The 2nd RISP Intensive Program on
"Rare Isotope Physics"
July 7, 2017

Nuclear Astrophysics with RI beams Lecture #2

Insik Hahn

Ewha Womans University

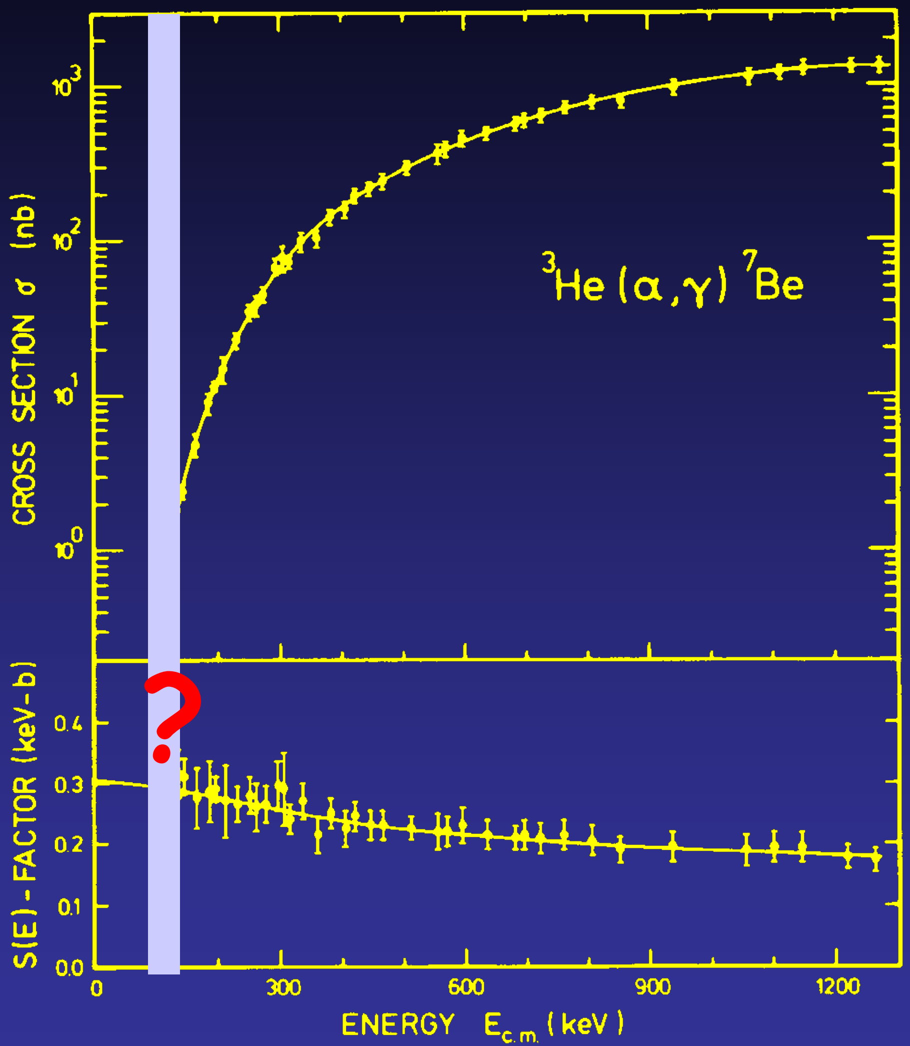
Revised rates for the stellar triple-α process from measurement of ^{12}C nuclear resonances

Hans O. U. Fynbo[1], Christian Aa. Diget[1], Uffe C. Bergmann[2], Maria J. G. Borge[3], Joakim Cederkäll[2], Peter Dendooven[4], Luis M. Fraile[2], Serge Franchoo[2], Valentin N. Fedosseev[2], Brian R. Fulton[5], Wenxue Huang[6], Jussi Huikari[6], Henrik B. Jeppesen[1], Ari S. Jokinen[6,7], Peter Jones[6], Björn Jonson[8], Ulli Köster[2], Karlheinz Langanke[1], Mikael Meister[8], Thomas Nilsson[2], Göran Nyman[8], Yolanda Prezado[3], Karsten Riisager[1], Sami Rinta-Antila[6], Olof Tengblad[3], Manuela Turrion[3], Youbao Wang[6], Leonid Weissman[2], Katarina Wilhelmsen[8], Juha Äystö[6,7] & The ISOLDE Collaboration[2]

[1] *Department of Physics and Astronomy, University of Aarhus, 8000 Århus C, Denmark*
[2] *CERN, CH-1211 Geneva 23, Switzerland*
[3] *Instituto Estructura de la Materia, CSIC, Serrano 113bis, E-28006, Madrid, Spain*
[4] *KVI, Zernikelaan, 9747 AA Groningen, The Netherlands*
[5] *Department of Physics, University of York, Heslington, YO10 5DD, UK*
[6] *Department of Physics, University of Jyväskylä, FIN-40351 Jyväskylä, Finland*
[7] *Helsinki Institute of Physics, FIN-00014 University of Helsinki, Finland*
[8] *Experimental Physics, Chalmers University of Technology and Göteborg University, S-41296 Göteborg, Sweden*

In the centres of stars where the temperature is high enough, three α-particles (helium nuclei) are able to combine to form ^{12}C because of a resonant reaction leading to a nuclear excited state[1]. (Stars with masses greater than ~0.5 times that of the Sun will at some point in their lives have a central temperature high enough for this reaction to proceed.) Although the reaction rate is of critical significance for determining elemental abundances in the

