. Particle ratios of mirror nuclei and pions
   - n/p, $^{3}H/^{3}He$, $^{7}Li/^{7}Be$, π^{-}/π^{+}, etc.
2. Collective flow
   - Directed (or side) and elliptic flow parameters of n, p, and heavier fragments
3. Pygmy dipole resonance
   - Energy spectra of gammas
   - Sizes of n-skins for unstable nuclei
4. Various isospin-dependent phenomena
   - Isospin fractionation and isoscaling in nuclear multifragmentation
   - Isospin diffusion (transport)

PDR at KOBRA

- Coulomb excitation of neutron-rich $^{130,132}Sn$ isotopes reveals a peak at ~10 MeV, which is absent for stable isotopes.
- Consistent with low-lying electric dipole strength.
- These results can be interpreted as an oscillation of a neutron skin relative to the core.



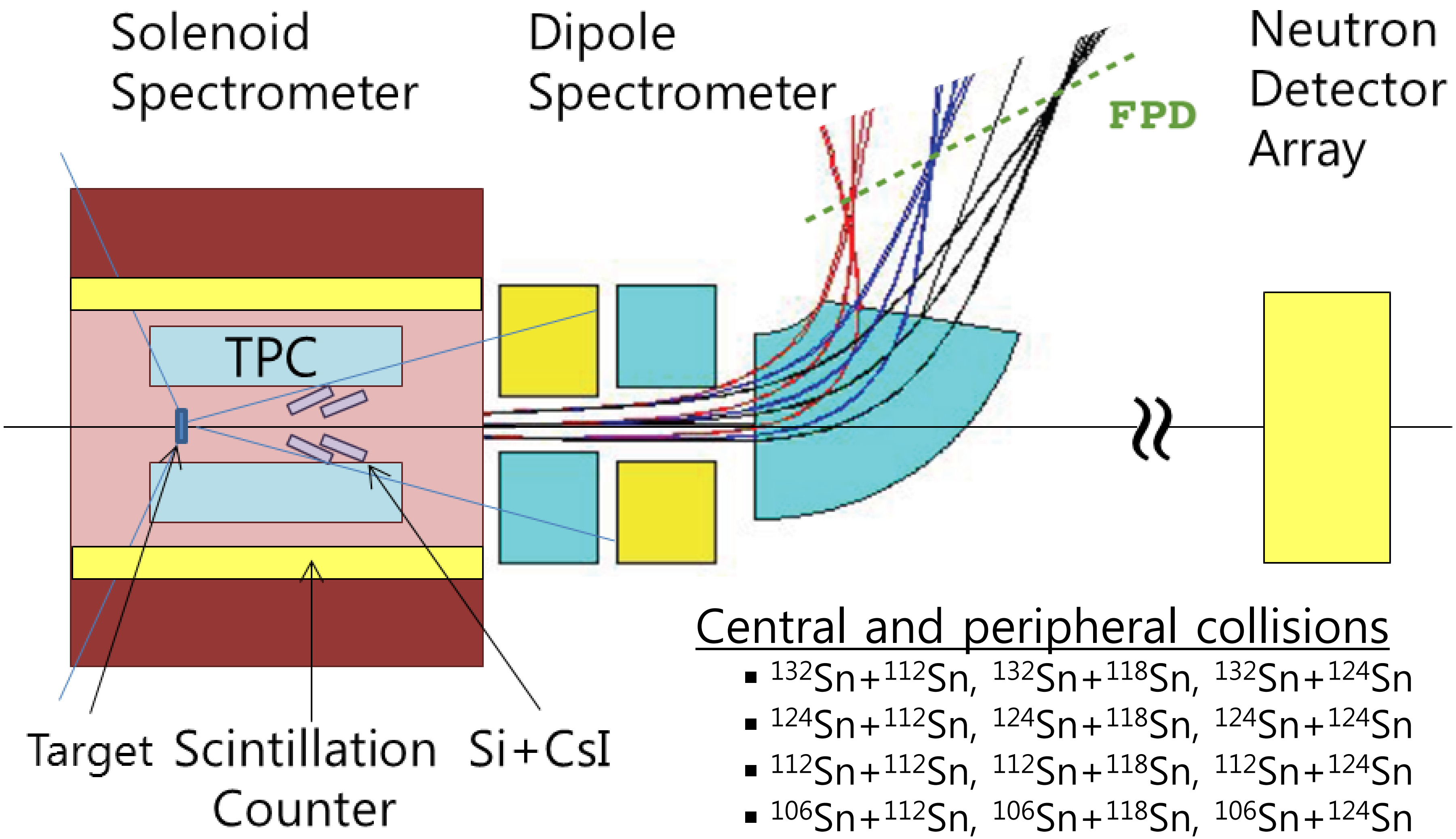
P. Adrich et al., PRL 95, 132501 (2005)



Experimental Requirements

1. We need to accommodate
   – Large acceptance
   – Precise measurement of momentum (or energy) for variety of particle species, including $\pi^{+/-}$ and neutrons, with high efficiency
   – Gamma detection for PDR
   – Keep flexibility for other physics topics
2. This leads to the design of **LAMPS**
   – Large-acceptance Multipurpose Spectrometer
   – Low-energy version to be built at F3 of KOBRA
   – Full version LAMPS at the high-energy experimental area

