The 7th BLTP JINR-APCTP Joint Workshop
July 14-19, 2013

Prospects for Nuclear Astrophysics Experiments in Korea

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Ewha Womans University

Outline

- Introduction
- Nuclear Astrophysics in Korea
  - Experimental groups
  - Selected experiments
- RIB accelerator (RAON)
  - Introduction of the facility
  - Proposed NAP experiments
- Summary

85 Years of Nuclear Astrophysics

A Story of Success

1928 Gamow-Factor
George Gamow

1931 Stellar Structure & Theory of White Dwarfs
Subramanyan Chandrasekhar

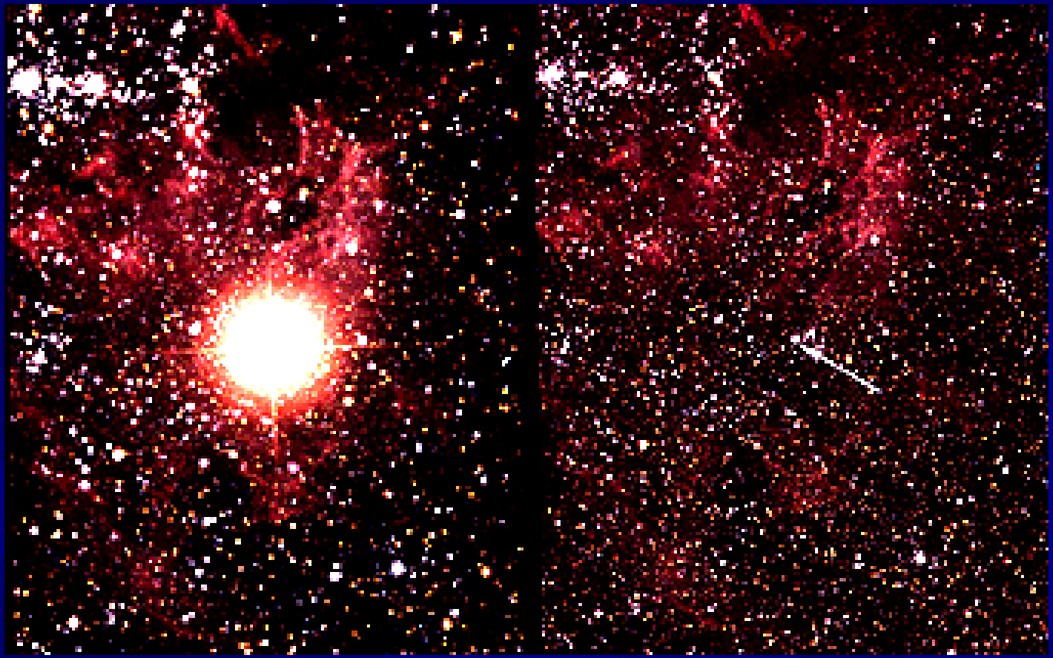
1938 CNO Cycle - C. F. von Weizsacker
CNO Cycle, pp Chain - Hans Bethe

1957 Nucleosynthesis of Elements in Stars
Margaret &Geoffrey Burbridge, William Fowler and Fred Hoyle = B^2FH

1983 Nobel Prize: William Fowler
Subramanyan Chandrasekhar

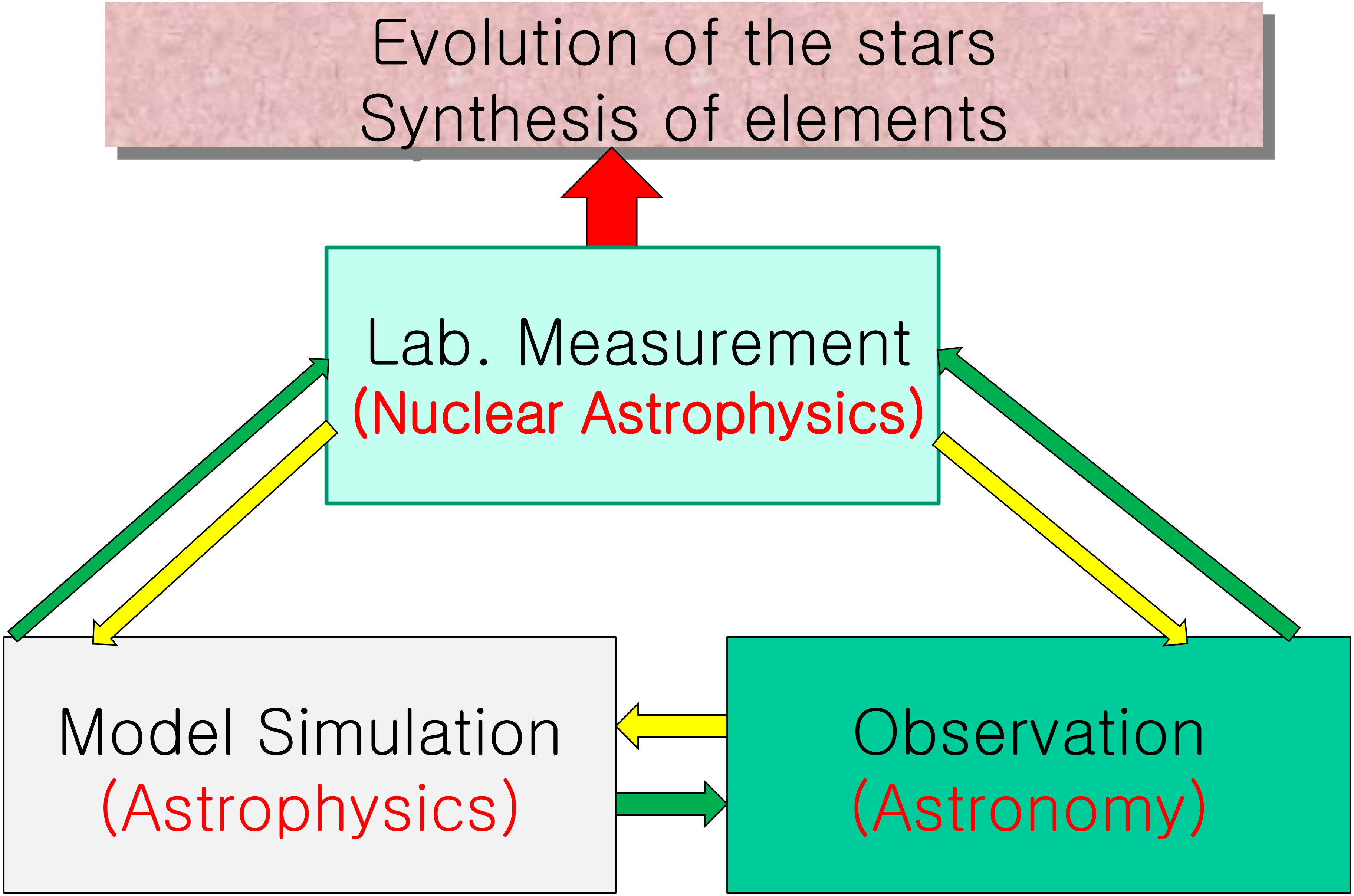
2002 Nobel Prize for Neutrino Detection
Raymond Davis & Masatoshi Koshiba
X-ray Astronomy - Riccardo Giacconi

Experimental Nuclear Astrophysics



Nuclear reactions in stars

- ⟹ produce energy
- ⟹ generate the elements



Evolution of the stars
Synthesis of elements

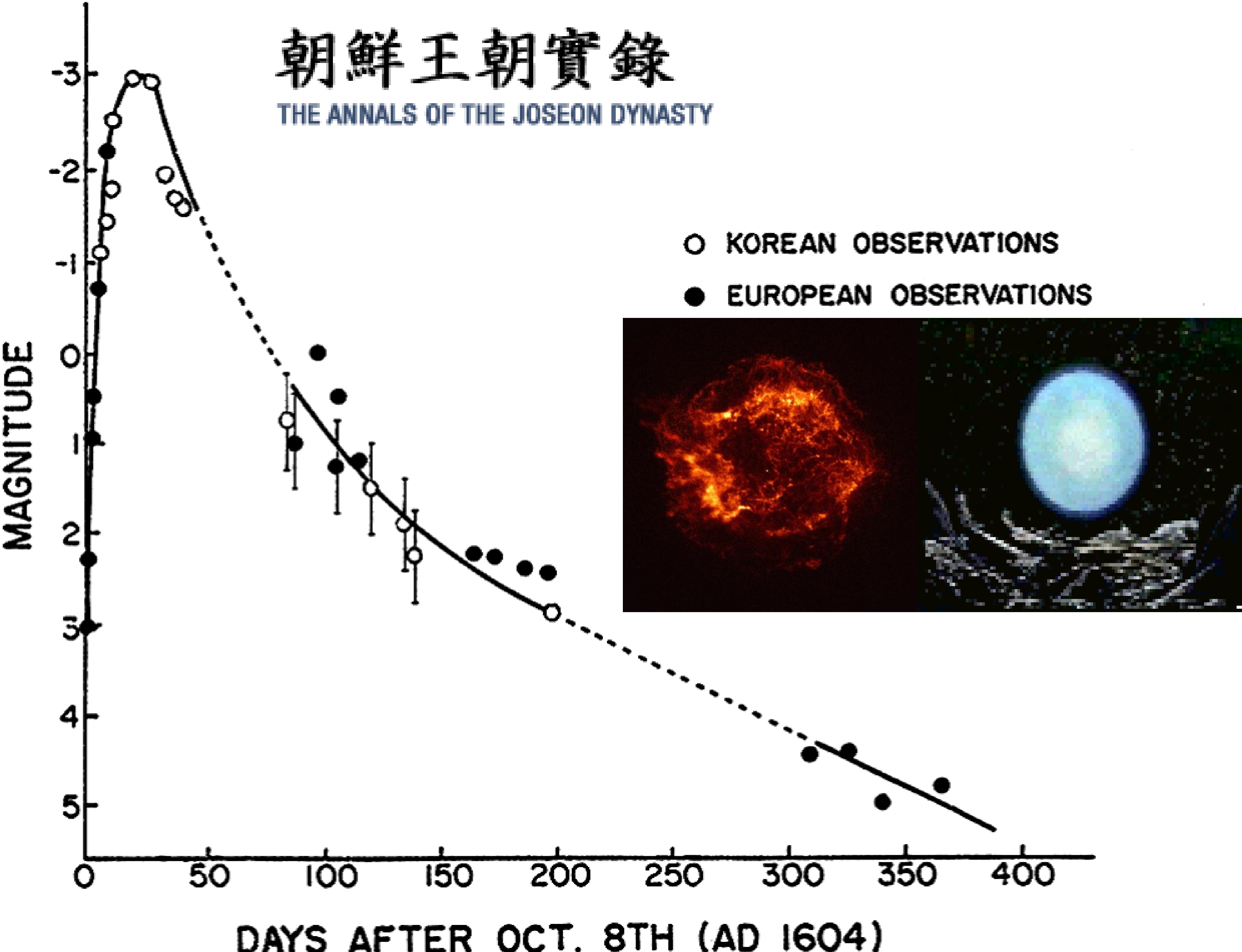
Lab. Measurement
(Nuclear Astrophysics)

Model Simulation
(Astrophysics)

Observation
(Astronomy)

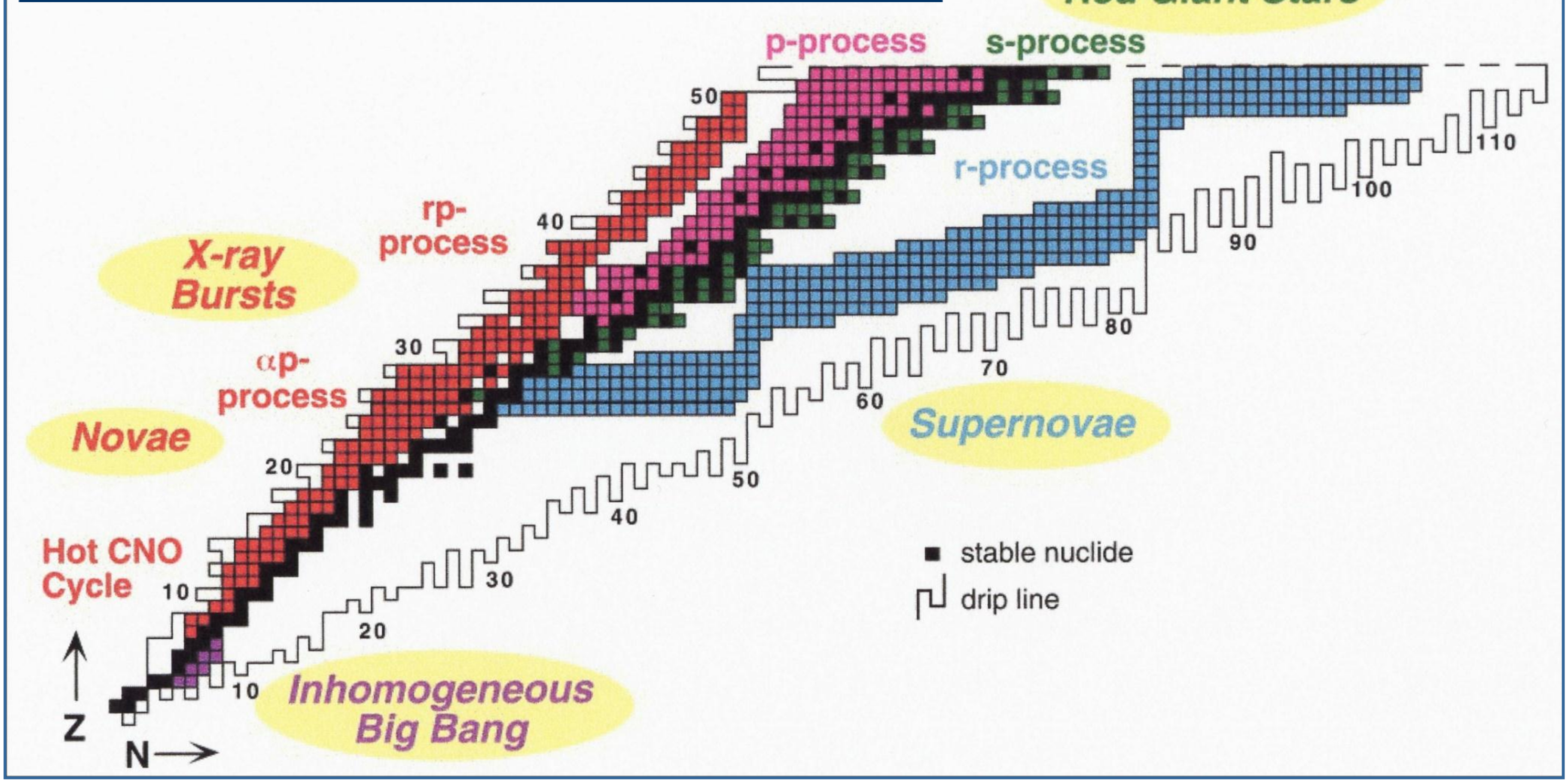
朝鮮王朝實錄

THE ANNALS OF THE JOSEON DYNASTY



M.S. Smith and K.E. Rehm,
Ann. Rev. Nucl. Part. Sci, 51 (2001)

293	2,771	3,064	NNDC (BNL, 2000)



In many cosmic phenomena, radioactive nuclei play an influential role, hence the need for Radioactive Ion Beams

1985 by Fowler (Nobel prize 1983)

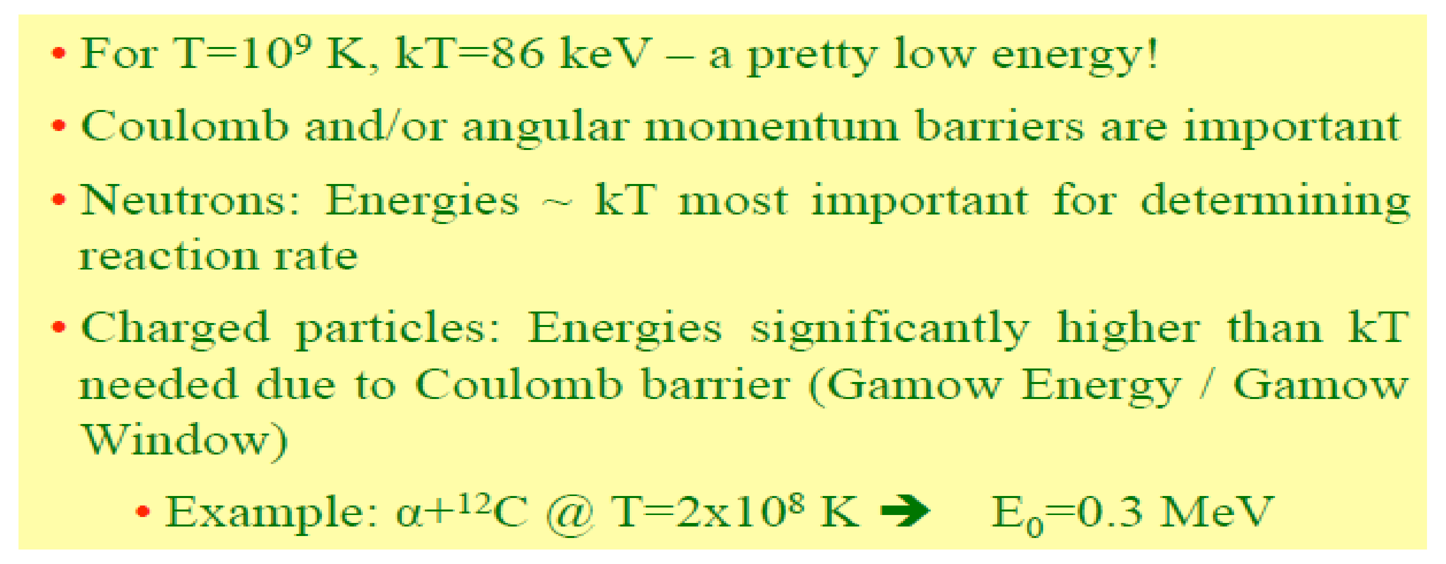
- "We stand on the verge of one of those exciting periods which occur in science from time to time. ...there is an urgent need for data on the properties and interactions of radioactive nuclei ... for use in nuclear astrophysics."