The astrophysical S-factor



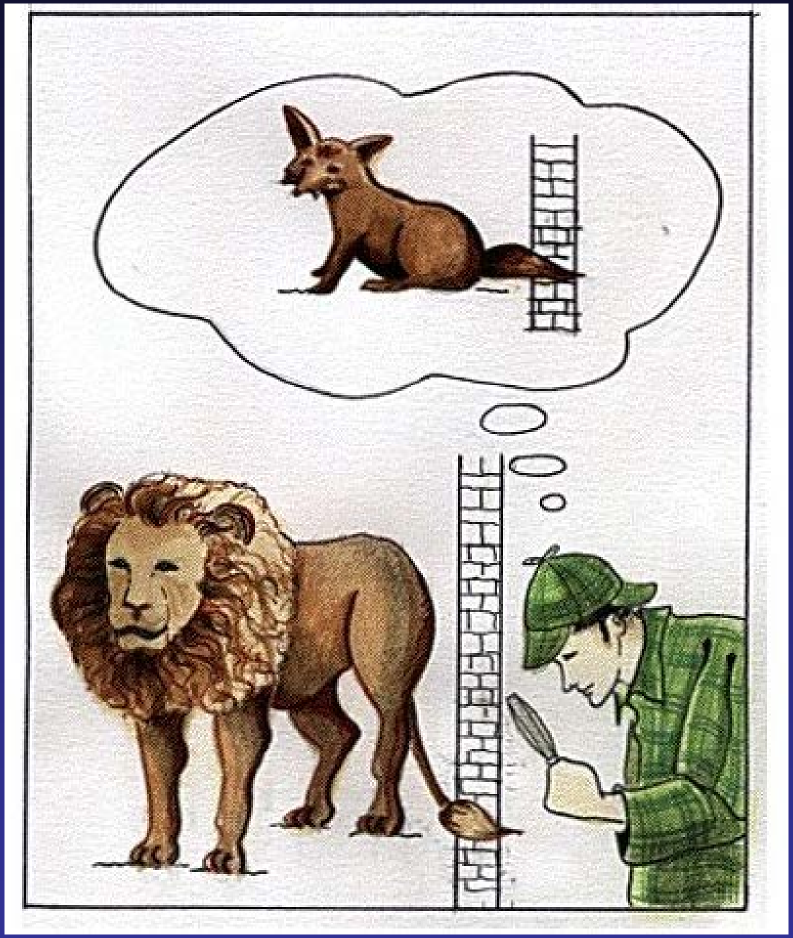
$$\sigma(E) = S(E)\cdot \exp(-2\pi\eta)\,/E$$

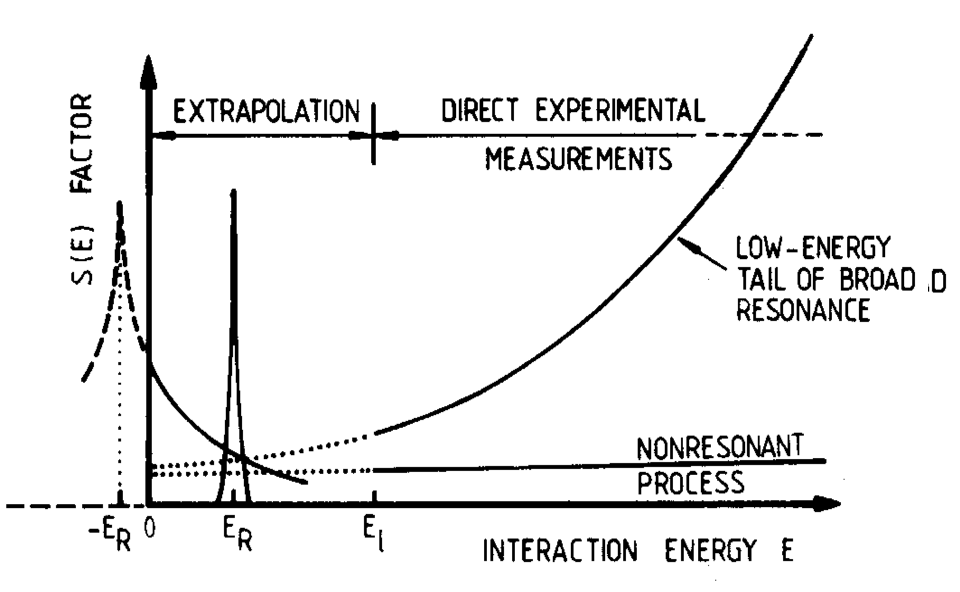
$$S(E) = E\cdot\sigma(E)\cdot\exp(2\pi\eta)$$

$$2\pi\eta = 31.29\, Z_1 Z_2 (\mu/E)^{0.5}$$

extrapolation is needed....