LAMPS

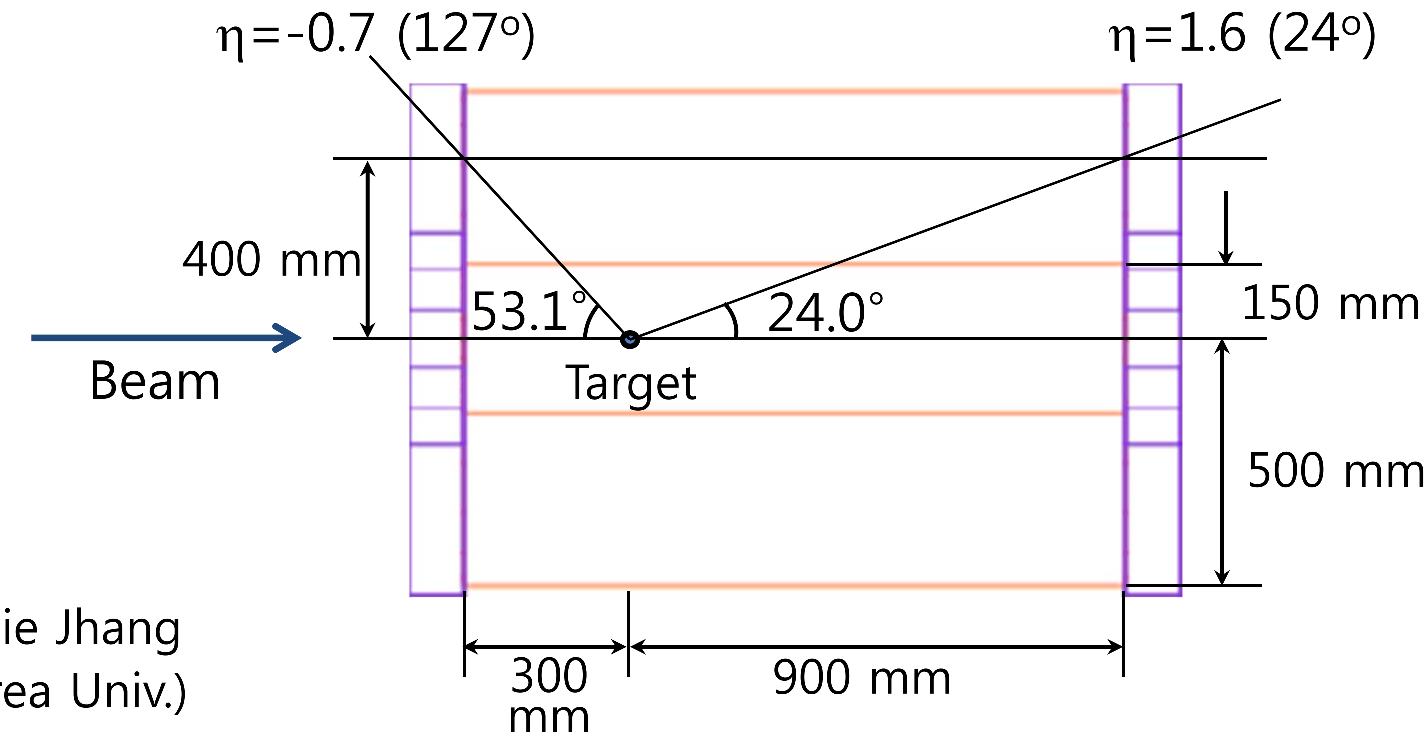


Central and peripheral collisions

- $^{132}Sn+^{112}Sn$, $^{132}Sn+^{118}Sn$, $^{132}Sn+^{124}Sn$
- $^{124}Sn+^{112}Sn$, $^{124}Sn+^{118}Sn$, $^{124}Sn+^{124}Sn$
- $^{112}Sn+^{112}Sn$, $^{112}Sn+^{118}Sn$, $^{112}Sn+^{124}Sn$
- $^{106}Sn+^{112}Sn$, $^{106}Sn+^{118}Sn$, $^{106}Sn+^{124}Sn$

  etc.