Experimental considerations

Nucleosynthetic reactions are typically dominated by Coulomb barriers

$$E_B = \frac{Z_1 Z_2 e^2}{R} = \frac{1.44 Z_1 Z_2}{R(fm)} \quad MeV$$

$$E_T \approx kT = 8.62\times10^{-8} T \;\; keV$$



- For T=10^9 K, kT=86 keV – a pretty low energy!
- Coulomb and/or angular momentum barriers are important
- Neutrons: Energies ~ kT most important for determining reaction rate
- Charged particles: Energies significantly higher than kT needed due to Coulomb barrier (Gamow Energy / Gamow Window)
  - Example: $\alpha+{}^{12}C$ @ T=2×10^8 K → E_0=0.3 MeV

Thermonuclear reactions in stars

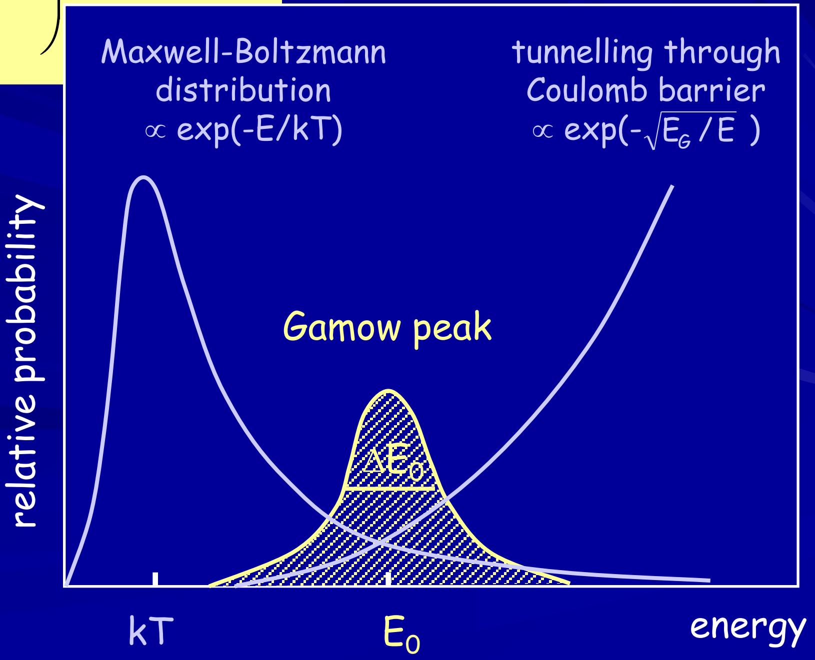
$$S(E) \equiv \sigma(E)E \exp\left(\frac{2\pi Z_1 Z_2 e^2}{\hbar v}\right)$$

$$\lambda = \langle \sigma v \rangle = \int_0^\infty \sigma(E) v(E) \Psi(E) dE$$

$$= \int_0^\infty \frac{S(E)}{E} \exp(-bE^{-1/2}) \sqrt{\frac{2E}{\mu}} \frac{2}{\sqrt{\pi}} \frac{E}{kT} \exp\left(-\frac{E}{kT}\right) \frac{dE}{(kTE)^{1/2}}$$

$$= \left(\frac{8}{\mu\pi}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \frac{S(E)}{E} \exp\left(-\frac{E}{kT} - bE^{-1/2}\right) dE$$

Indirect measurement
vs.
Direct measurements

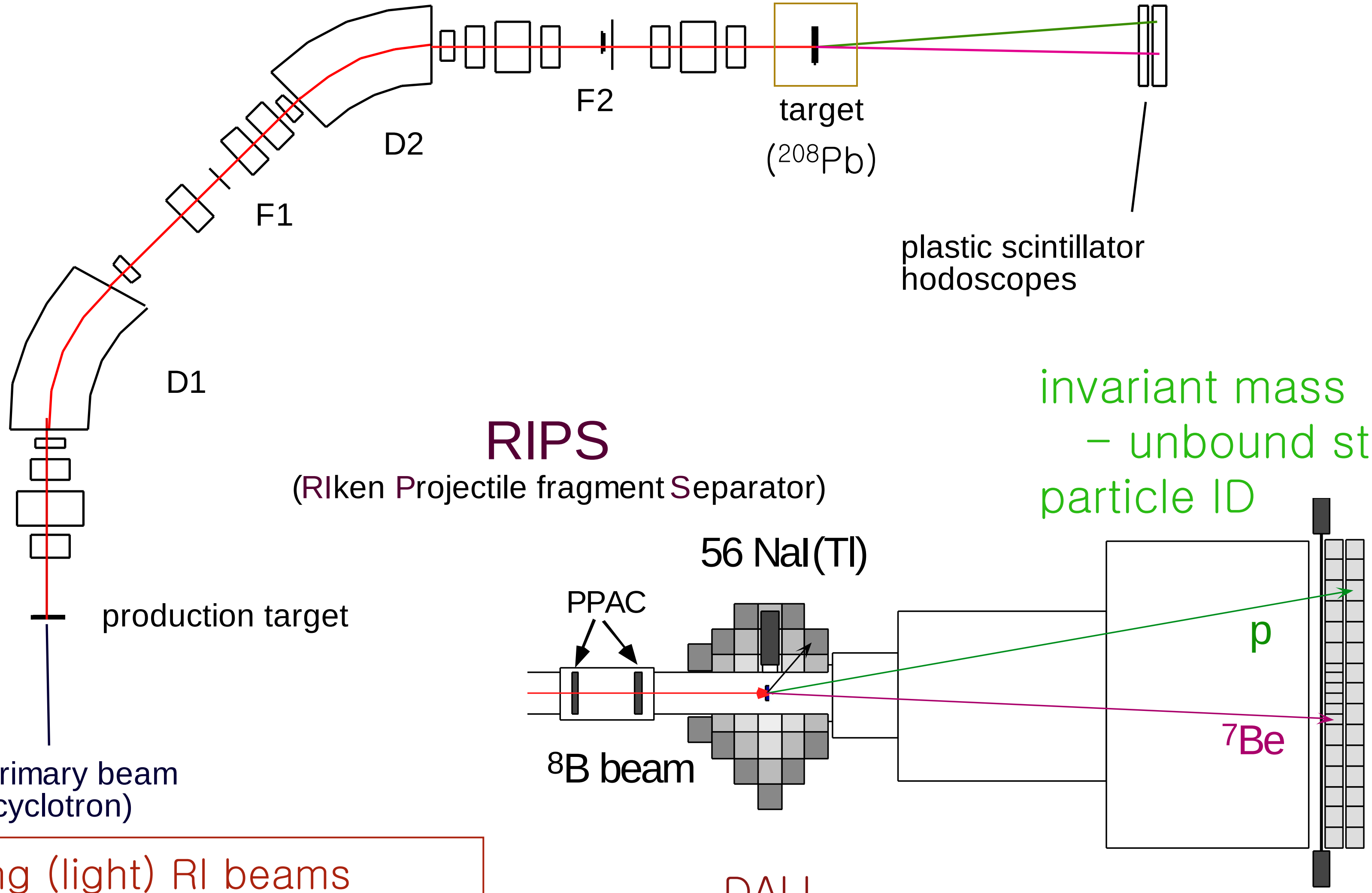


Experimental Nuclear Astrophysics Group

Name	Affiliation	Experiments	
Y. K. Kim	RISP/Hanyang Univ.	CNS	
Y. K. Kwon	RISP	CNS	
J. H. Lee	RISP	CNS	
J. Y. Moon	RISP		
C. S. Lee	Chungang Univ.	CNS, ORNL	27Al, 26Si, 18F
C. B. Moon	Hoseo Univ.	RIKEN	11Li
S.H. Choi	SNU	CNS/RIKEN	
A. Kim	SNU	CNS	14O(a,p)
S. H. Park	KAERI	TRIUMF, U. W	7Be(p,g)
K. Y. Chae	SKKU	ORNL	18F, 17F
K. I. Hahn	Ewha Womans Univ.	Yale, CNS, ORNL	18Ne, 8B, 3H
S. C. Jeong	KEK	KEK, RIKEN	
H. Y. Lee	Los Alamos	Notre Dame, ANL	
H. S. Jung	Notre Dame	CNS	

^{8}B CD Experiment at RIKEN

50 – 90 MeV/nucleon



RIPS

(RIken Projectile fragment Separator)

invariant mass
– unbound states
particle ID

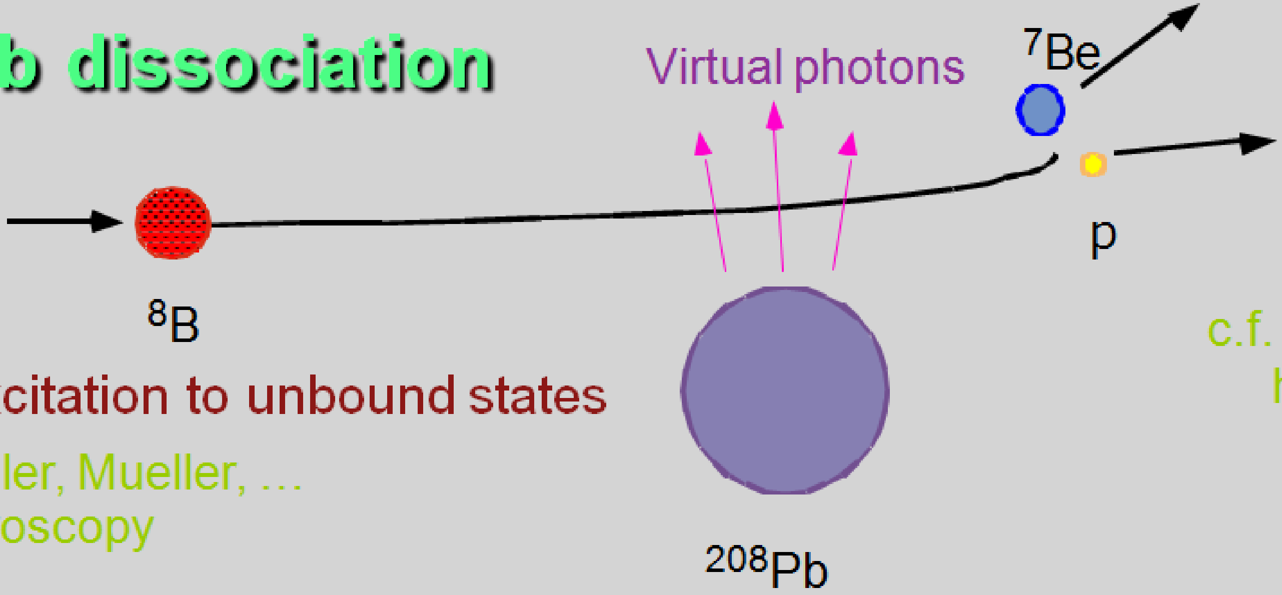
strong (light) RI beams

DALI
γ ray
– bound states

HODO

March 1992

Coulomb dissociation



c.f. Nakamura
halo nuclei

= Coulomb excitation to unbound states

c.f. Mueller, Mueller, …
spectroscopy

^{8}B+^{208}Pb –> ^{7}Be+p+^{208}Pb (C.D.)

↓ virtual photon theory or DWBA

^{8}B(γ,p)^{7}Be (abs.)

↓ detailed balance

^{7}Be(p,γ)^{8}B (capt.)

large σ
thick target (intermediate energy)

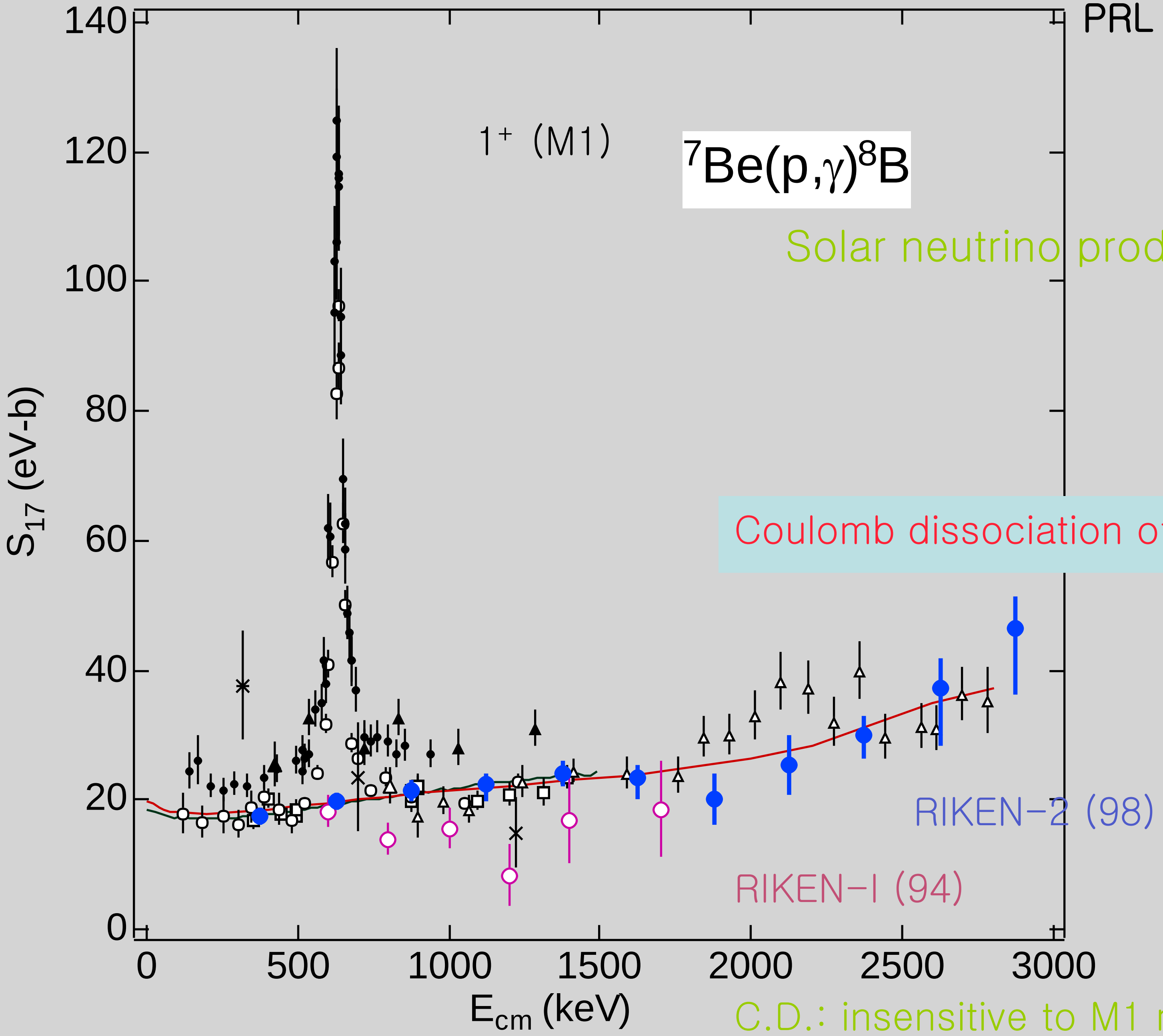
experiments with R.I. beams

PRL 73, 2682 (1994)