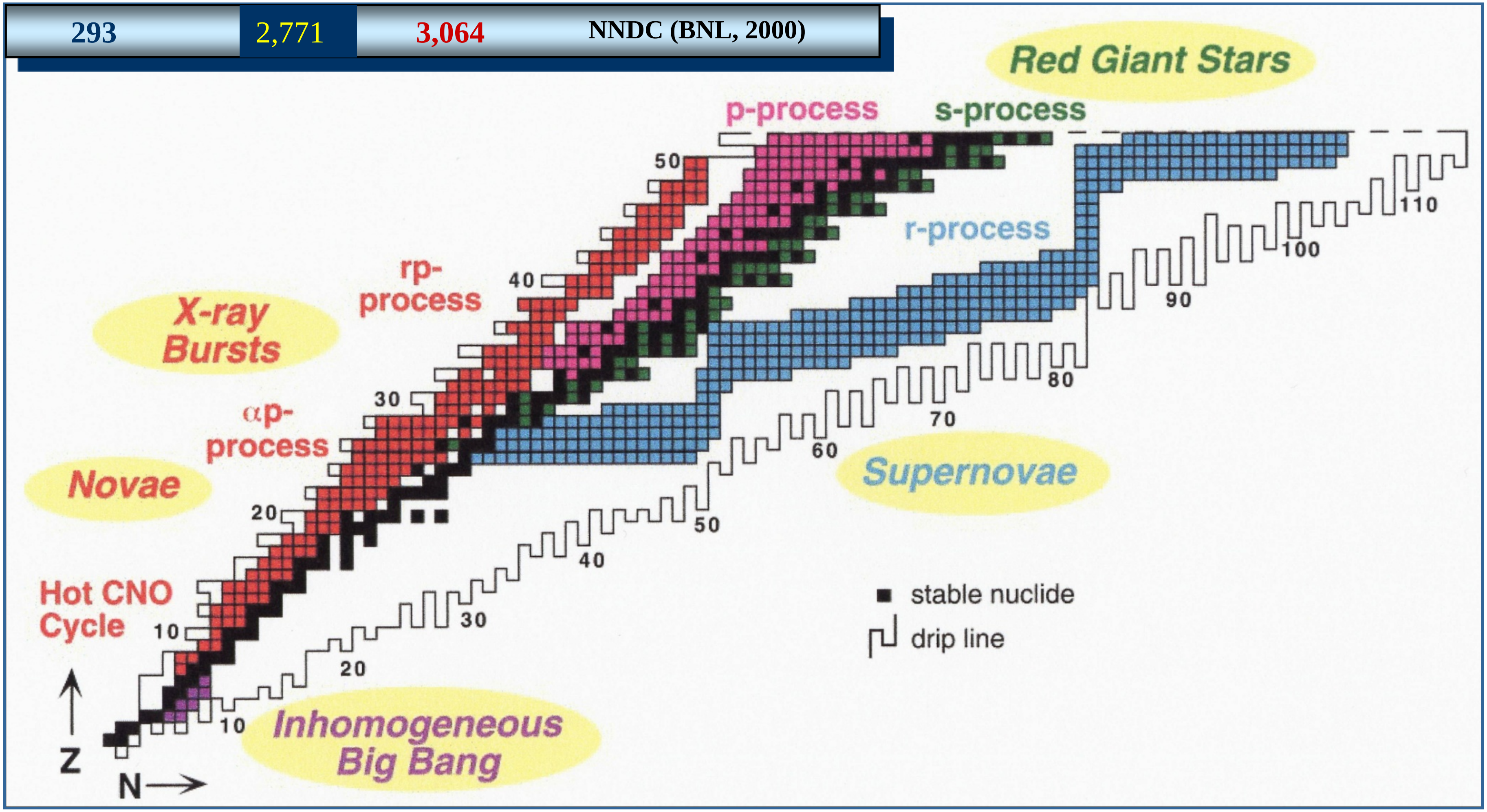
but...





sometimes extrapolation fails !!

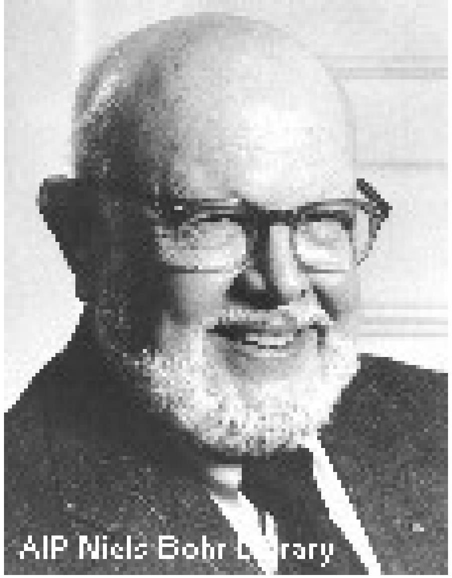
M.S. Smith and K.E. Rehm,
Ann. Rev. Nucl. Part. Sci, 51 (2001)



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

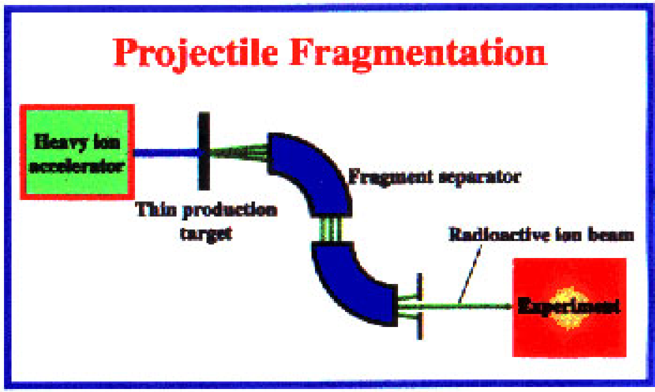
1985 by Fowler (Nobel prize 1983)

- "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."



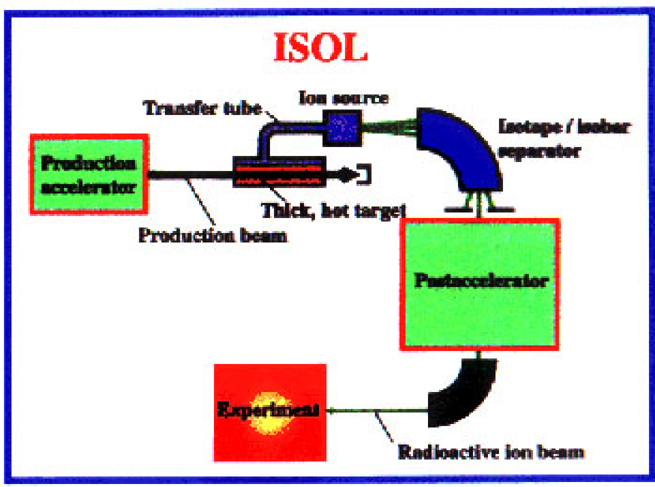
John M. D'Auria

Production of Radioactive Ion Beams



In-Flight Fragmentation
(heavy ion energetic beams)