Time Projection Chamber



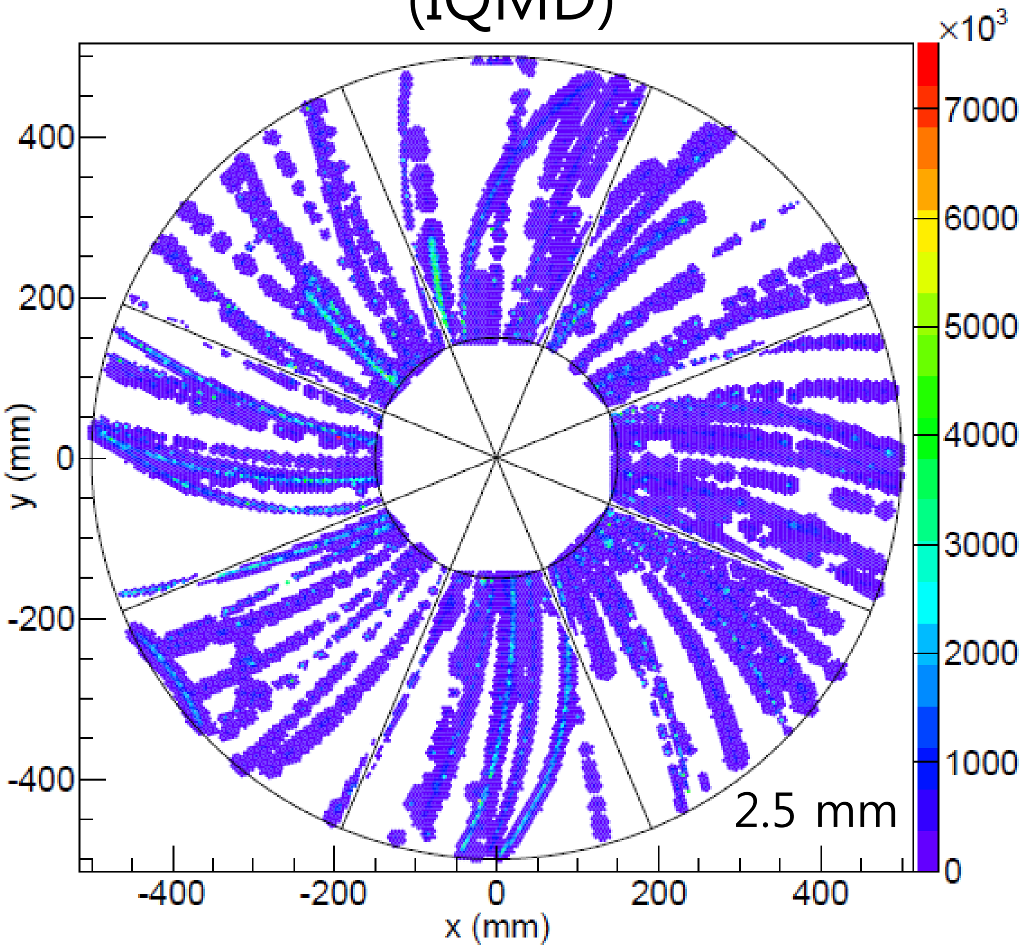
Genie Jhang
(Korea Univ.)

- Simulation with triple GEM readouts at both ends by Garfield++
  - Gas mixture: Ar 90%+CO_2 10%, Voltage for each foil: 450 V
  - <Gain> ~ $1.4X10^6$, <Drift velocity> ~ 50 μm/sec
  - <Dispersion> after 60 cm (maximum drift distance) < 3 mm

Time Projection Chamber

Central Au+Au at 250 AMeV (IQMD)

Genie Jhang (Korea Univ.)



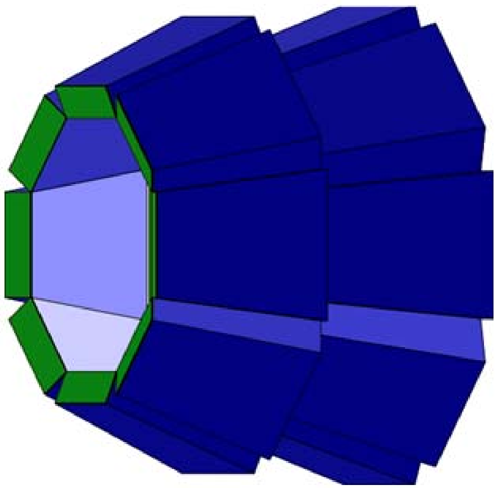
Color scale: the number of electrons in each pad

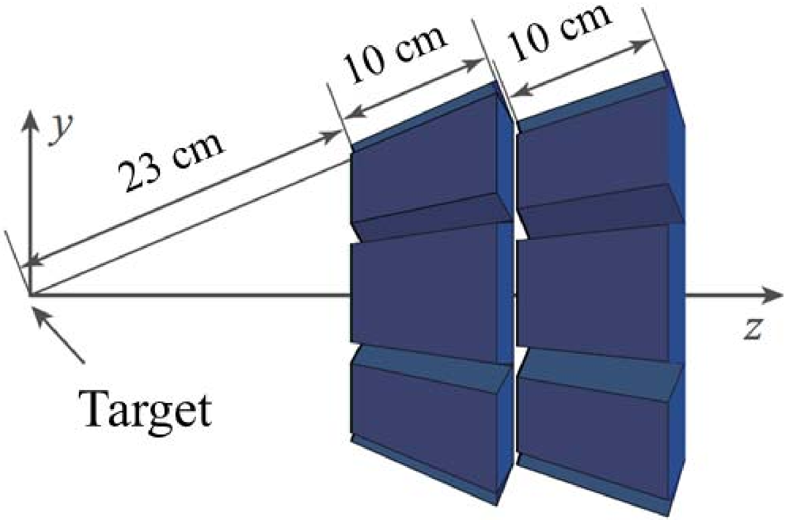
- Pad
  - Shape: hexagonal
  - Total number 90,000 for 2.5 mm 20,000 for 5 mm
- Signal processing
  - GET: General Electronics for TPC