^{7}Be(p,γ)^{8}B

Solar neutrino production

Coulomb dissociation of ^{8}B



C.D.: insensitive to M1 resonance

some of the theorists in (Nuclear) Astrophysics

M. K. Cheoun @ Soongsil Univ.

-. Neutrino Reaction in Nuclear Astrophysics
ν-processes in Nucleosynthesis

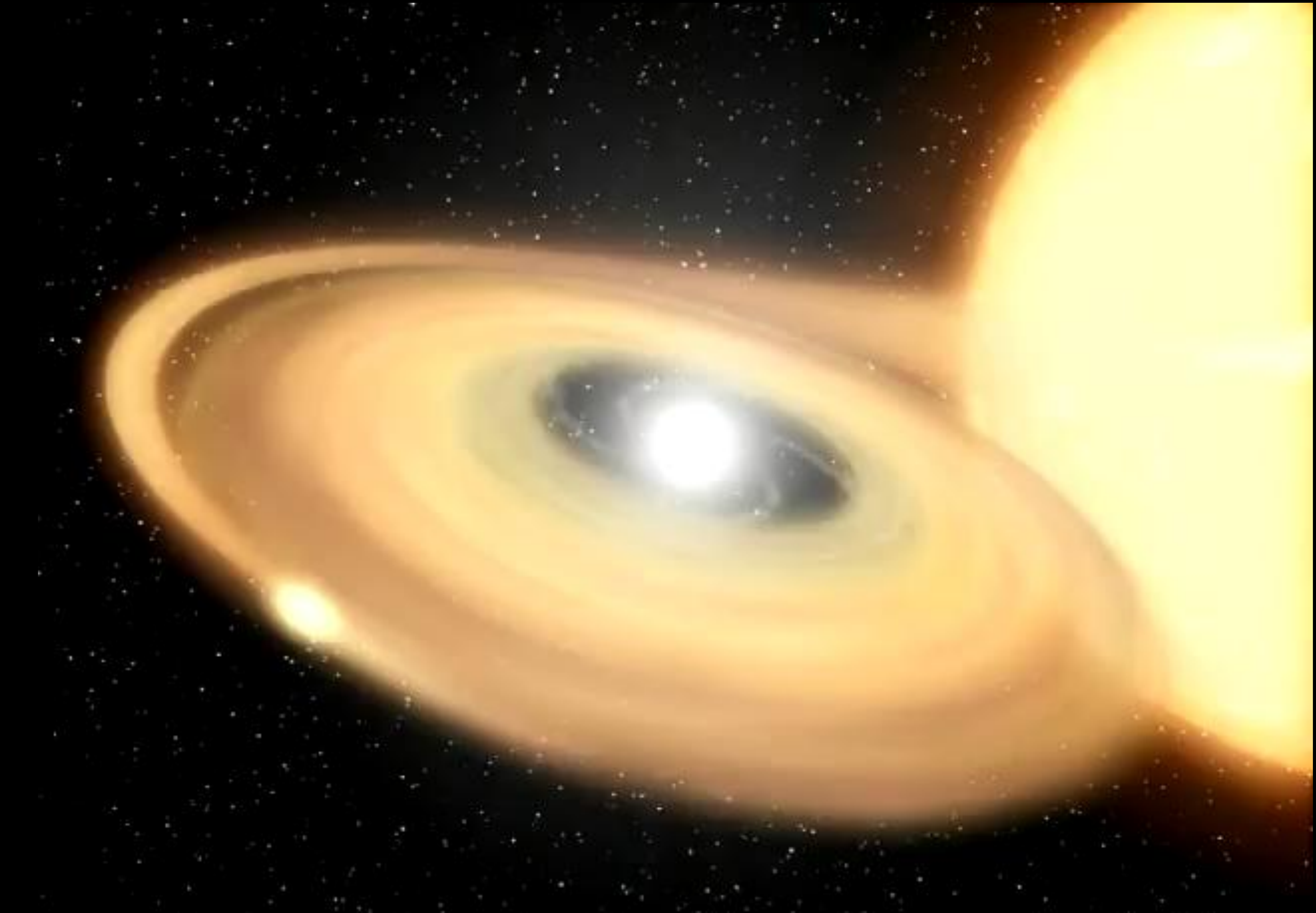
H. K. Lee @ Hanyang Univ.

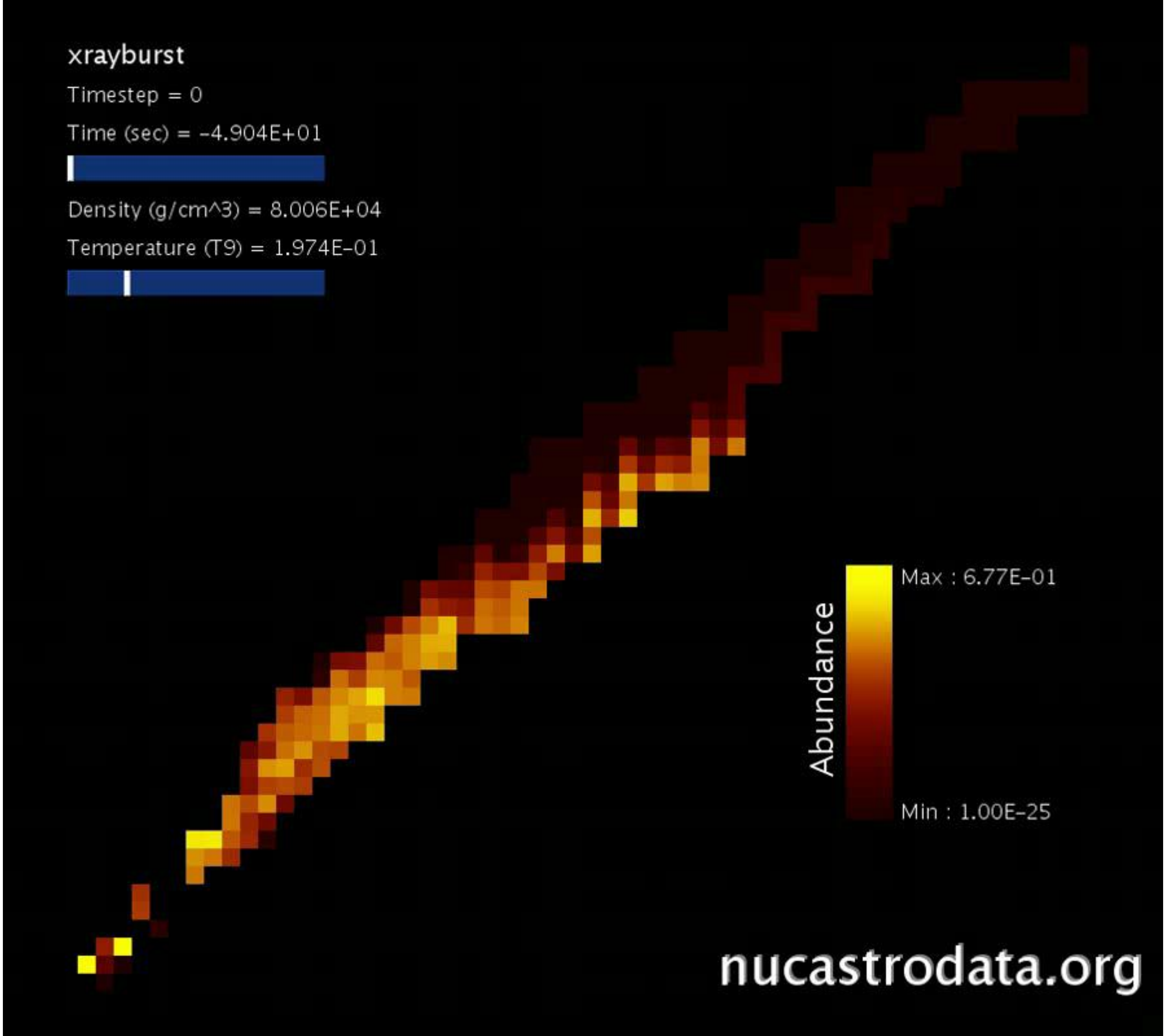
-. Nuclear Symmetry Energy and Compact Stars

C. H. Lee @ Pusan Univ.

-. Gamma-ray burst, Hypernovae, Supernovae, neutron star

Nova models





xrayburst

Timestep = 0

Time (sec) = -4.904E+01

Density (g/cm^3) = 8.006E+04

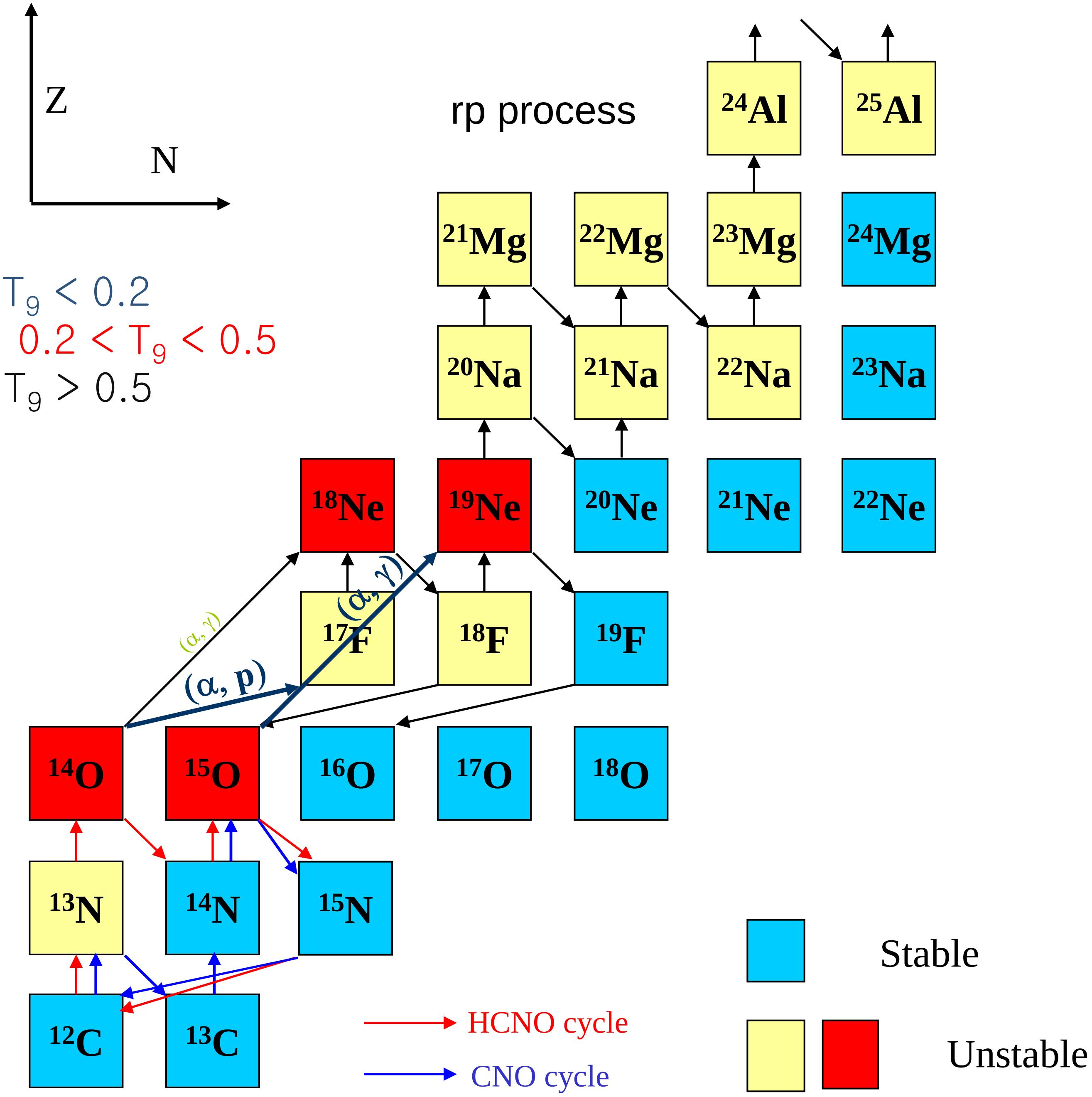
Temperature (T9) = 1.974E-01

nucastrodata.org

CNO cycle : $T_9 < 0.2$

HCNO cycle: $0.2 < T_9 < 0.5$

rp process : $T_9 > 0.5$

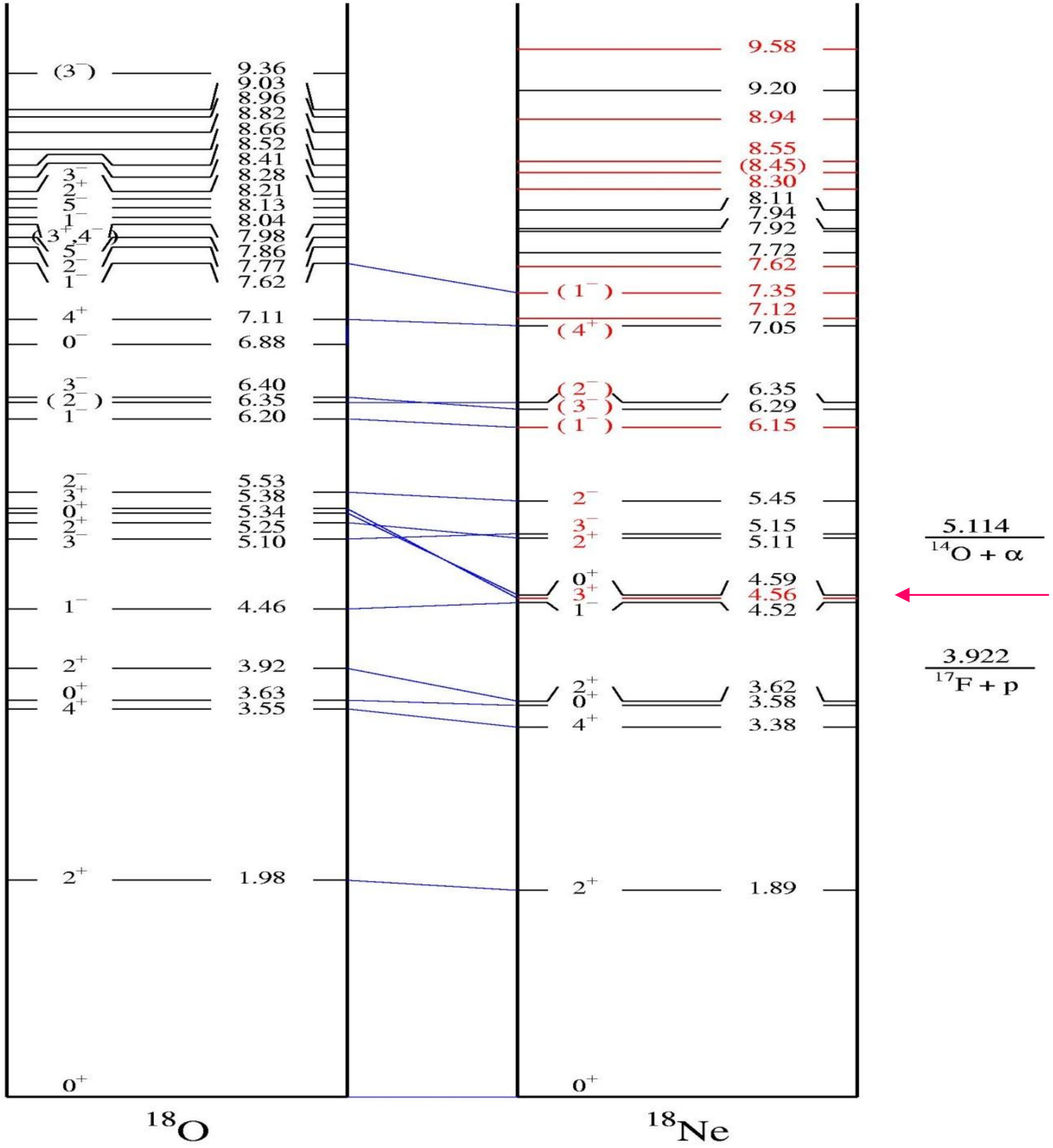


Measurements

- Direct measurements are desirable ways to measure the $^{15}O(\alpha,\gamma)^{19}Ne$ and $^{14}O(\alpha,p)^{17}F$ reactions over indirect methods.
- Only became possible after new generation of accelerators that can make $^{14,15}O$ and ^{17}F beams in the late 90's.
- There are still large uncertainties of the reaction relevant to X-ray burst and novae.