- GSI (Germany)
- NSCL (USA)
- RIKEN (Japan)
- GANIL (France



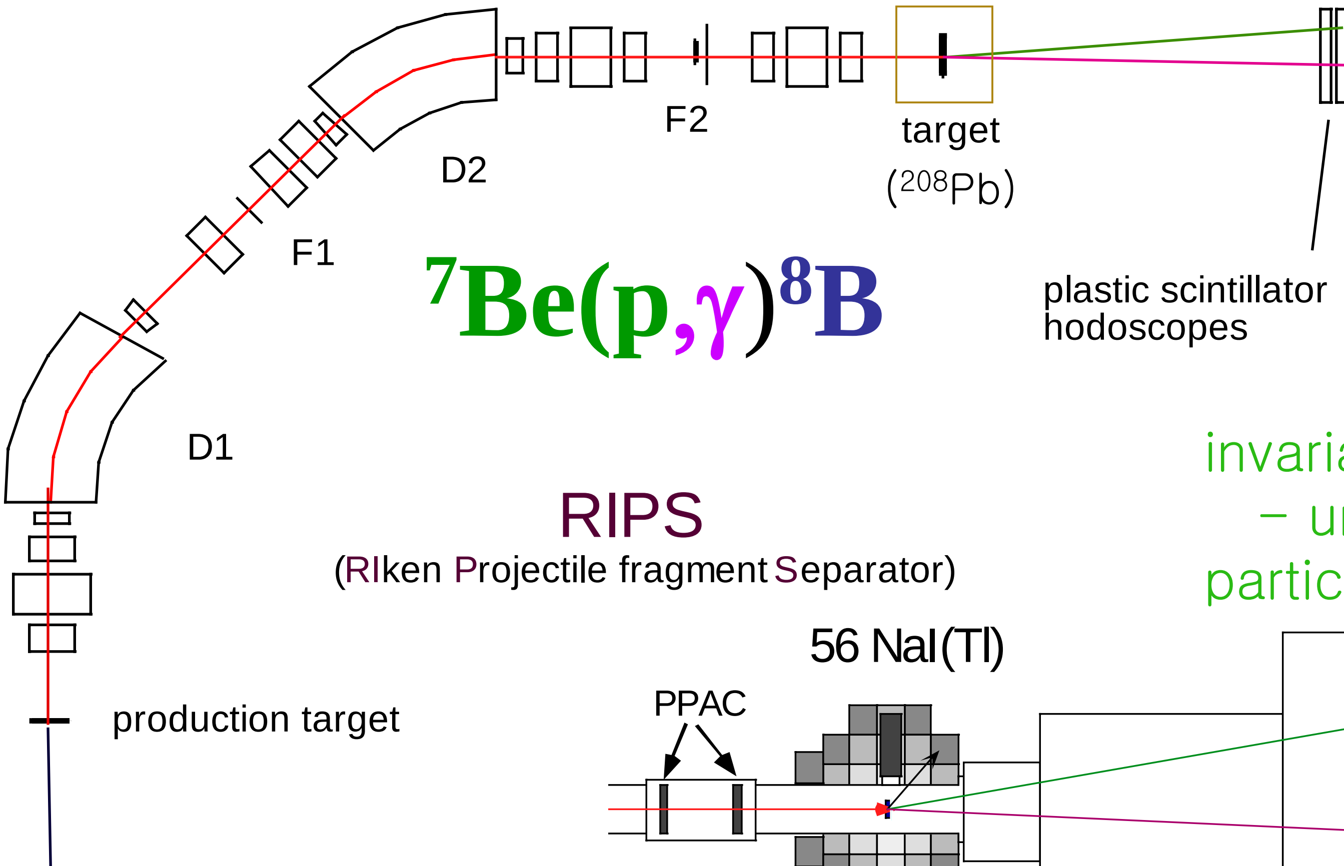
ISOL Method
(2 accelerators)

ISOLDE (Cern)
Louvain (Belgium)
ISAC (Canada)
HRIBF (ORNL)
SPIRAL (France)
Jyvaskala (Finland)

TAMU,UND

^{8}B CD Experiment at RIKEN

50 – 90 MeV/nucleon



^{7}Be(p,γ)^{8}B

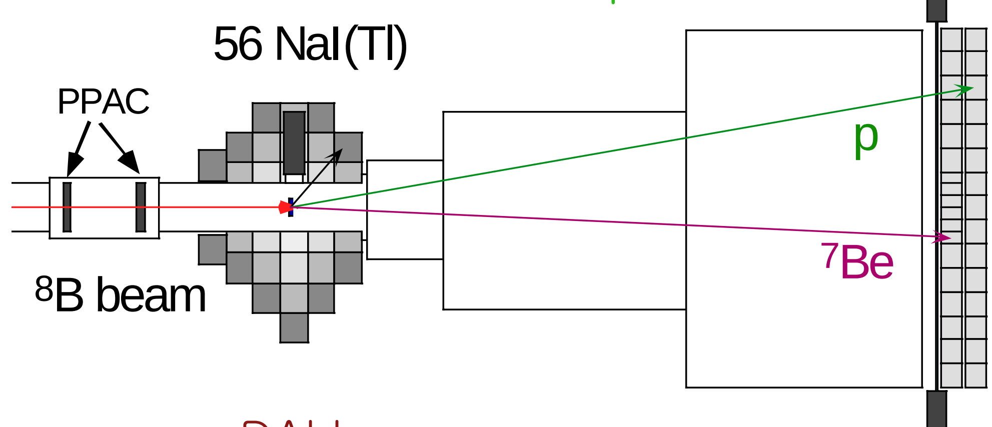
RIPS

(RIken Projectile fragment Separator)