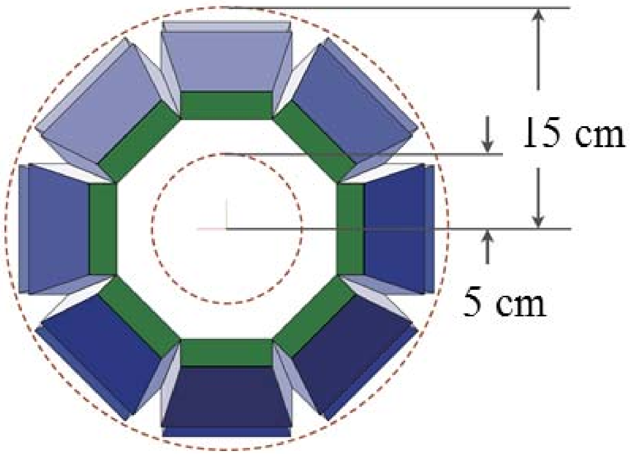
Si-CsI

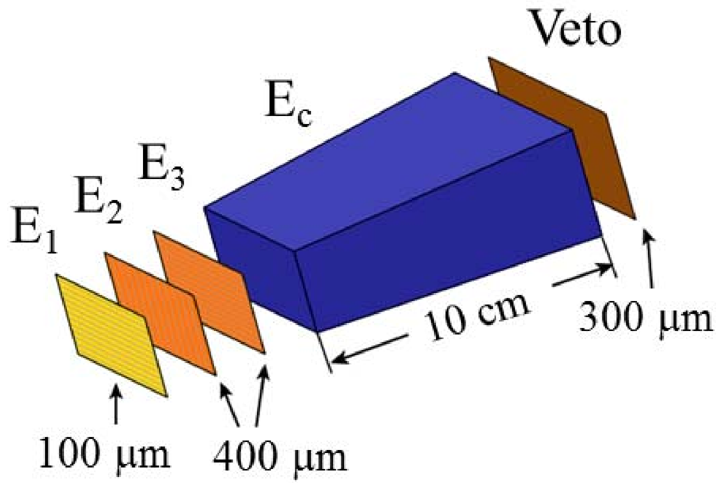
$1.6 < \eta < 2.1$
$(14^{o} < \theta_{Lab} < 24^{o})$

Suhyun Lee & Songkyo Lee
(Korea Univ.)



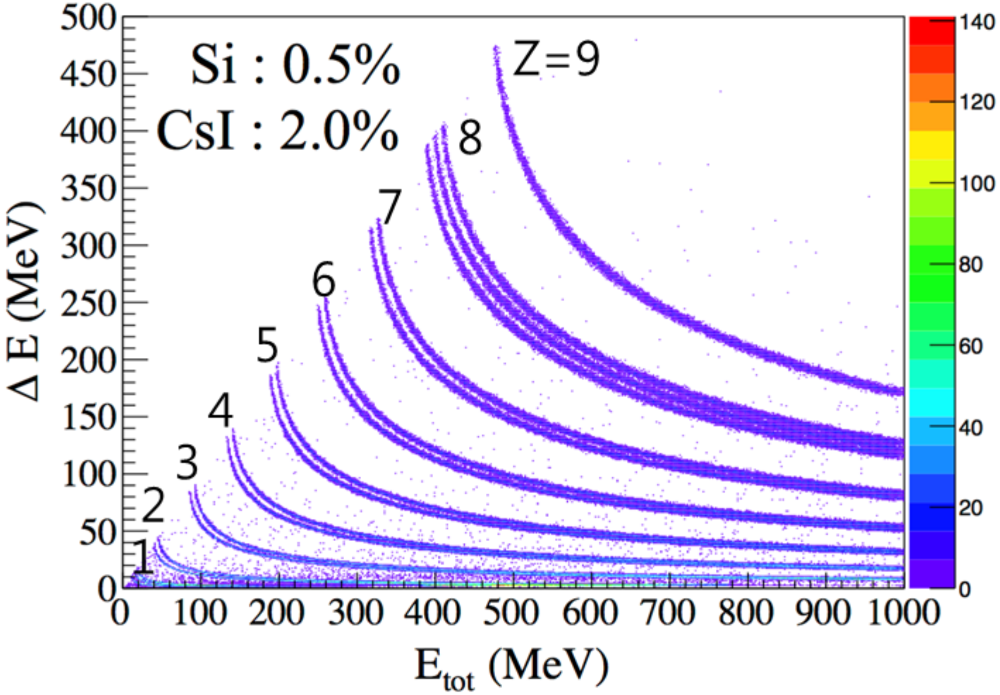






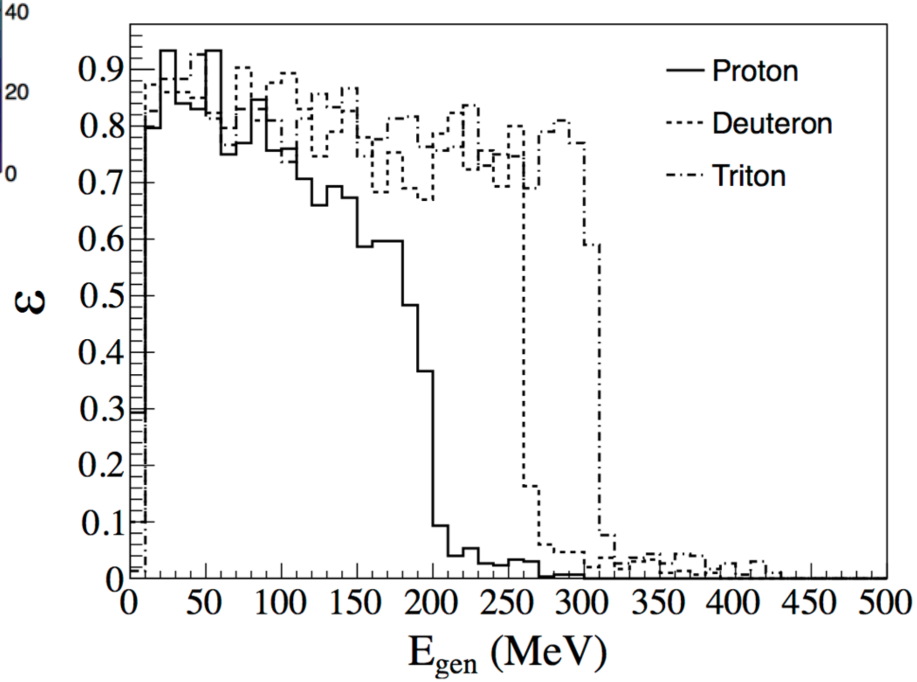
Si-CsI

Suhyun Lee & Songkyo Lee
(Korea Univ.)