Measurements

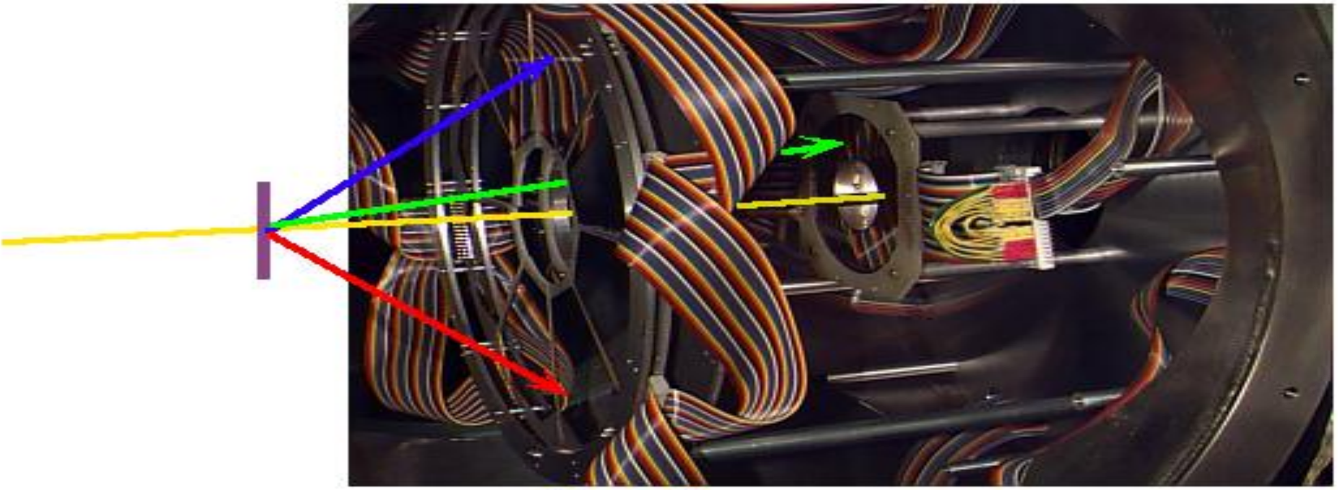
- Direct measurements have a serious problem due to their very low cross sections
- Indirect measurements
  - Transfer reactions (selectivity, resolution)
  - $^{20}Ne(p,t)\,^{18}Ne$, $^{16}O(^{3}He,n)^{18}Ne$,
    $^{12}C(^{12}C,\,^{6}He)^{18}Ne$,
    $^{19}F(^{3}He,t)^{19}Ne$, $^{16}O(^{6}Li,t)\,^{19}Ne$, etc.
  - Resonant elastic scattering
  - $^{4}He(^{14}O,\alpha)^{14}O$ and $^{4}He(^{15}O,\alpha)^{15}O$

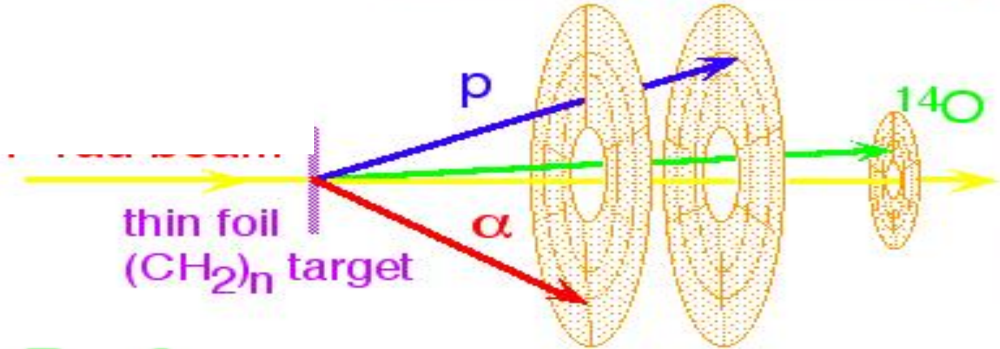


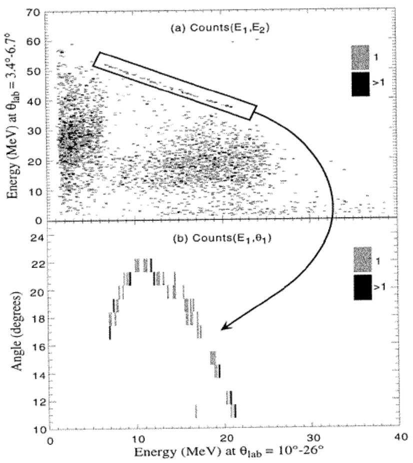
4.592 PRL 83 (1999)

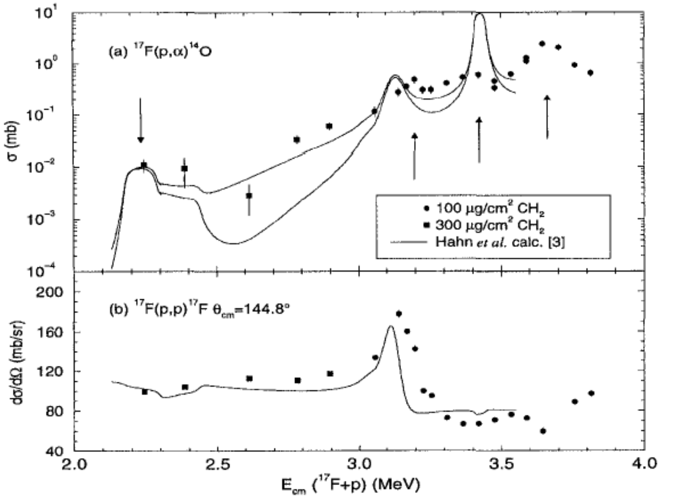
Hahn et al. (96)

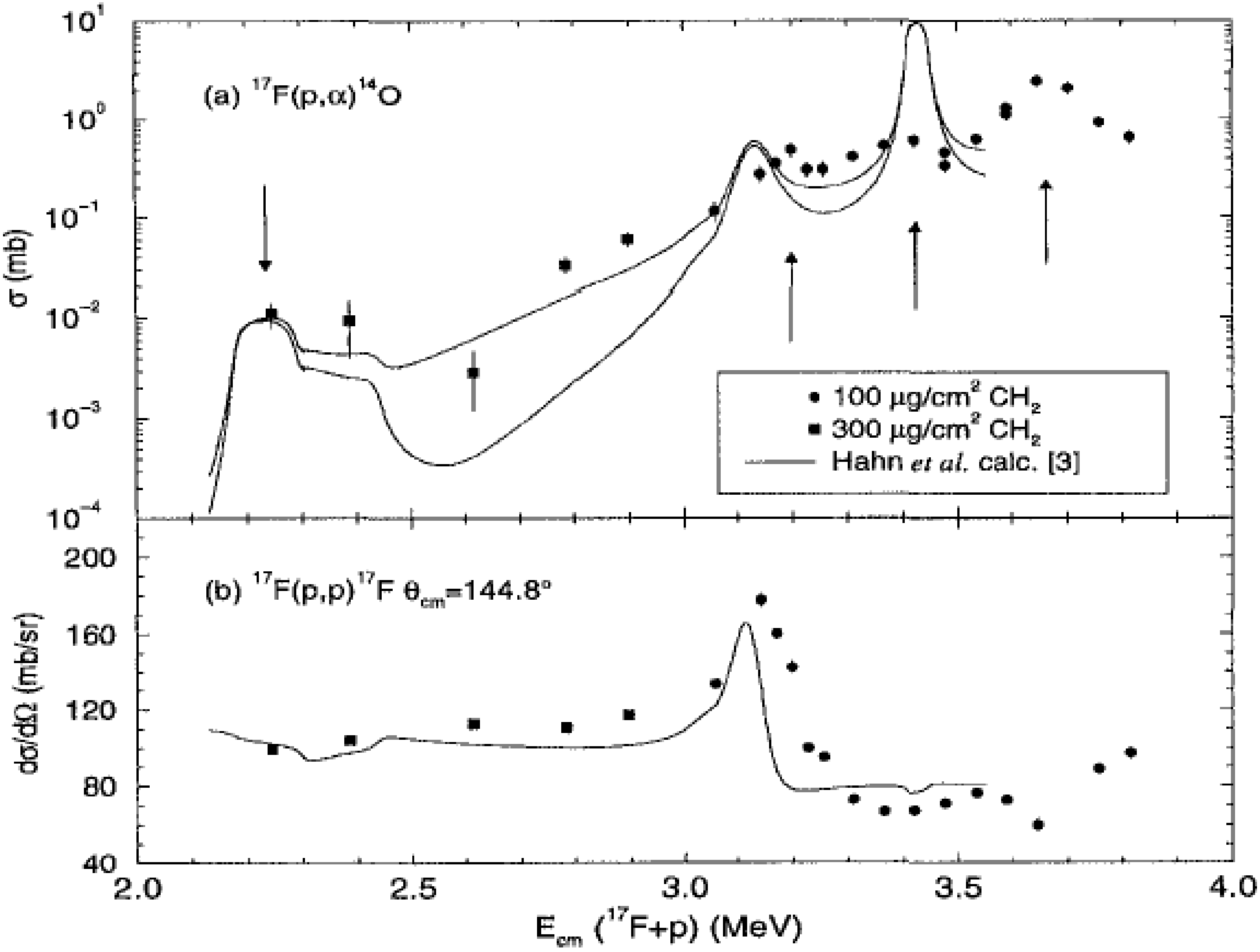
p(^{17}F,^{14}O)a Experiment at ORNL










(a) $^{17}F(p,\alpha)^{14}O$
σ (mb)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
● 100 μg/cm² CH₂
■ 300 μg/cm² CH₂
Hahn et al. calc. [3]
(b) $^{17}F(p,p)^{17}F$ θ_{cm}=144.8°
dσ/dΩ (mb/sr)
200
160
120
80
40
2.0
2.5
3.0
3.5
4.0
E_{cm} (^{17}F+p) (MeV)

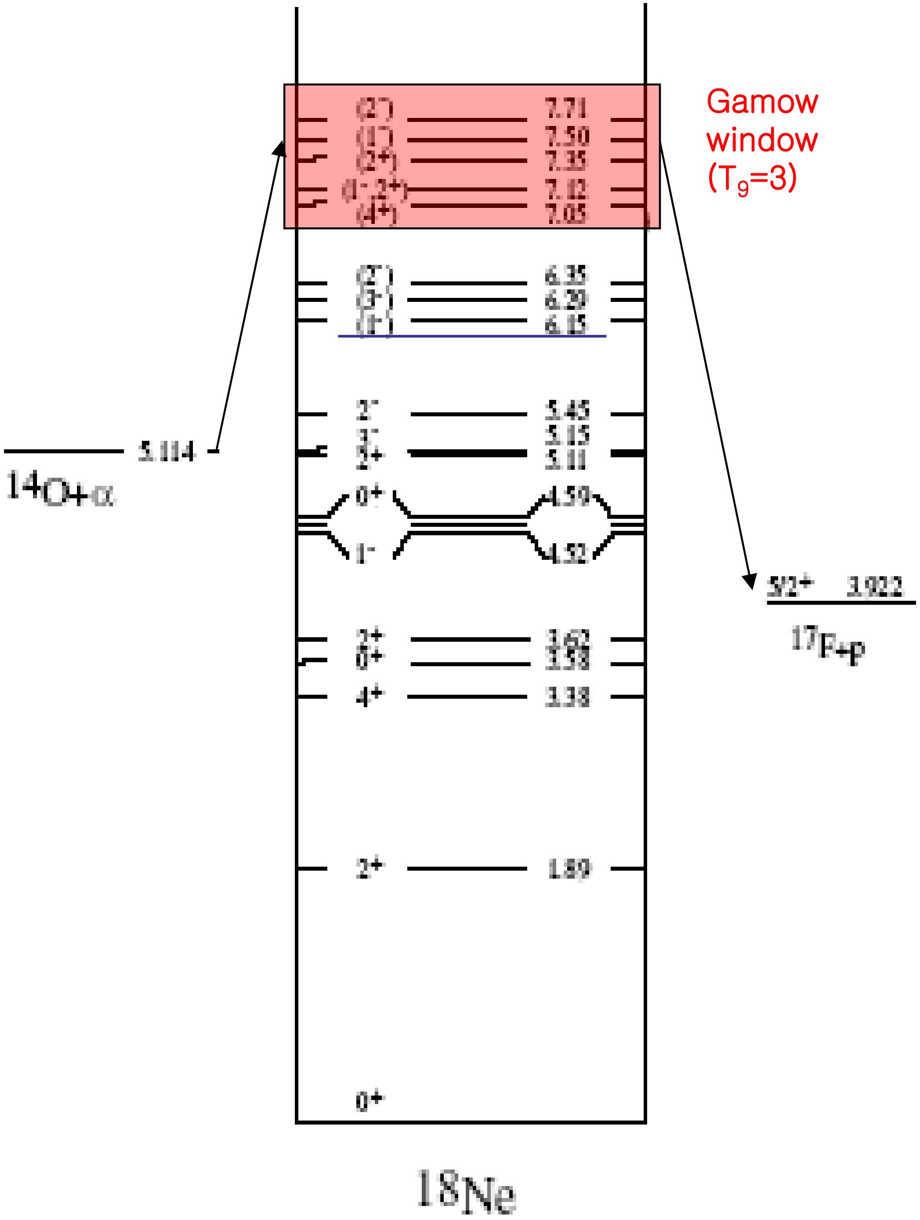
- ^{14}O(a,p)^{17}F reaction rate is strongly affected by resonant states of ^{18}Ne.

- However, there are large uncertainties in ^{14}O(a,p)^{17}F reaction rate.

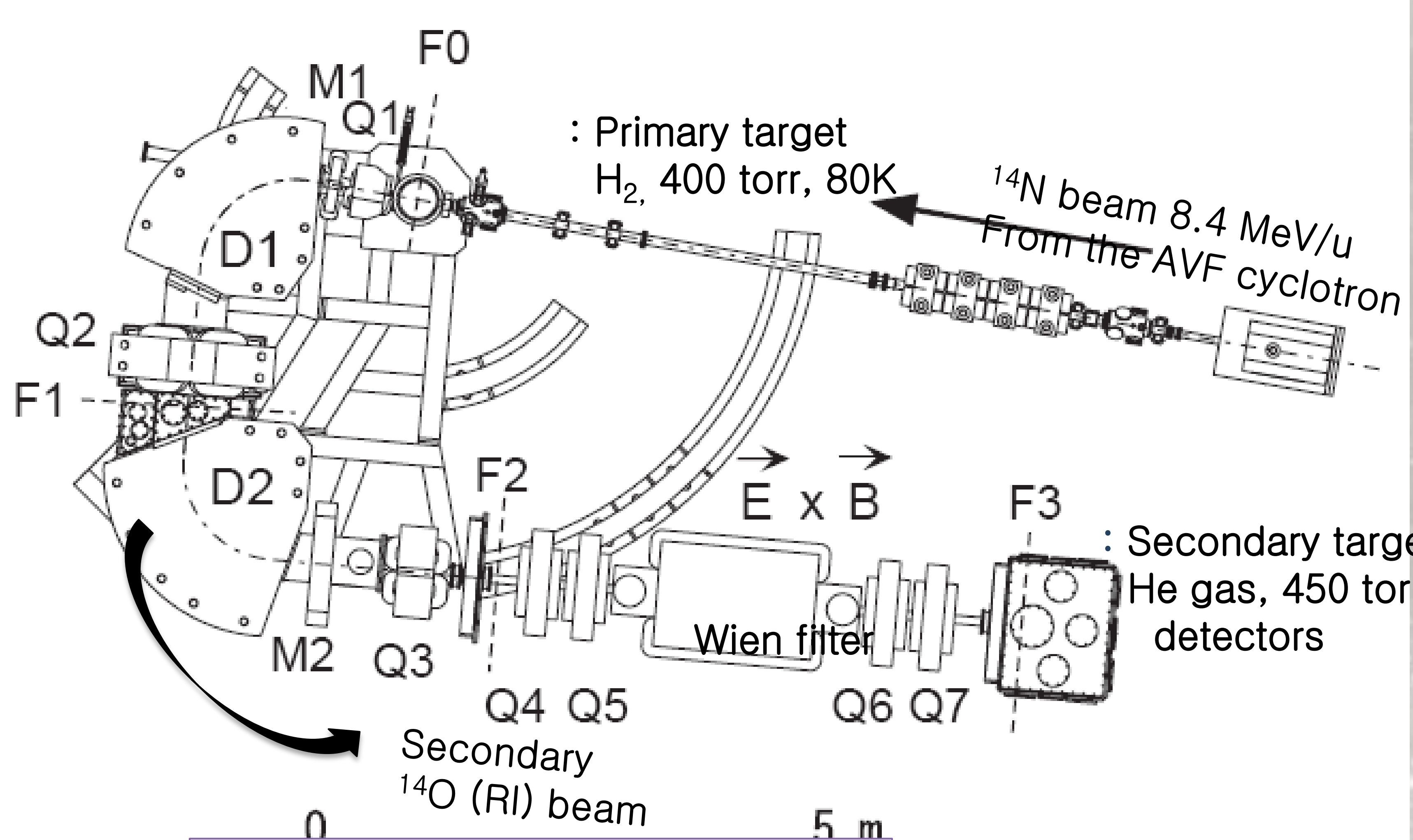
- People have measured the time-reverse reaction ^{17}F(p,a)^{14}O.

- Previous other measurements were indirect experiments, which were to measure the resonance properties of ^{18}Ne.