invariant mass

– unbound states

particle ID



strong (light) RI beams

DALI

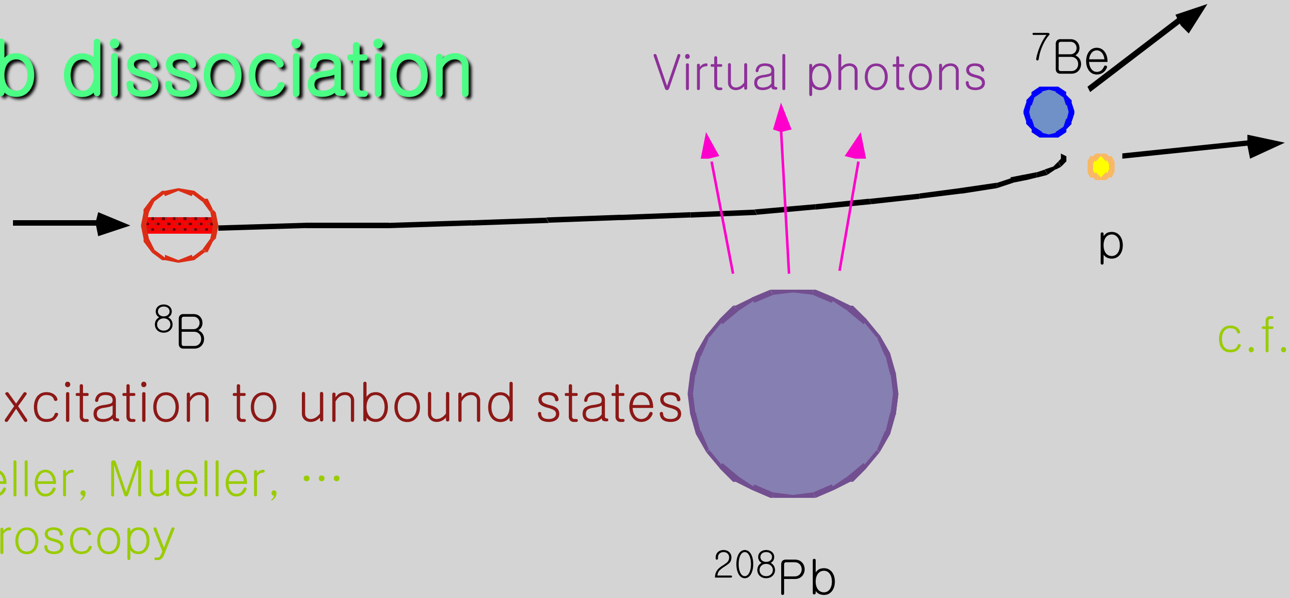
γ ray

– bound states

HODO

Oct 2005

Coulomb dissociation



= Coulomb excitation to unbound states

c.f. Mueller, Mueller, …
spectroscopy

c.f. Nakamura
halo nuclei

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

↓ virtual photon theory or DWBA

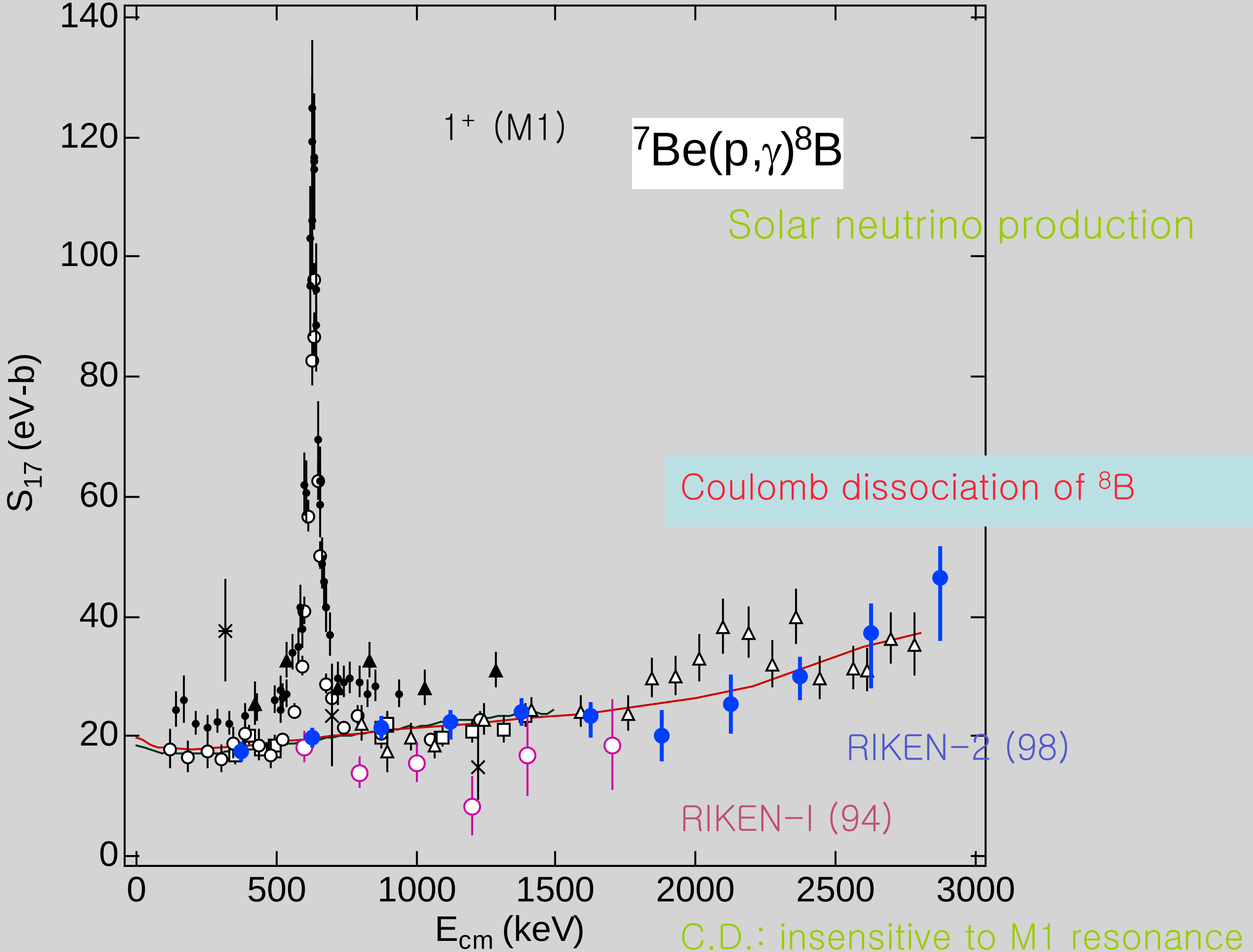
^{8}B(γ,p)^{7}Be (abs.)