$\Delta E=E_1+E_2+E_3$

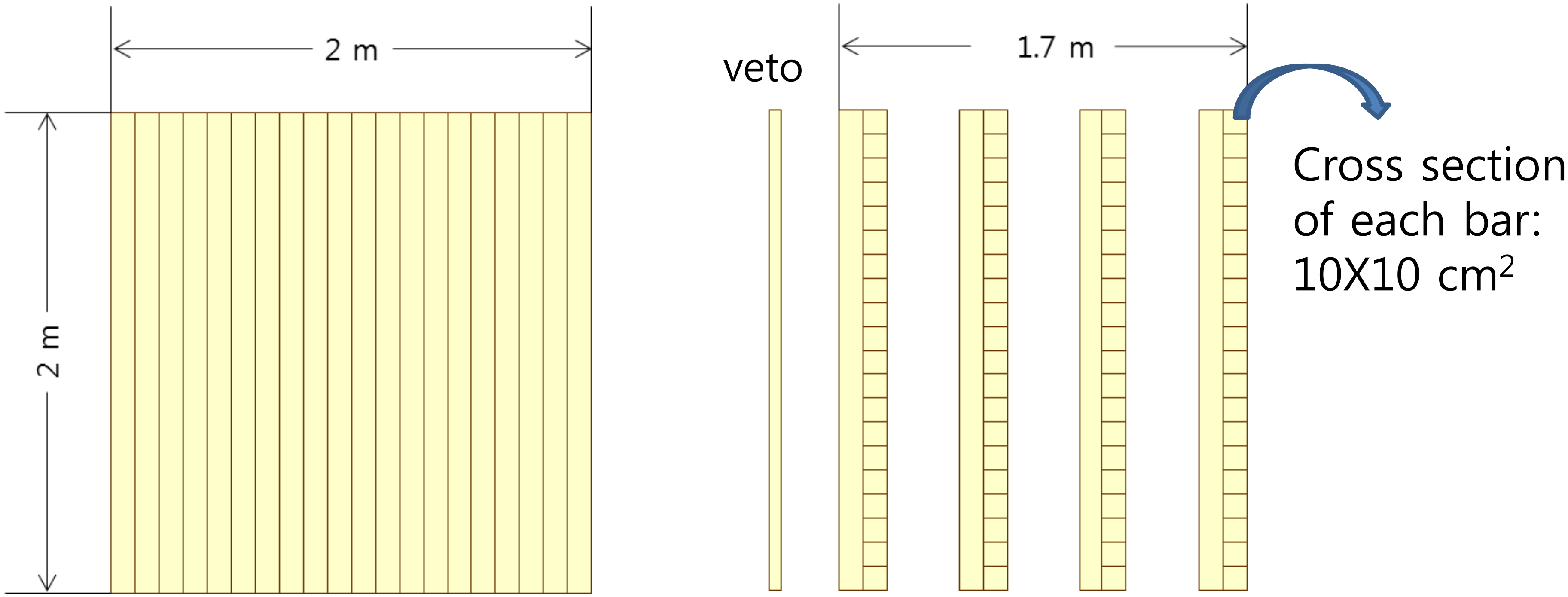
$E_{tot}=\Delta E+E_c$



- $\Delta E=E_1+E_2+E_3$ is preferred at high energies
- $\Delta E=E_1$ is preferred at low energies

Neutron Detector Array

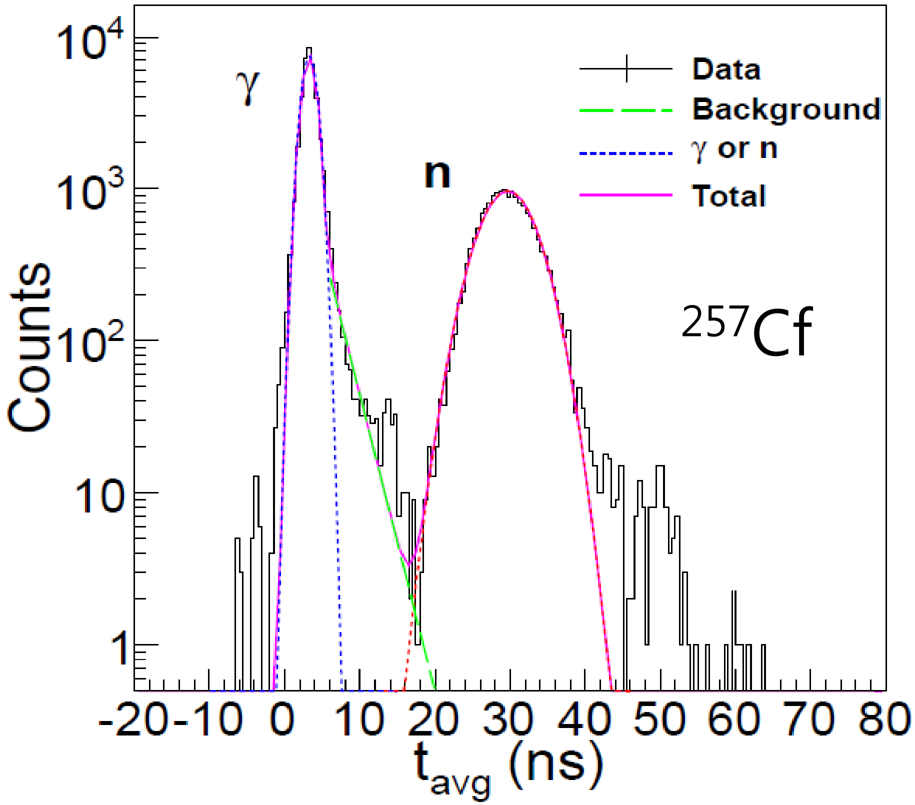
Kisoo Lee & Eunah Joo (Korea Univ.)