⇨ We performed <u>direct measurement of ^{14}O(a,p)^{17}F and ^{14}O(a,a)^{14}O.</u>



We measured the 14O+alpha experiment in June, 2008



: Primary target
H_2, 400 torr, 80K

^{14}N beam 8.4 MeV/u
From the AVF cyclotron

: Secondary target.
He gas, 450 torr
detectors

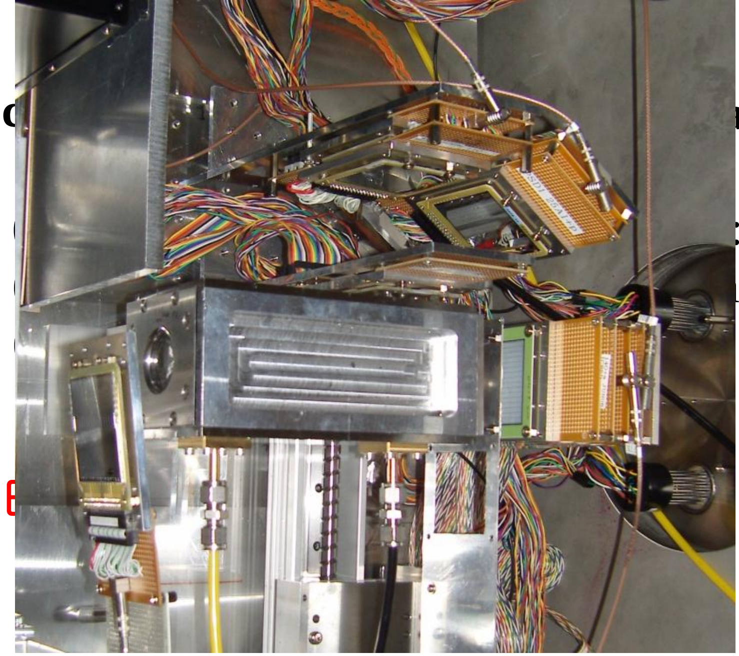
Secondary
^{14}O (RI) beam

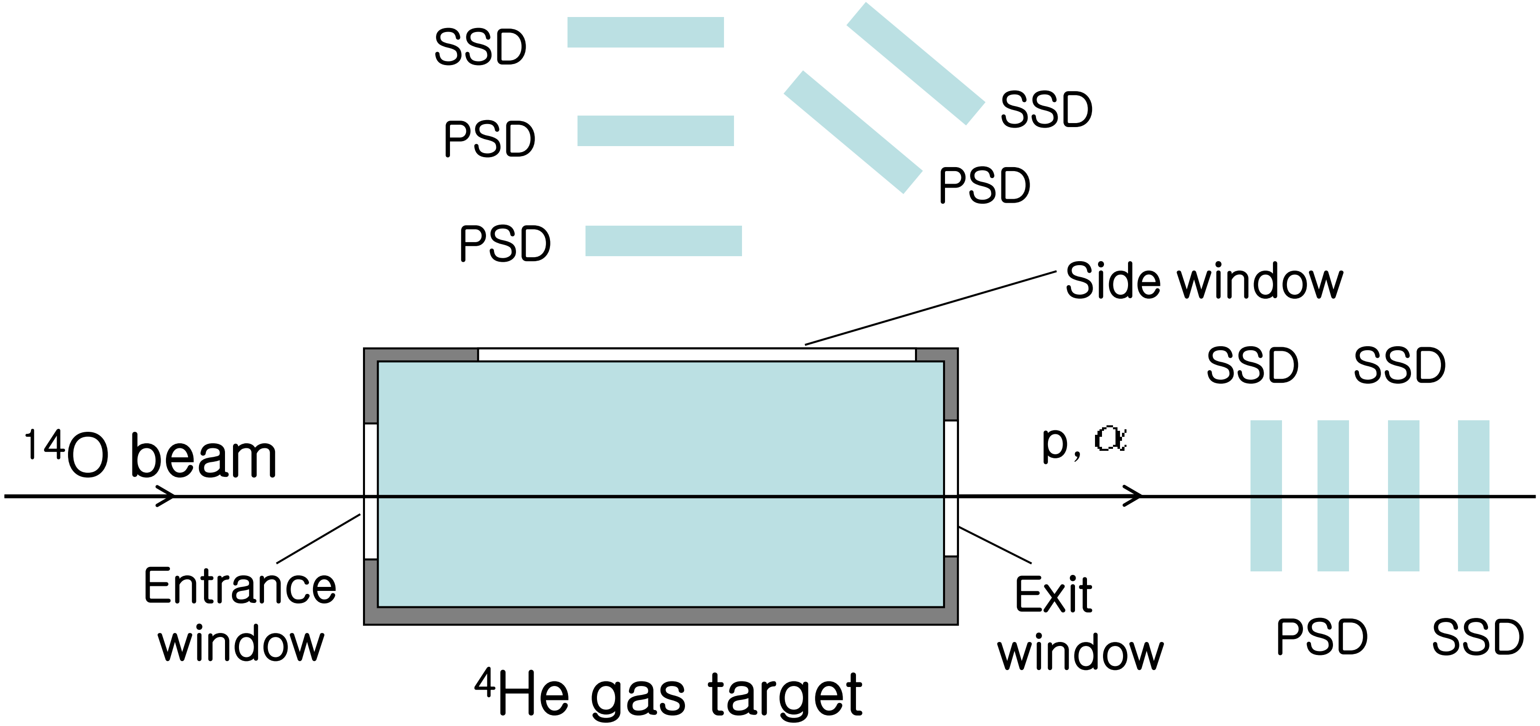
^{14}O secondary beam was produced through reaction ^{14}N (p,n) ^{14}O

- **Secondary beam c** **ary target (^{4}He gas)**

count rate: ~10^5 /s (: 150mm (room temp. ,440 torr)
energy: 24.0 MeV (g/cm^2
36.0 MeV (

-> E scanned.





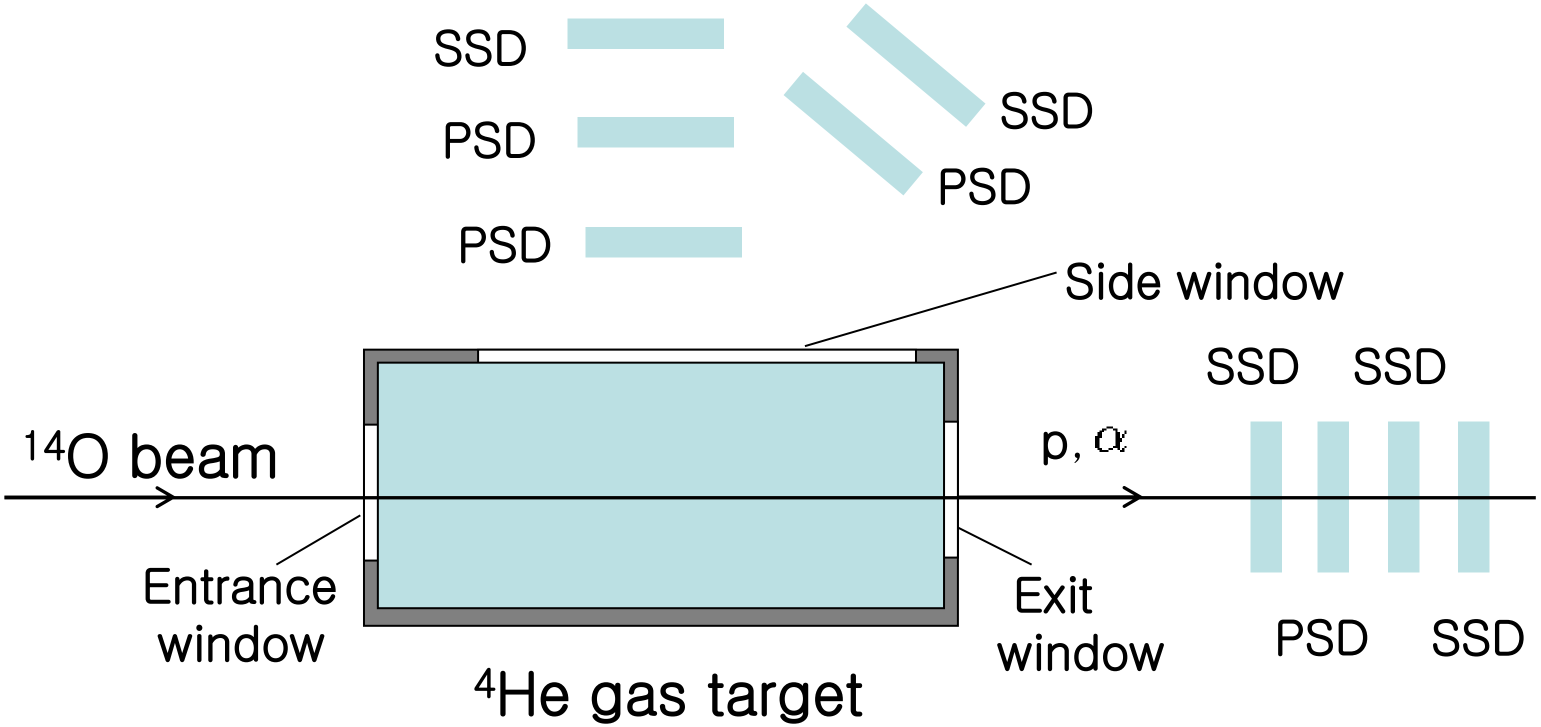
- **Secondary beam condition (^{14}O)**

  count rate: ~10^5 /s (on target)
  energy: 24.0 MeV (low energy)
  36.0 MeV (high energy)

- **Secondary target (^{4}He gas)**

  thickness: 150mm (room temp. ,440 torr)
  ->1.43mg/cm^2

-> Ex = 7.2 ~ 13.1 MeV in ^{18}Ne was scanned.



Analysis & Results

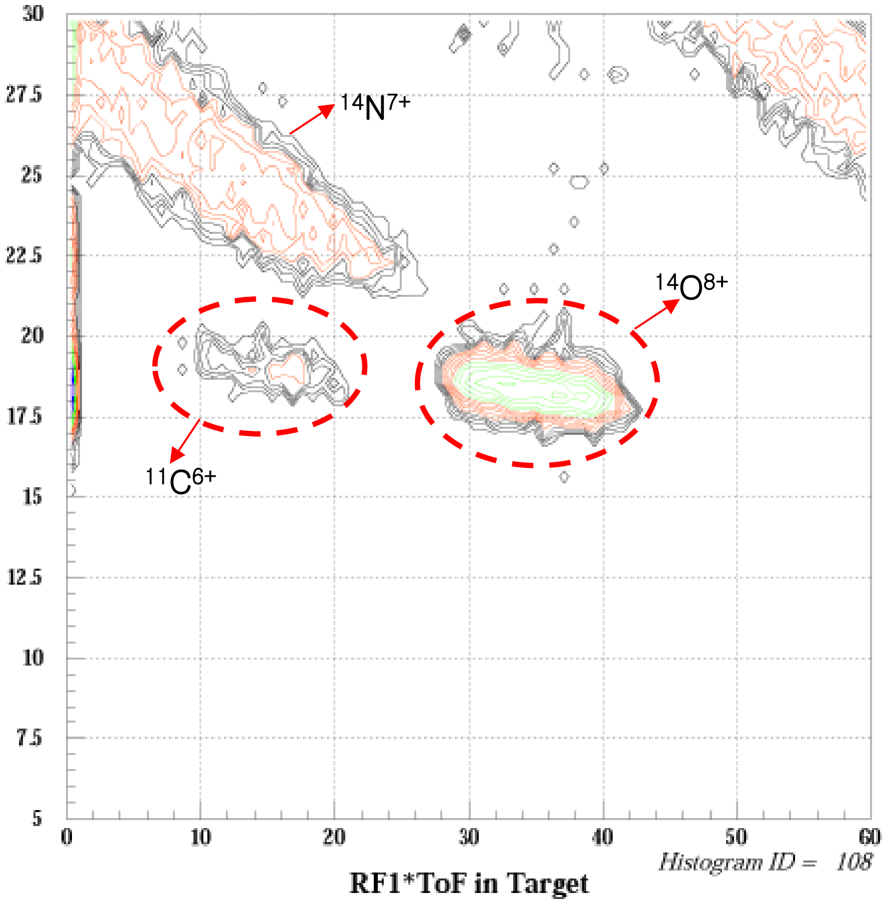
- Reconstruction of recoiled particles spectrum
  ：thick target method (effective thickness & solid angle)
  relativistic kinematics

  1. $^{14}O(\alpha,\alpha)^{14}O$
  2. $^{14}O(\alpha,p)^{17}F$

- Energy calibration of detector
  ：alpha source , proton beam and ^{14}N beam

- Background subtraction
  ：empty target run, Ar gas run

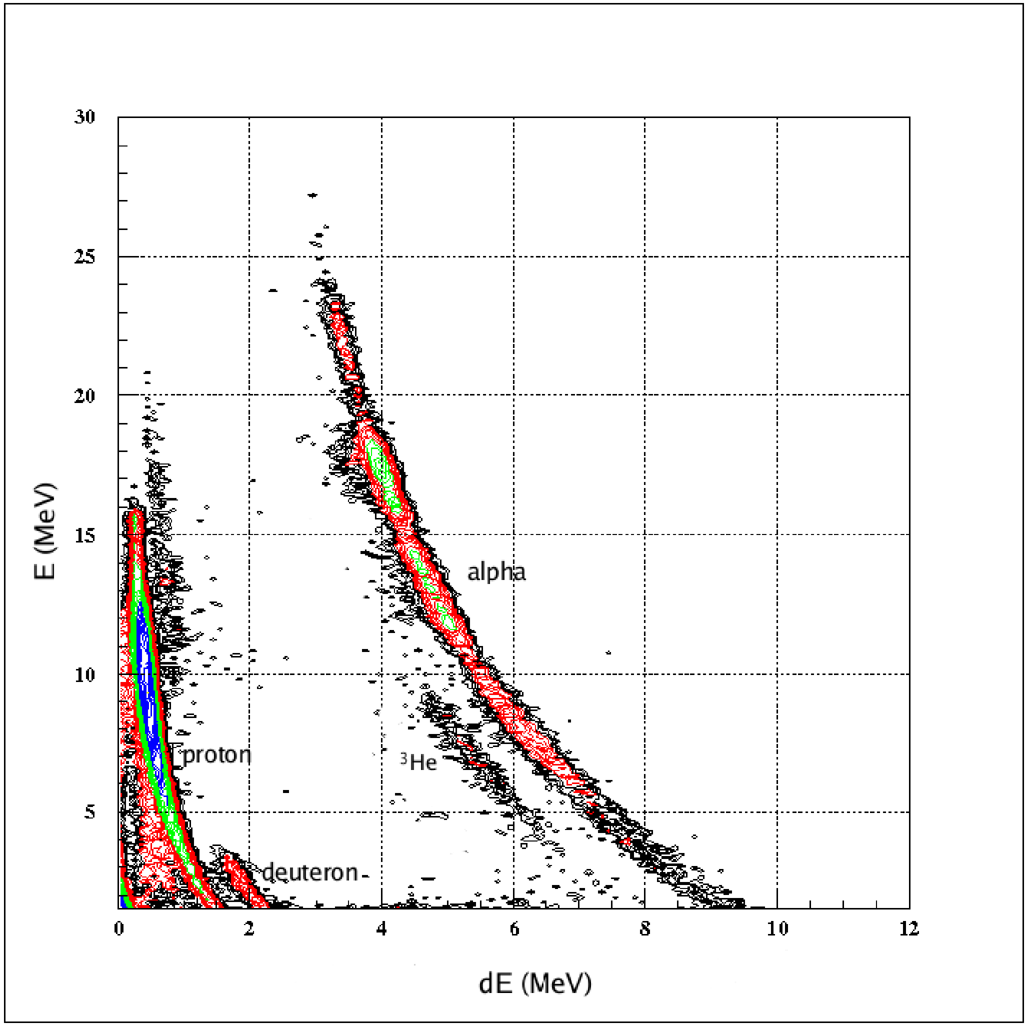
Separation of secondary beam



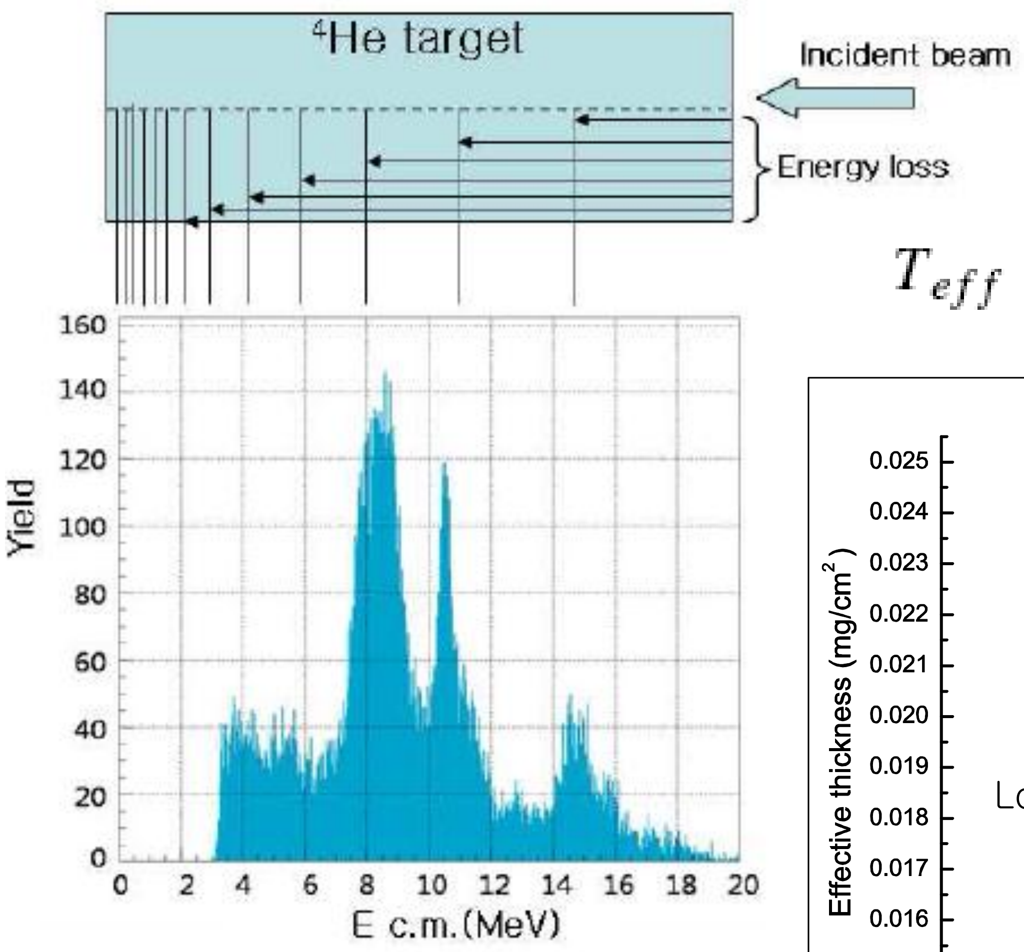
Two dimensional plot of
RF1 vs TOF at F3

^{14}O beam was distinguished very cleanly.