↓ detailed balance

^{7}Be(p,γ)^{8}B (capt.)

large σ
thick target (intermediate energy)

experiments with R.I. beams



C.D.: insensitive to M1 resonance

Selected Experiments with RIB

Astrophysically Important Nuclear Reactions

$^{7}Be(p,\gamma)^{8}B$

$^{8}Li(\alpha,n)^{11}B$

$^{12}C(\alpha,\gamma)^{16}O$

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

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

$^{17,18}F(p,\alpha)^{14,15}O$

$^{25}Al(p,\gamma)^{26}Si$

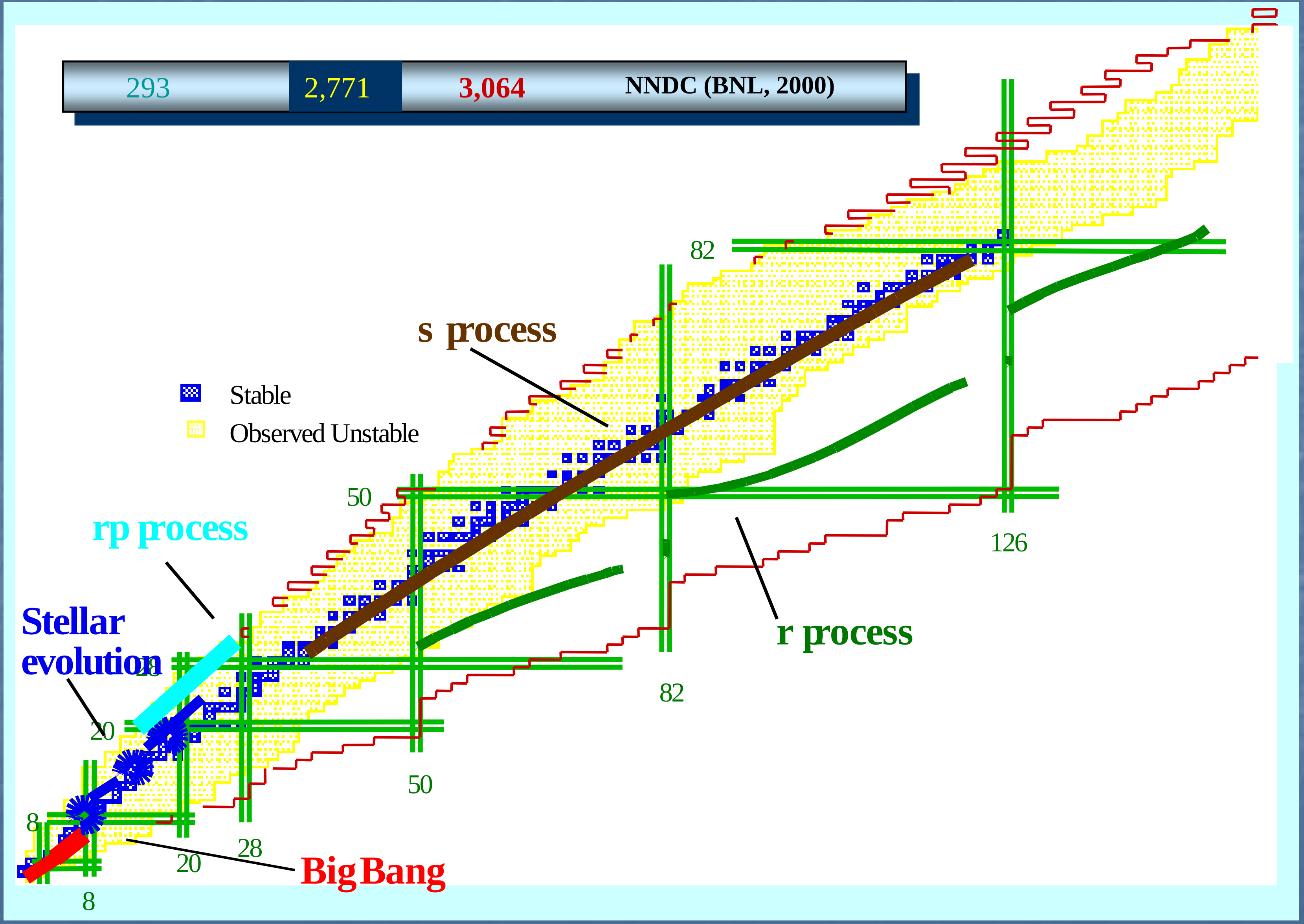
$^{56}Ni(p,\gamma)^{57}Cu$

$^{85}Kr(n,\gamma)^{86}Kr$

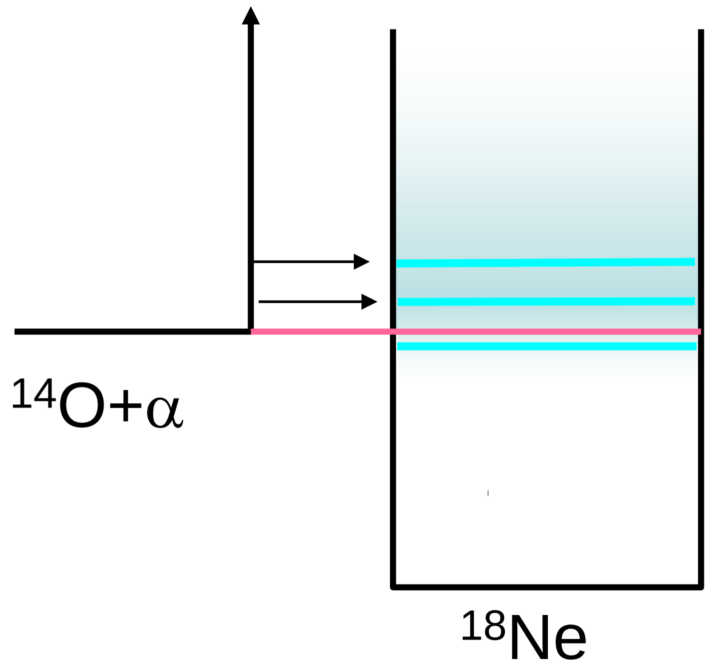
$^{134}Cs(n,\gamma)^{135}Cs$

...