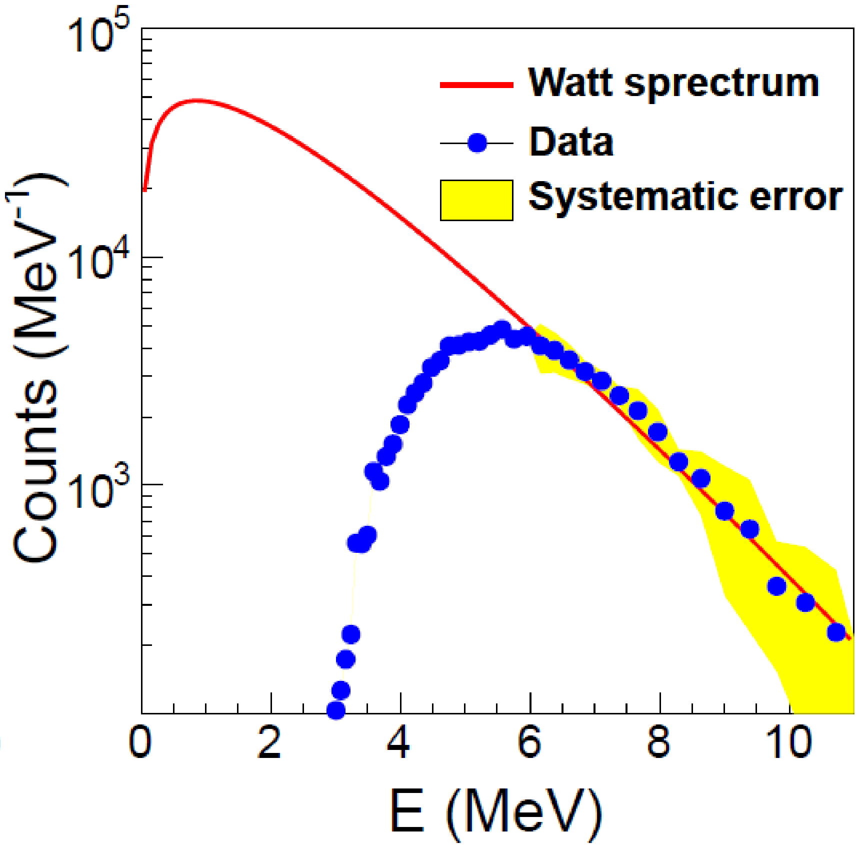


- Construction of the prototype and test with radiation sources
  - Dimension: 0.1X0.1X1.0 m^3
  - Sources: ^{60}Co and ^{257}Cf
  - Time resolution: 488 ps, Position resolution: ~8 cm for CFD

Neutron Detector Array

Kisoo Lee & Benard Mulilo (Korea Univ.)