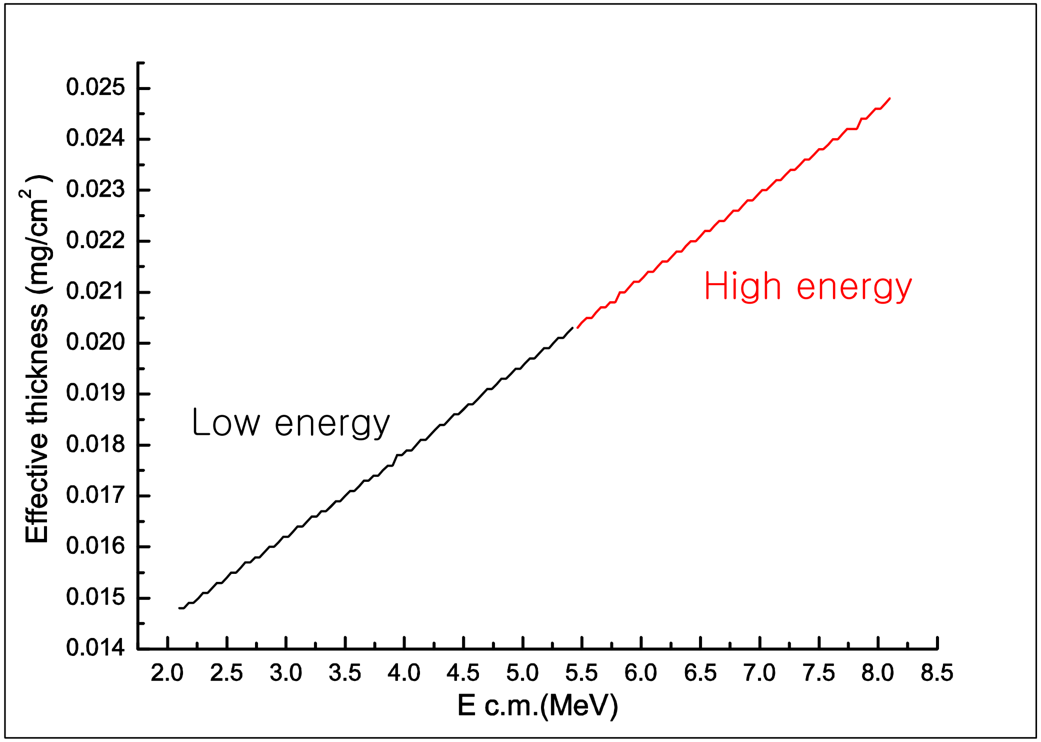
dE-E plot of recoiled particles



Effective thickness



$$T_{eff} = Range(E_n) - Range(E_{n-1})$$



Aram Kim (2010)

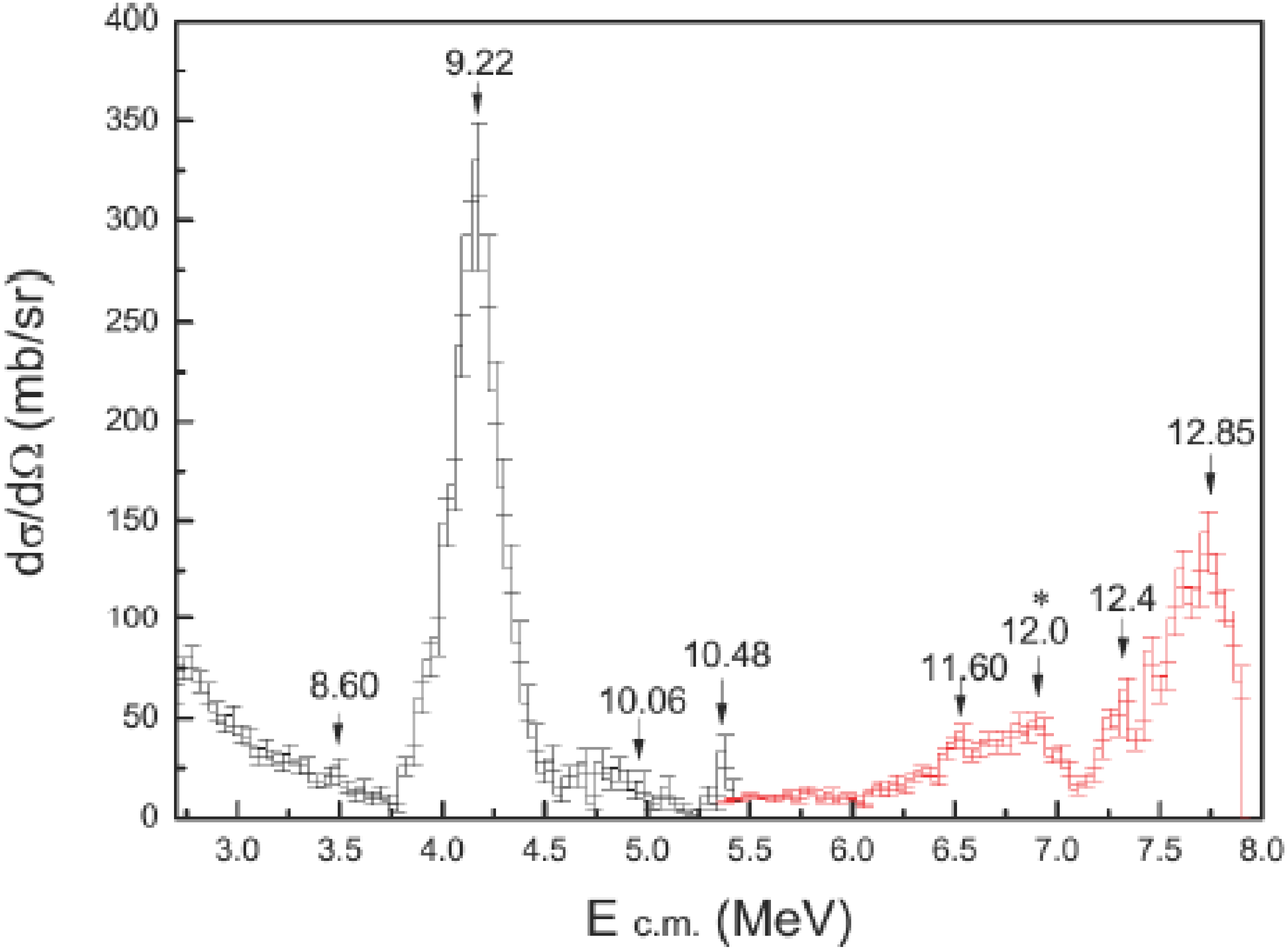
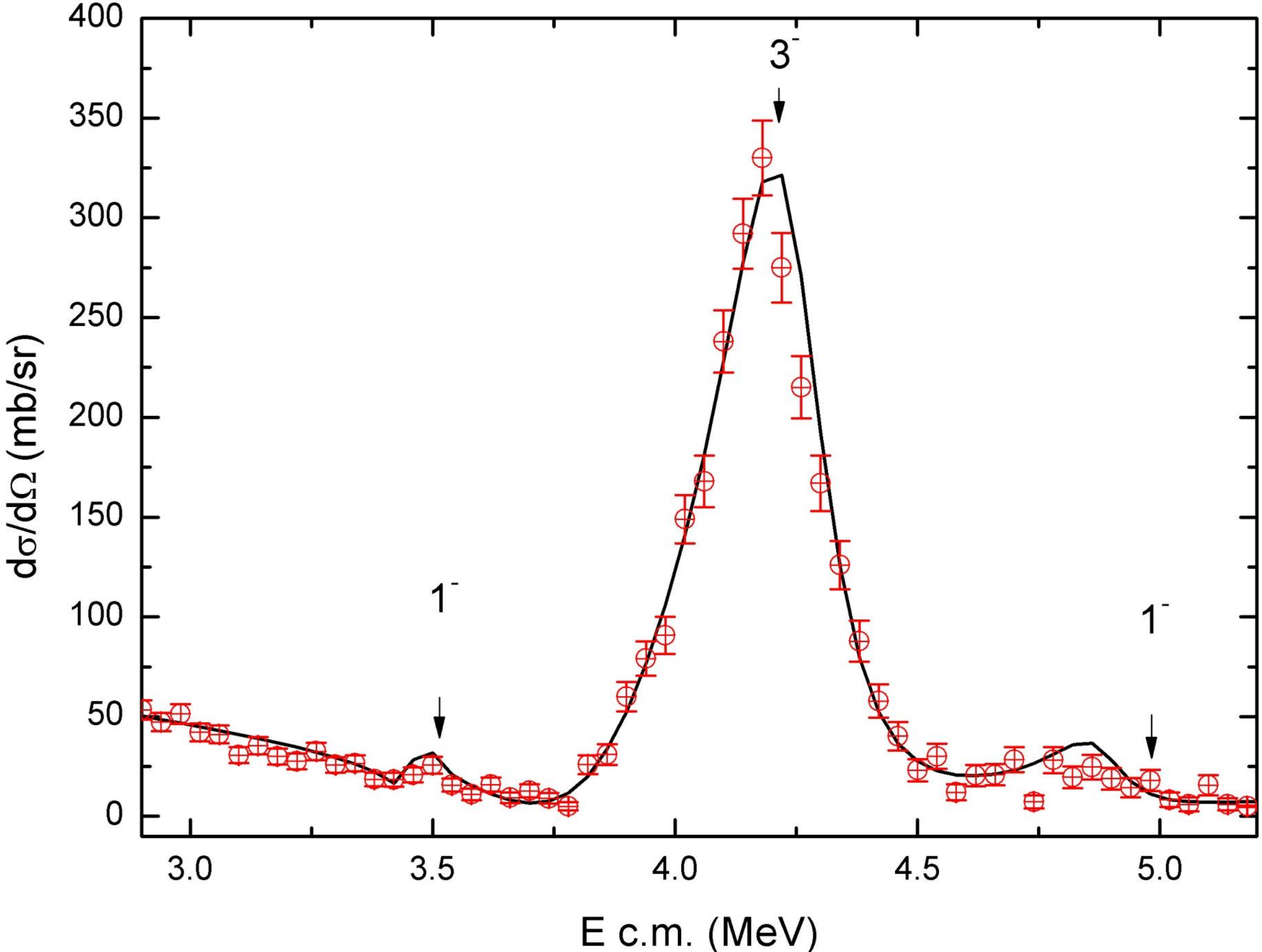


Fig. 5. (Color online) Excitation function of the $^{14}O(\alpha,\alpha)^{14}O$ reaction at the 0 degrees telescope. The level marked by $*$ has not been seen before.

Fitting result

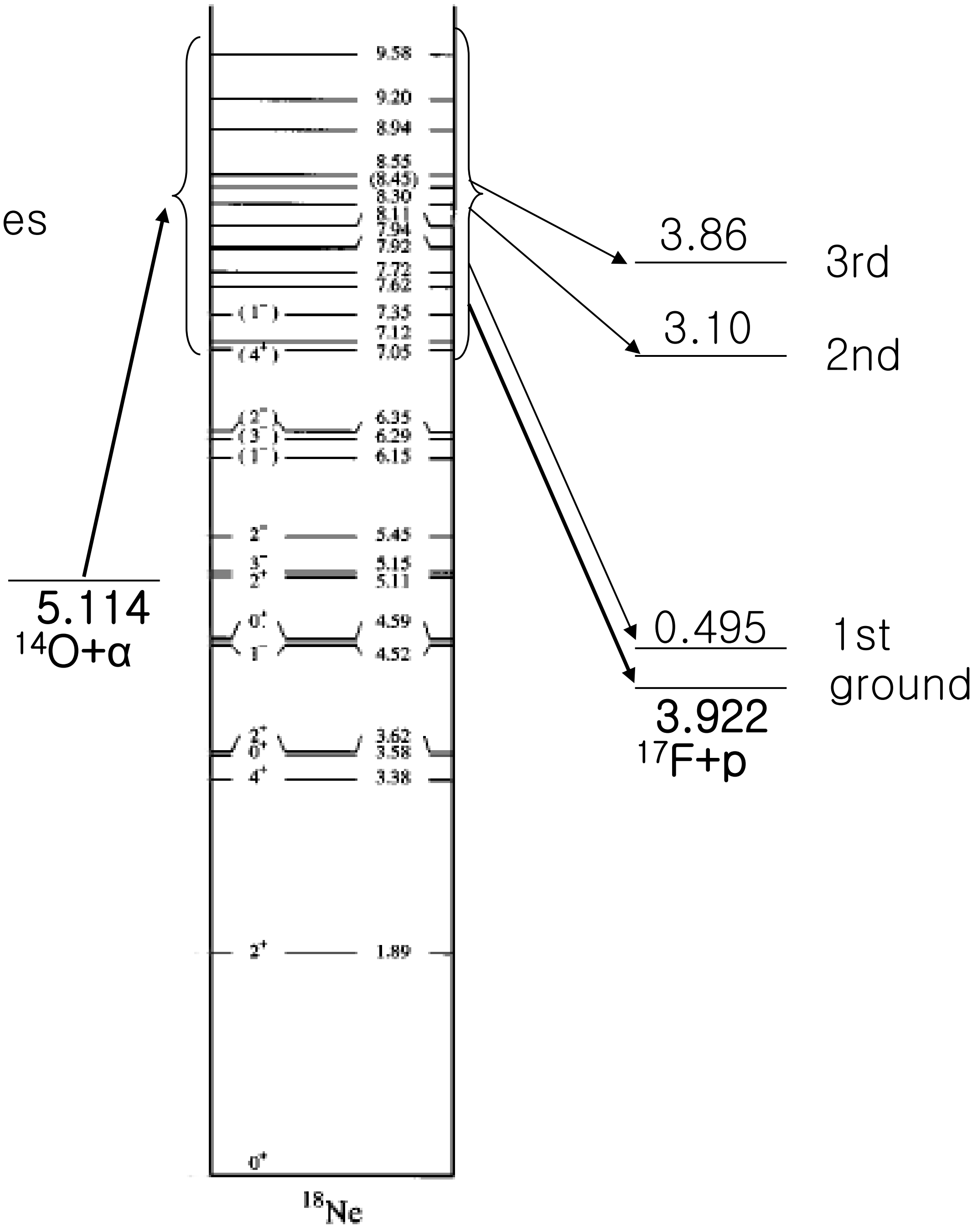


Reconstruction of proton spectra

Distinction Of proton decay branches of ^{18}Ne* by using the thick target method.

TOF **vs.** Energy

Protons have different TOF value according to the energy.