별에서 핵합성(Nucleosynthesis)



Break-out: $^{14}O(\alpha,p)$

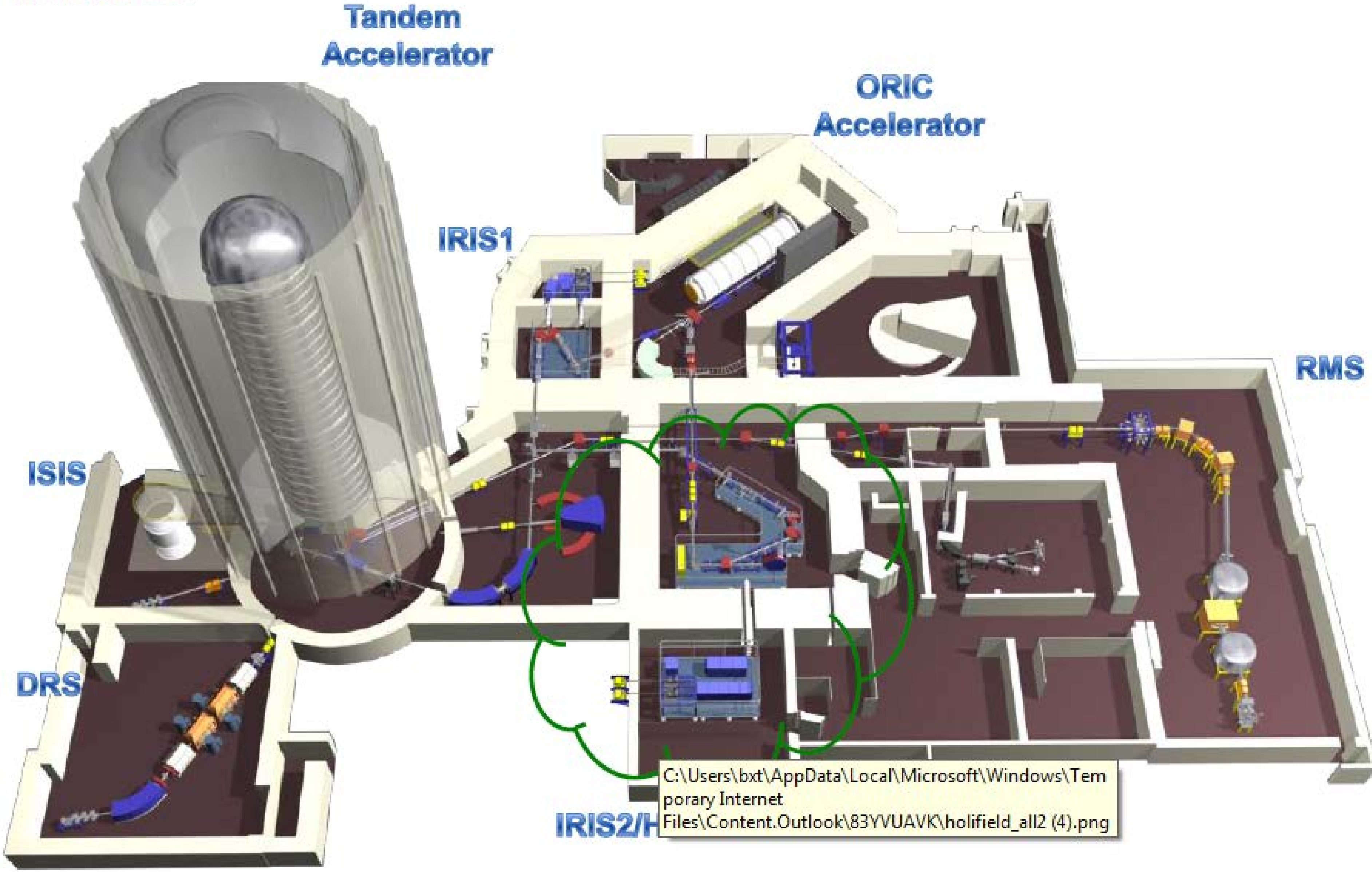


$^{14}O(\alpha,p)^{17}F$ $^{17}F(p,\alpha)^{14}O$ $^{17}F(p,p)^{17}F$

Measurements

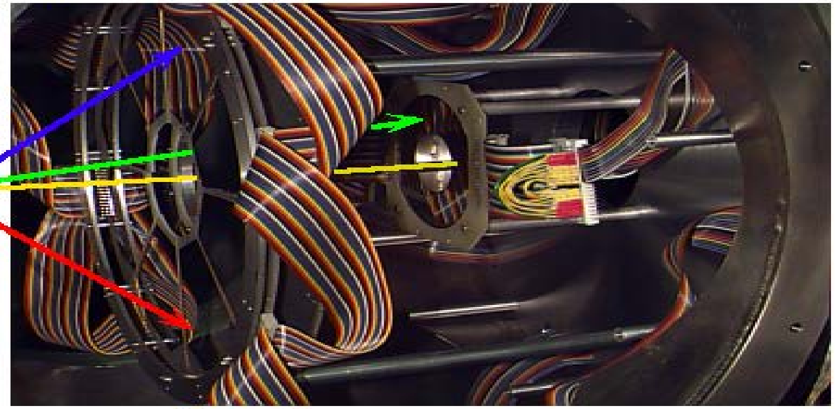
- Direct measurements are desirable ways to measure the $^{15}O(\alpha,\gamma)^{19}Ne$ and $^{14}O(\alpha,p)^{17}F$ reactions over indirect methods.
- Only became possible after new generation of accelerators that can make $^{14,15}O$ and ^{17}F beams in the late 90's.
- There are still large uncertainties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