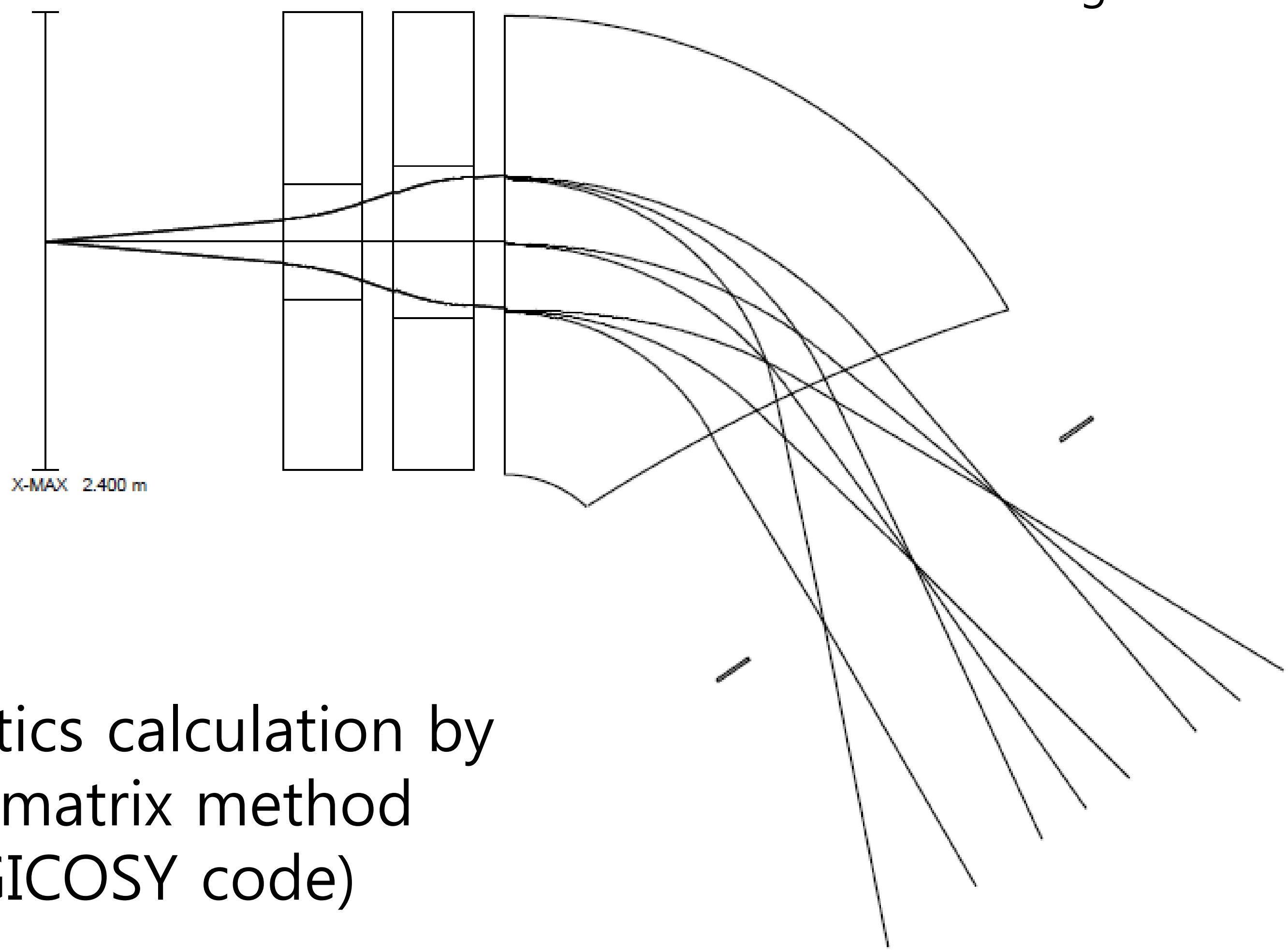




- Watt spectrum: $dN/dE \propto e^{-aE} \sinh\sqrt{bE}$
  with a=0.88 MeV^{-1} and b=2.0 MeV^{-1}
  Ref) B. Watt, Physical Review 87, 1037 (1952)

Dipole Spectrometer

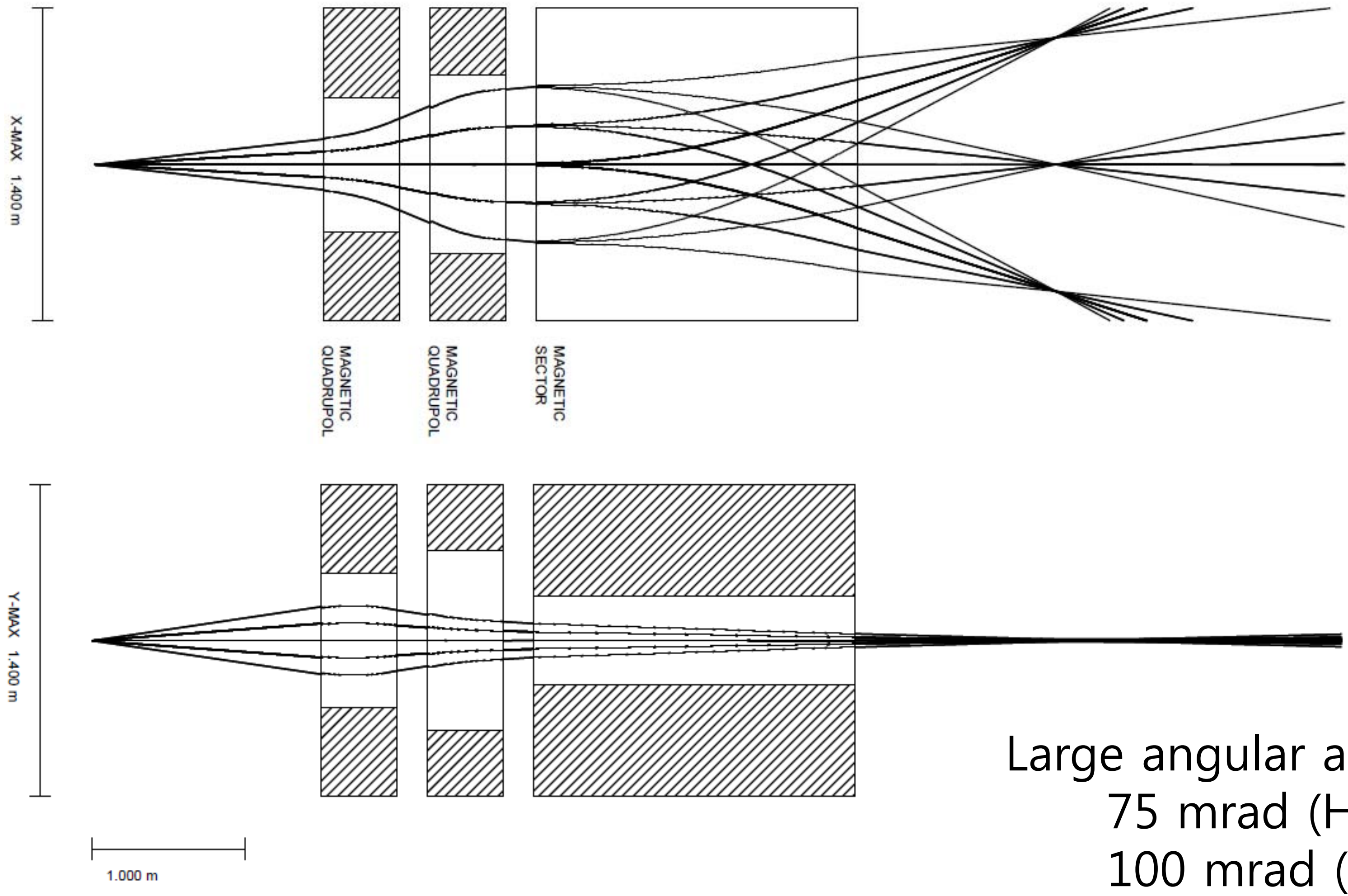
Songkyo Lee (Korea Univ.)
Chong Cheoul Yun (IBS)