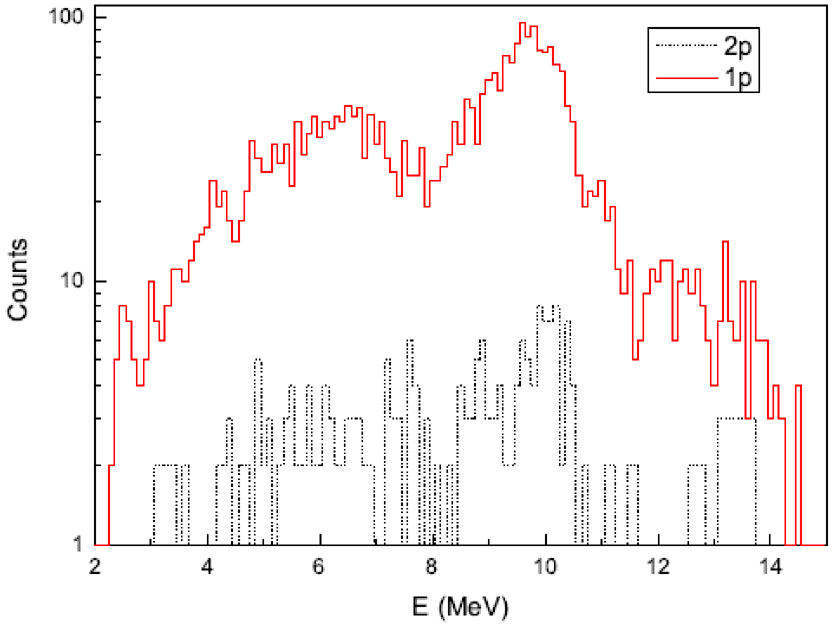
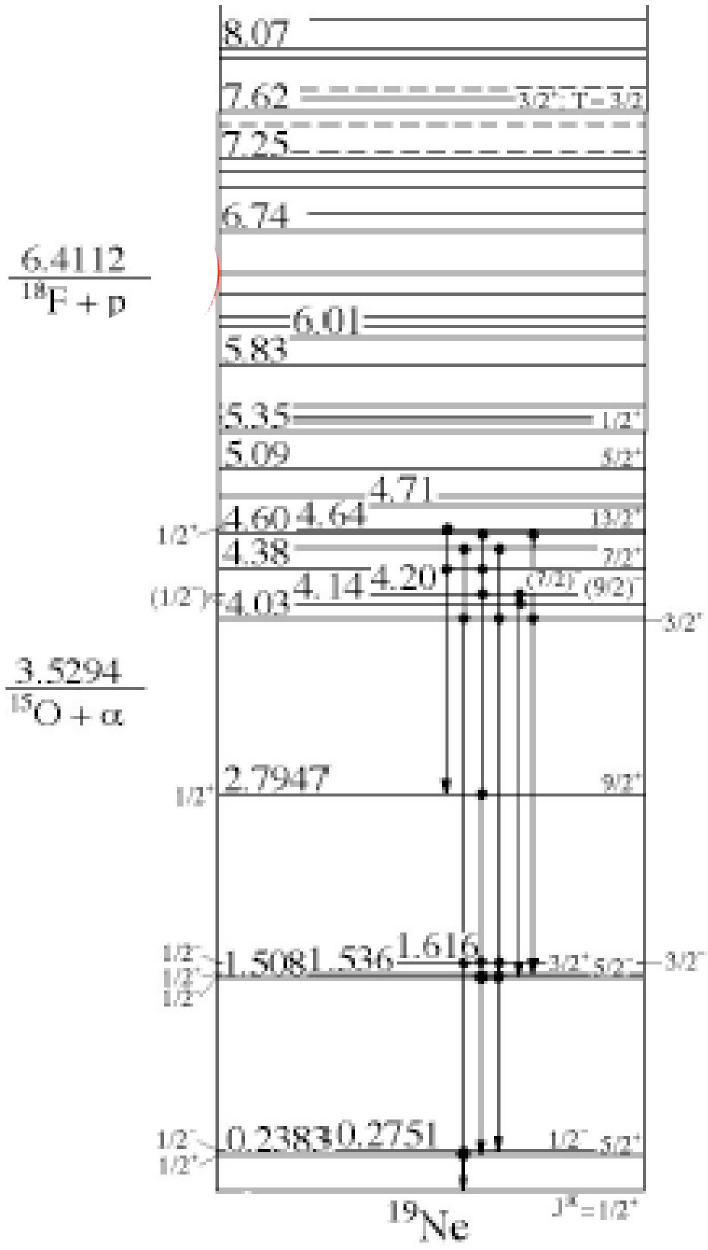
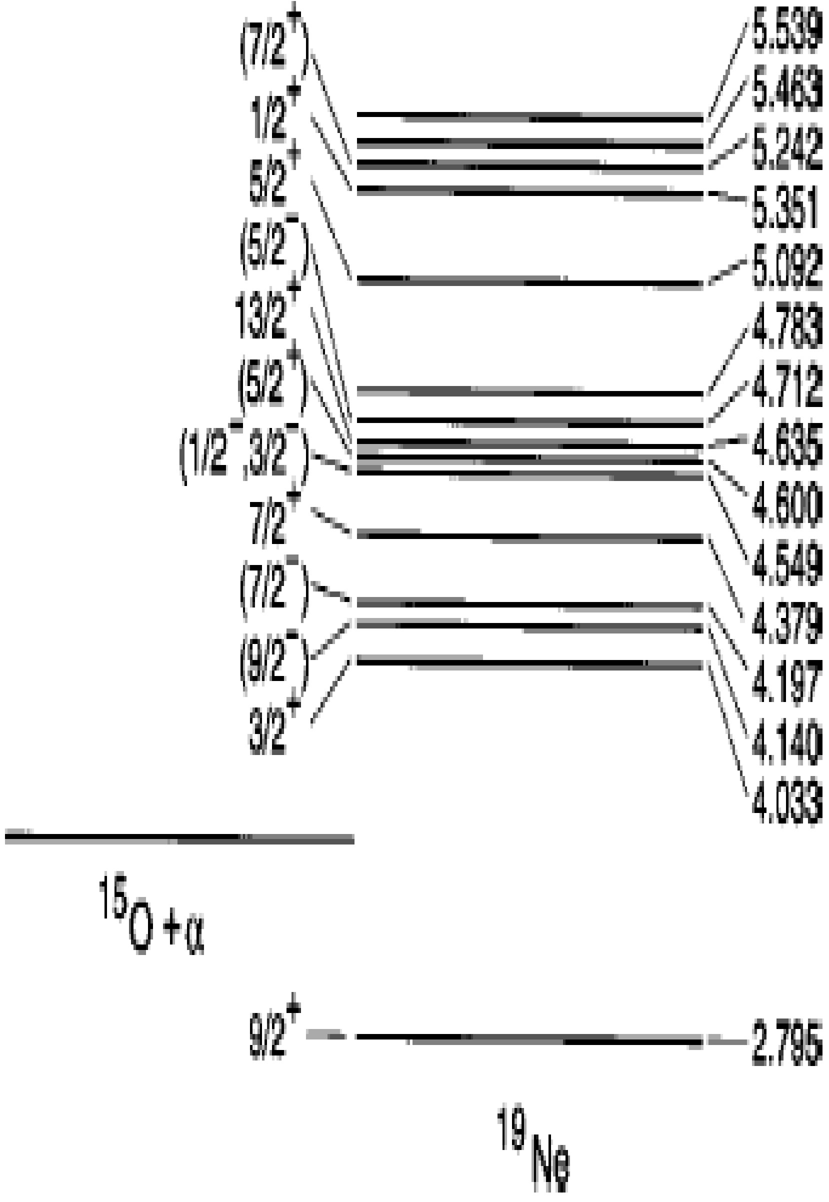


FIG. 4. The energy distribution of single and double proton events. The x axis represents the energy summation of ΔE-E detector. The scale of y axis is logarithmic.

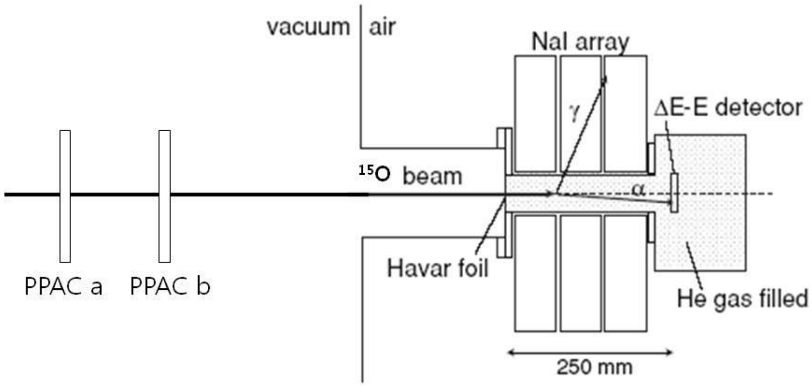

8.07
7.62
3/2+; T=3/2
7.25
6.74
6.4112
18F + p
6.01
5.83
5.35
1/2+
5.09
5/2+
4.71
4.60
4.64
13/2+
1/2+
4.38
7/2+
(1/2-)
4.03
4.14
4.20
(7/2-)
(9/2-)
3/2+
3.5294
15O + α
1/2+
2.7947
9/2+
1/2-
1/2
1/2
1.508
1.536
1.616
3/2+
5/2-
3/2-
1/2-
1/2+
0.2383
0.2751
1/2-
5/2+
19Ne
Jπ=1/2+


(7/2+)
1/2+
5/2+
(5/2-)
13/2+
(5/2+)
(1/2-,3/2-)
7/2+
(7/2-)
(9/2-)
3/2+
5.539
5.463
5.242
5.351
5.092
4.783
4.712
4.635
4.600
4.549
4.379
4.197
4.140
4.033
15O + α
9/2+
2.795
19Ne

Run Plan

- ^{15}O + alpha test experiment in 2013

Energy of ^{15}O (Eth=3.529MeV)	He gas pressure	To scan Energy region up to 6 MeV
Before the window 37 MeV	0.1 atm	1500 mm (2.49 μg/cm^2)
After the window 28.6 MeV	0.5 atm	300 mm (12.5 μg/cm^2)



Expected excitation function of ^{15}O(α,α)^{15}O

Rare Isotope Accelerator

- Korea will build a RIB accelerator facility
  - KoRIA -> RAON
- Superconducting Linear Accelerator
  - various charged particles (p~U)
  - U : 200 MeV/u with 8 p microA
  - In-flight fragmentation / fission
- Cyclotron
  - Proton : 70 MeV with 1mA
  - ISOL
- Re-acceleration of RIB from ISOL

Physics Objectives

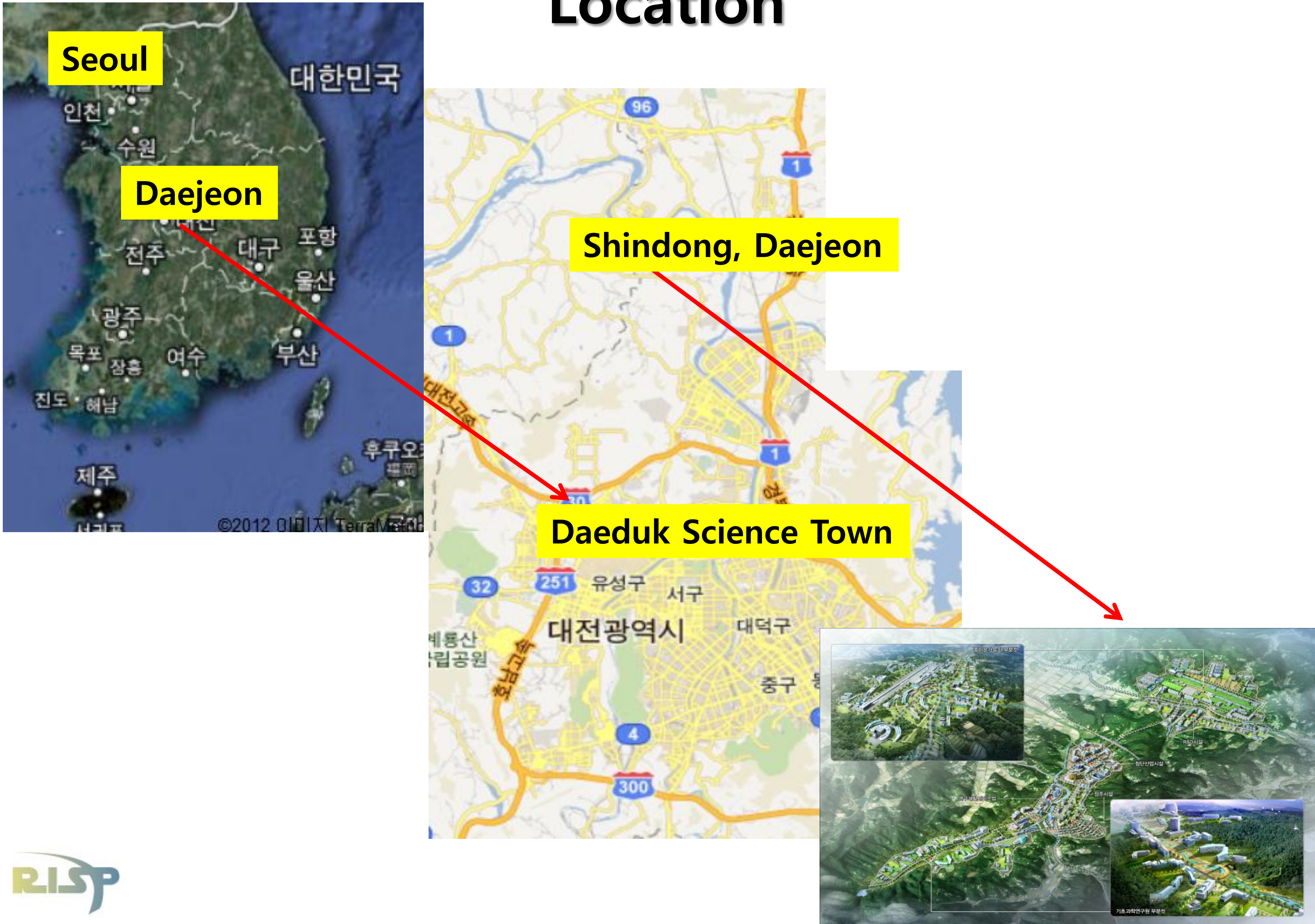
- Nuclear Physics
  - New Radioactive Isotopes
  - New, comprehensive understanding of nuclei
- Nuclear Astrophysics
  - Properties of radioactive isotopes
  - Cross section measurements with RIB
  - Origin of elements in the Universe

RISP(Rare Isotope Science Project) Status and Plan

- Conceptual Design Report (Mar. 2010 - Feb. 2011)
- IAC review (Jul. 2011 – Oct. 2011)
- Rare Isotope Science Project started in IBS (Dec. 2011)
  - Director : Prof. S. K. Kim
  - Deputy Director: Prof. Y. K. Kim
- Conceptual Design of the Building and Conventional Facilities (May 2012)
- Baseline Design Summary (by July 2012)
- Technical Design Report (by July 2013)
- Ground Breaking (2014)

From Y. K. Kim

Location



Seoul

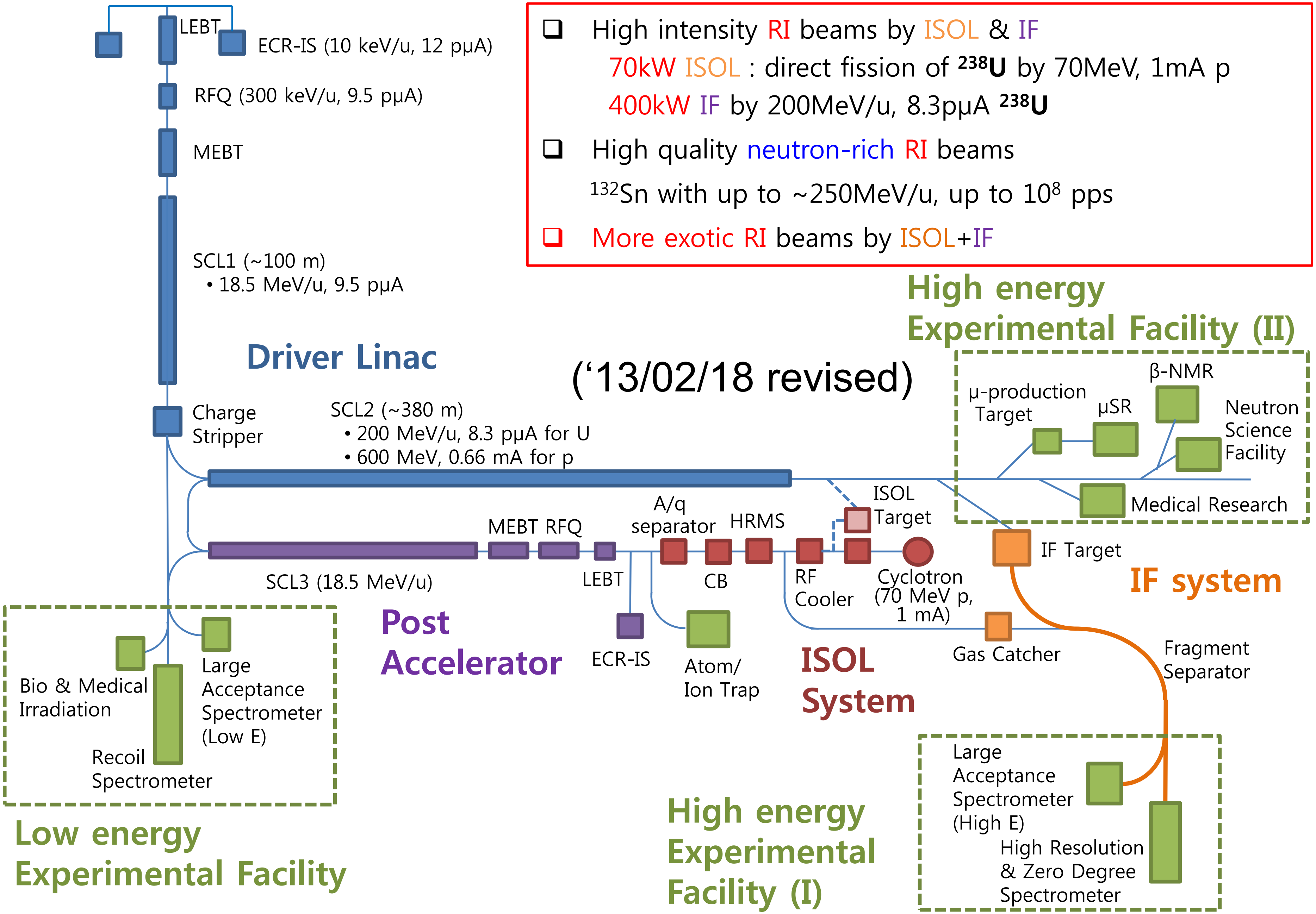
Daejeon

Shindong, Daejeon

Daeduk Science Town

RAON [raon] is the new name of the Korean Rare Isotope Accelerator

RAON : RISP Accelerator Complex



- ❑ High intensity RI beams by ISOL & IF
  - 70kW ISOL : direct fission of ^{238}**U** by 70MeV, 1mA p
  - 400kW IF by 200MeV/u, 8.3pμA ^{238}**U**
- ❑ High quality neutron-rich RI beams
  - ^{132}Sn with up to ~250MeV/u, up to 10^8 pps
- ❑ More exotic RI beams by ISOL+IF

('13/02/18 revised)