Ion optics calculation by the matrix method (GICOSY code)

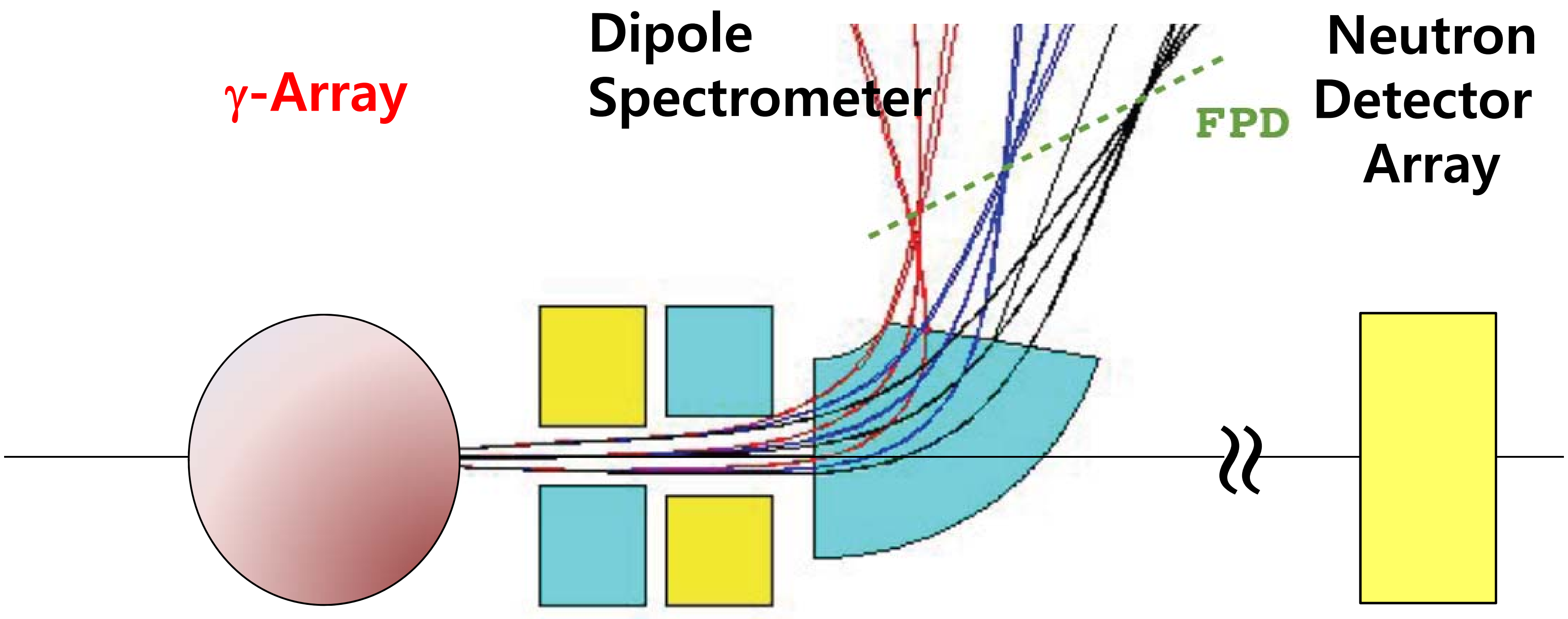
Dipole Spectrometer

Songkyo Lee (Korea Univ.) & Chong Cheoul Yun (IBS)



Large angular acceptance
75 mrad (H)
100 mrad (V)

Coulomb Breakup



- PDR/GDR measurements
  $^{124,130,132}Sn+^{208}Pb$, $^{68,70,72}Ni+^{208}Pb$, $^{50,54,60}Ca+^{208}Pb$, etc.
- Photoabsorption measurements
  Various 1n and 2n removal cross sections for unstable nuclei
- Measurement of E* from gamma, beam fragment, and neutron(s)

Summary

1. RAON
   – First large-scale facility for nuclear physics in Korea
2. KOBRA
   – Broad acceptance recoil spectrometer at low-energy experimental area
   – To cover nuclear structure, nuclear astrophysics, super-heavy elements, and nuclear symmetry energy
3. LAMPS
   – Large-acceptance multipurpose spectrometer at high-energy experimental area
     (Low-energy version of LAMPS at KOBRA)
   – Primary purpose is to measure the nuclear symmetry energy at sub- and supra-saturation densities
   – Useful also to study various photoabsorption processes

Stay tuned!