Accelerator System

Beam Requirement of Accelerator System

Accelerator	Driver Linac		Post Acc.	Cyclotron
Particle	proton	U^{+79}	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

From Y. K. Kim

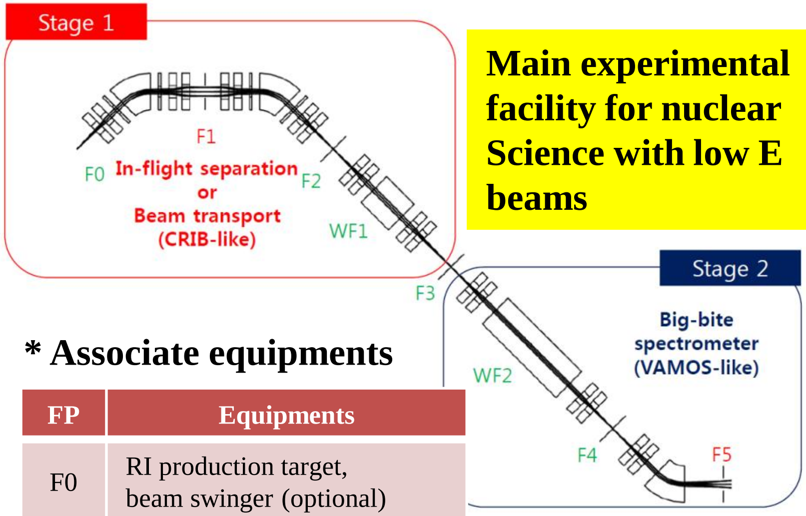
From Y. K. Kwon

KOBRA (KOrea Broad acceptance Recoil spectrometer and Apparatus)

KOBRA
High performance
spectrometer with detection system

@

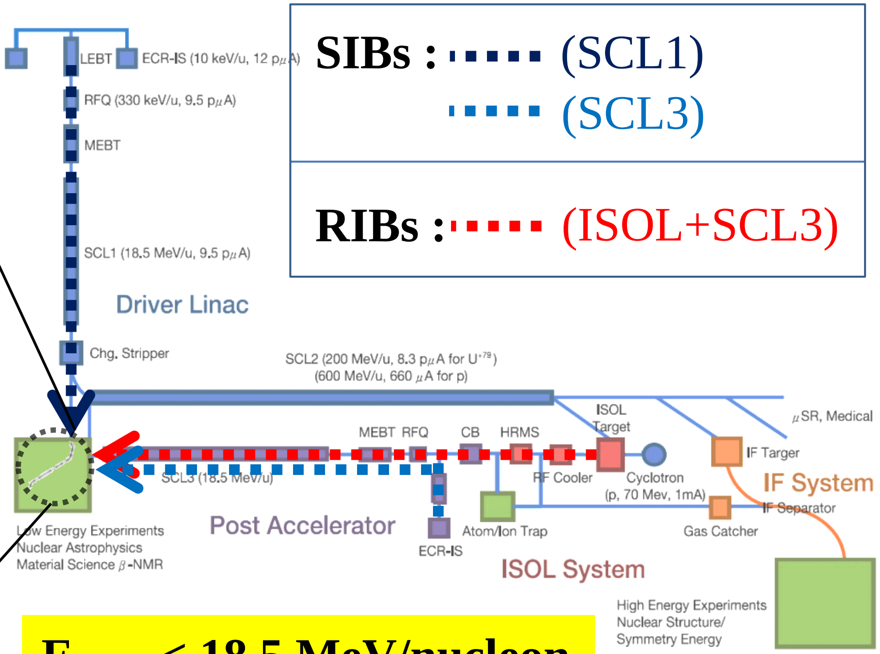
RAON
High quality & Low Energy
stable and radioactive ion beams



Main experimental facility for nuclear Science with low E beams

*** Associate equipments**

FP	Equipments
F0	RI production target, beam swinger (optional)
F3	gas-jet target, gamma-array, detection system, β-NMR
F5	Focal plane detection system



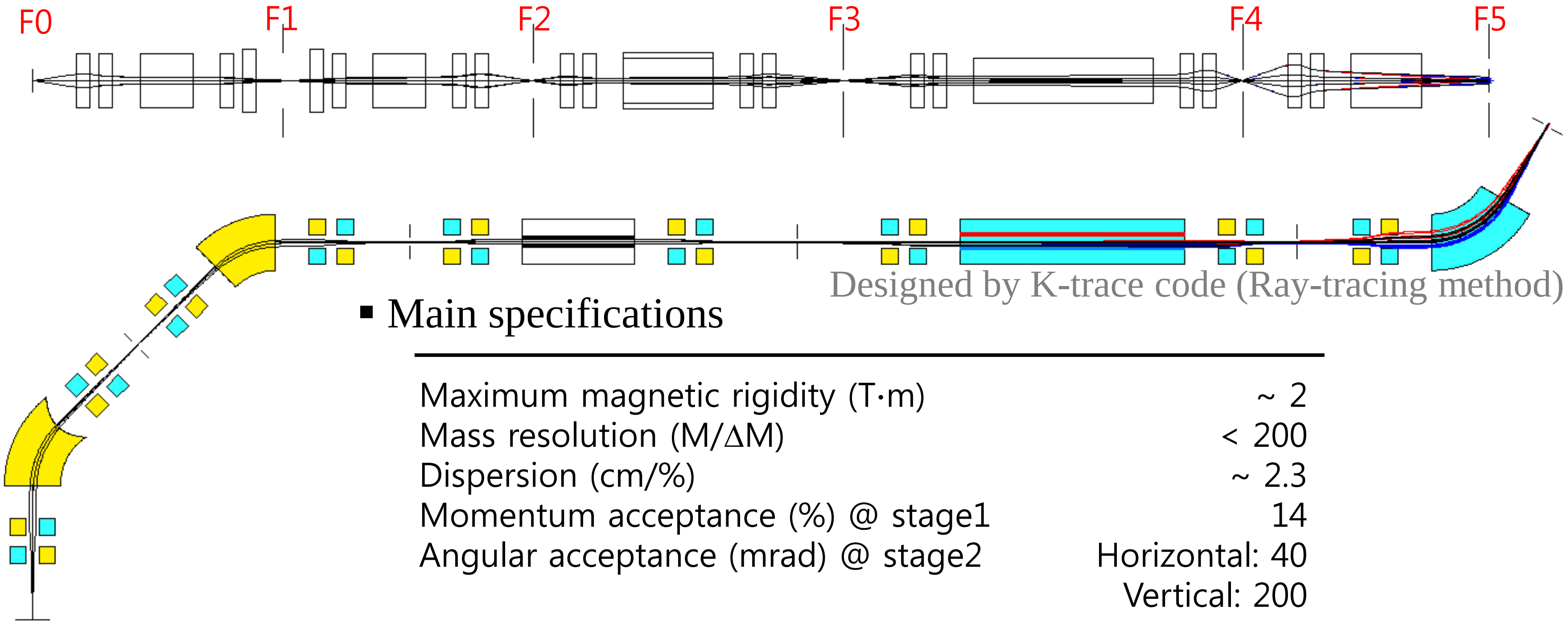
SIBs : ▪▪▪▪▪ (SCL1)
▪▪▪▪▪ (SCL3)

RIBs : ▪▪▪▪▪ (ISOL+SCL3)

$E_{beam} < 18.5$ MeV/nucleon

From Y. K. Kwon

Concept of the KOBRA



Designed by K-trace code (Ray-tracing method)

- Main specifications

Maximum magnetic rigidity (T·m)	~ 2
Mass resolution (M/ΔM)	< 200
Dispersion (cm/%)	~ 2.3
Momentum acceptance (%) @ stage1	14
Angular acceptance (mrad) @ stage2	Horizontal: 40 Vertical: 200

- Two stage
  - Stage 1 (F0~F3) : Production and separation of RIBs via In-Flight method with high intensity SIBs from LINAC
  - Stage 2 (F3~F5) : Big-bite spectrometer with Wien filter

- Secondary target is located at F3
  - Enough space around F3 (~3m) : In-beam gamma-ray spectroscopy, symmetry energy, SHE, spin physics, charged particle spectroscopy etc

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

✧ Motivation

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

  : breakout path from hot-CNO to rp-process

  : key reaction to understand nucleosynthesis under explosive stellar environments

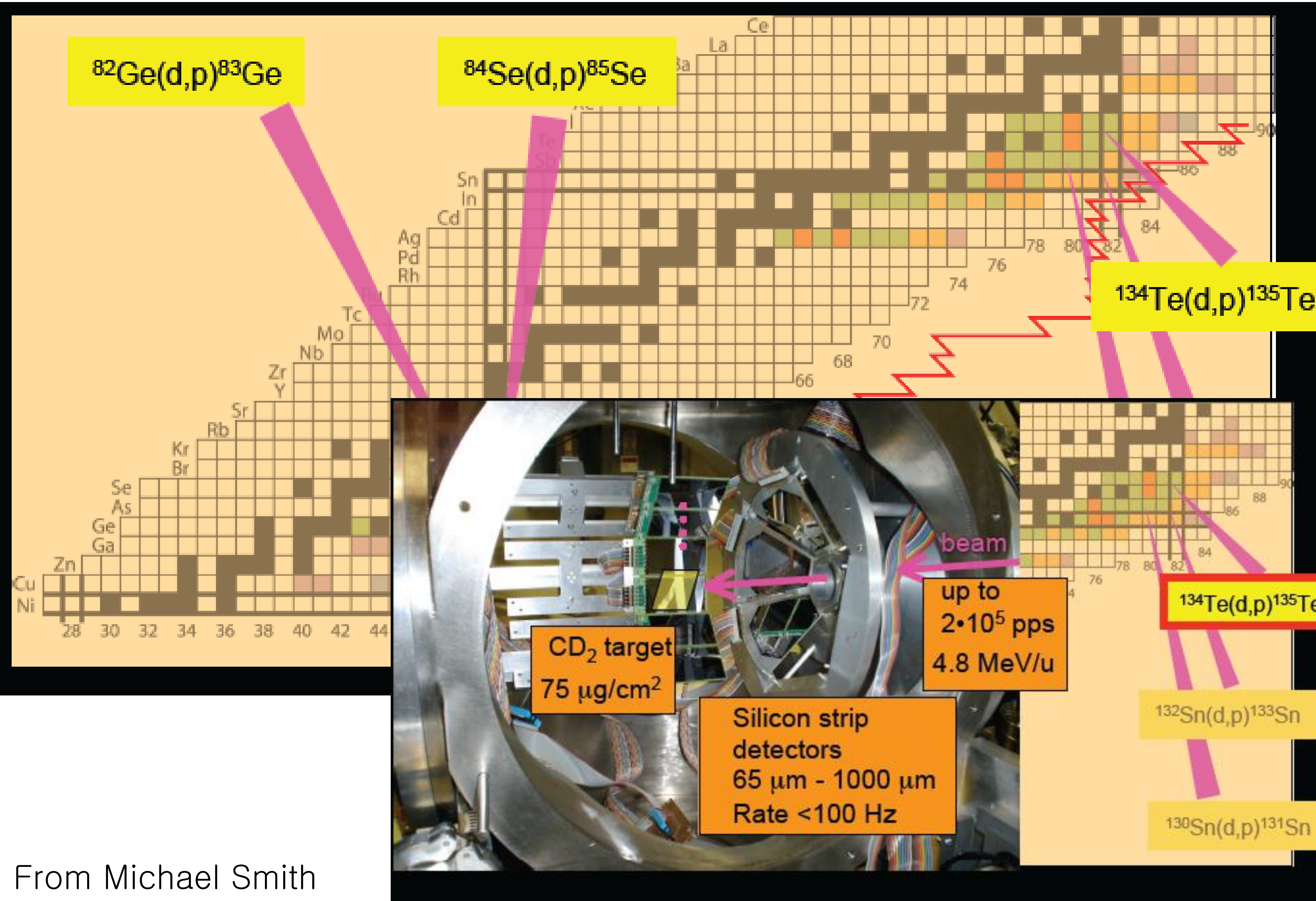
✧ Experimental Challenges

- For direct measurement of cross section we need

  : ^{15}O RI beam intensity > 10^{10}pps, Helium-4 target density > 10^{18} atoms/cm^2, recoil detection efficiency > 40% → **then ~1 counts/hr**

Measurement	Required RIB intensity	Beam production	Expected outputs
^{15}O+alpha : elastic scatt.ering	> 10^6 pps	IF @KOBRA	Resonant parameters
$^{15}O(^6Li,d)^{19}Ne$: alpha transfer reaction	> 10^8 pps	IF @KOBRA	Spectroscopic factors from angular distribution
Direct measurement	> 10^{10} pps	ISOL	Reaction rates **(final goal!!)**

r-process reactions



$^{82}Ge(d,p)^{83}Ge$

$^{84}Se(d,p)^{85}Se$

$^{134}Te(d,p)^{135}Te$

$^{132}Sn(d,p)^{133}Sn$

$^{130}Sn(d,p)^{131}Sn$

beam

up to
$2 \cdot 10^5$ pps
4.8 MeV/u

CD_2 target
75 $\mu g/cm^2$

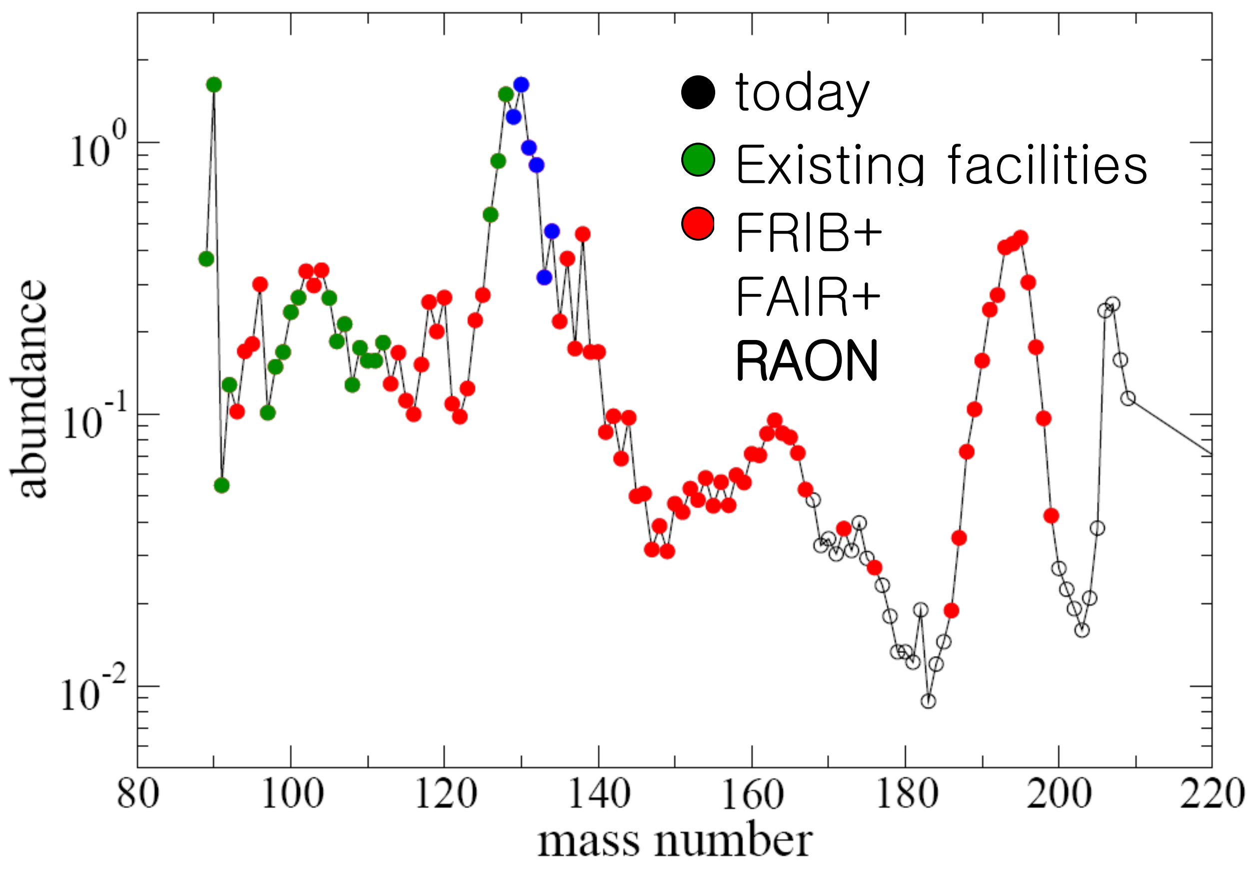
Silicon strip
detectors
65 μm - 1000 μm
Rate <100 Hz

From Michael Smith

New Era due to RIB Facilities

At present, except for a few cases (blue), output of models cannot be matched to measured abundances.

Future RIB facilities will allow one to constrain r-process models using abundance data



A colored dot means that the relevant

could be measured.

Constrain r-process environment by comparison of simulations with observation!

From Langanke

Summary

- Alpha resonant scattering ^{14}O, and direct measurements of ^{17}F(p,α) and ^{14}O(α,p) were successfully performed using radioactive ion beams.

- Measurements using RI beams will give us a deeper understanding of explosive stellar sites
  - X-ray burst, novae, supernovae etc

- There will be a lot of opportunities for nuclear astrophysics at RAON