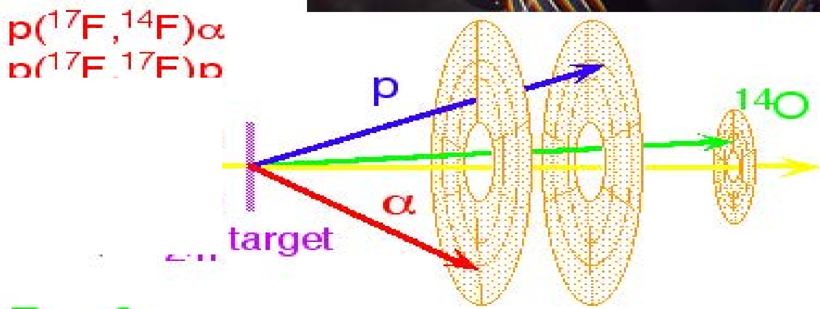
HRIBF

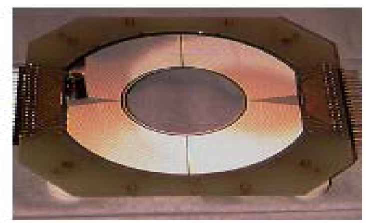


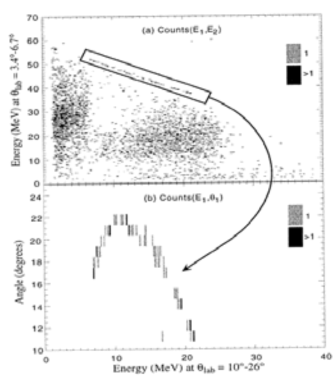
Tandem Accelerator
ORIC Accelerator
IRIS1
RMS
ISIS
DRS
IRIS2/H
C:\Users\bxt\AppData\Local\Microsoft\Windows\Temporary Internet Files\Content.Outlook\83YVUAVK\holifield_all2 (4).png

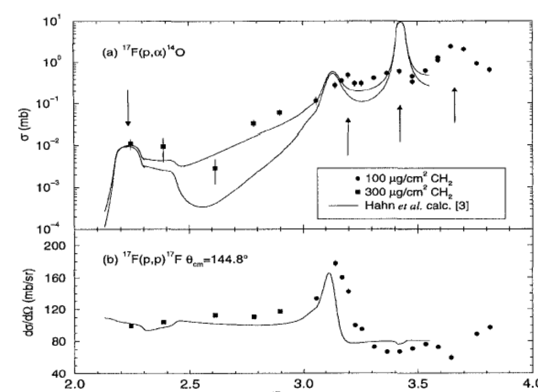
p(^{17}F,^{14}O)α Experiment at ORNL





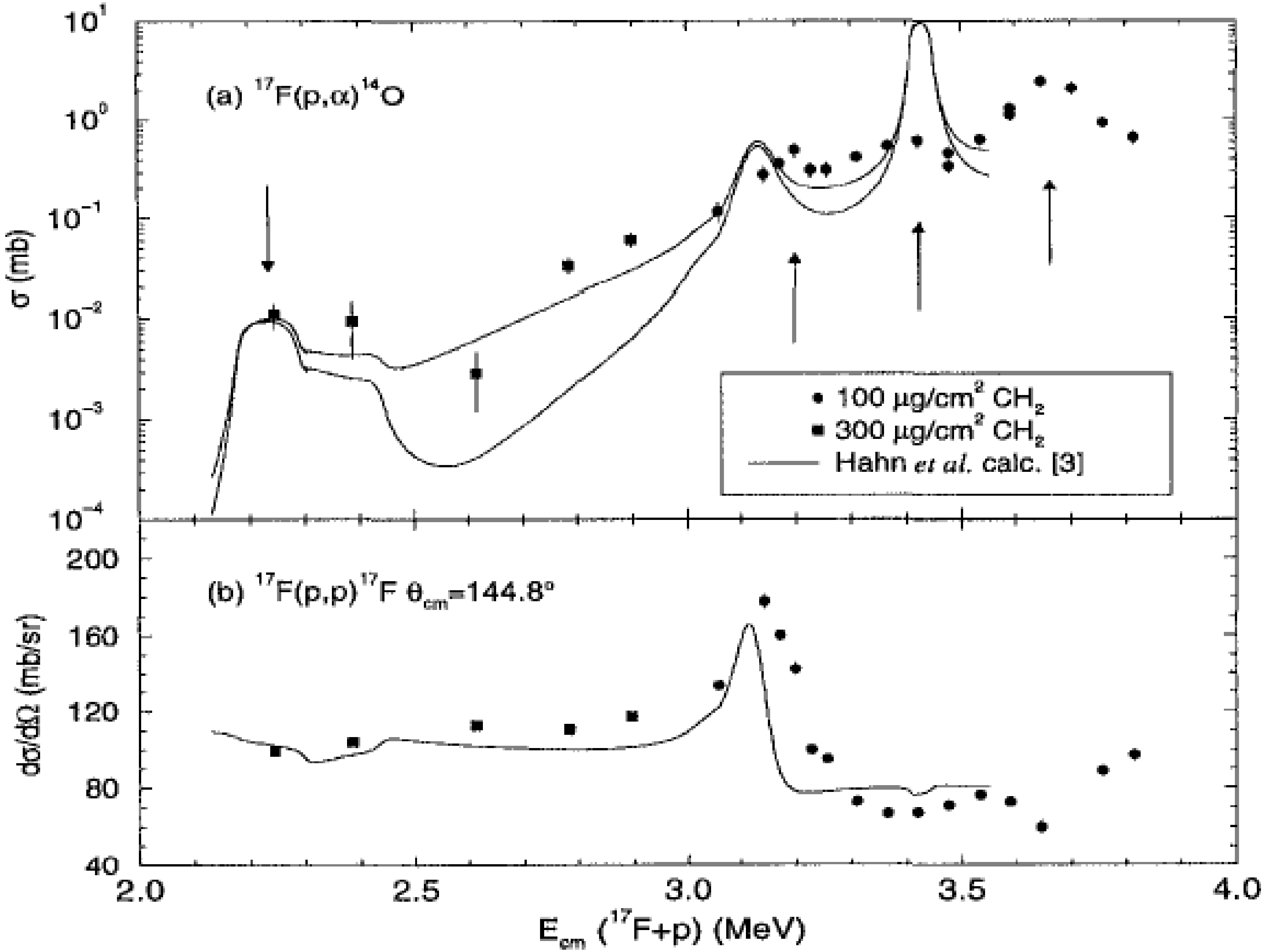






Performance

- Completed RIB experiments: ^{17,18}F(p,p), ^{17,18}F(p,α), ^{17}F(p,p')
- High Energy Resolution, Low Backgrounds

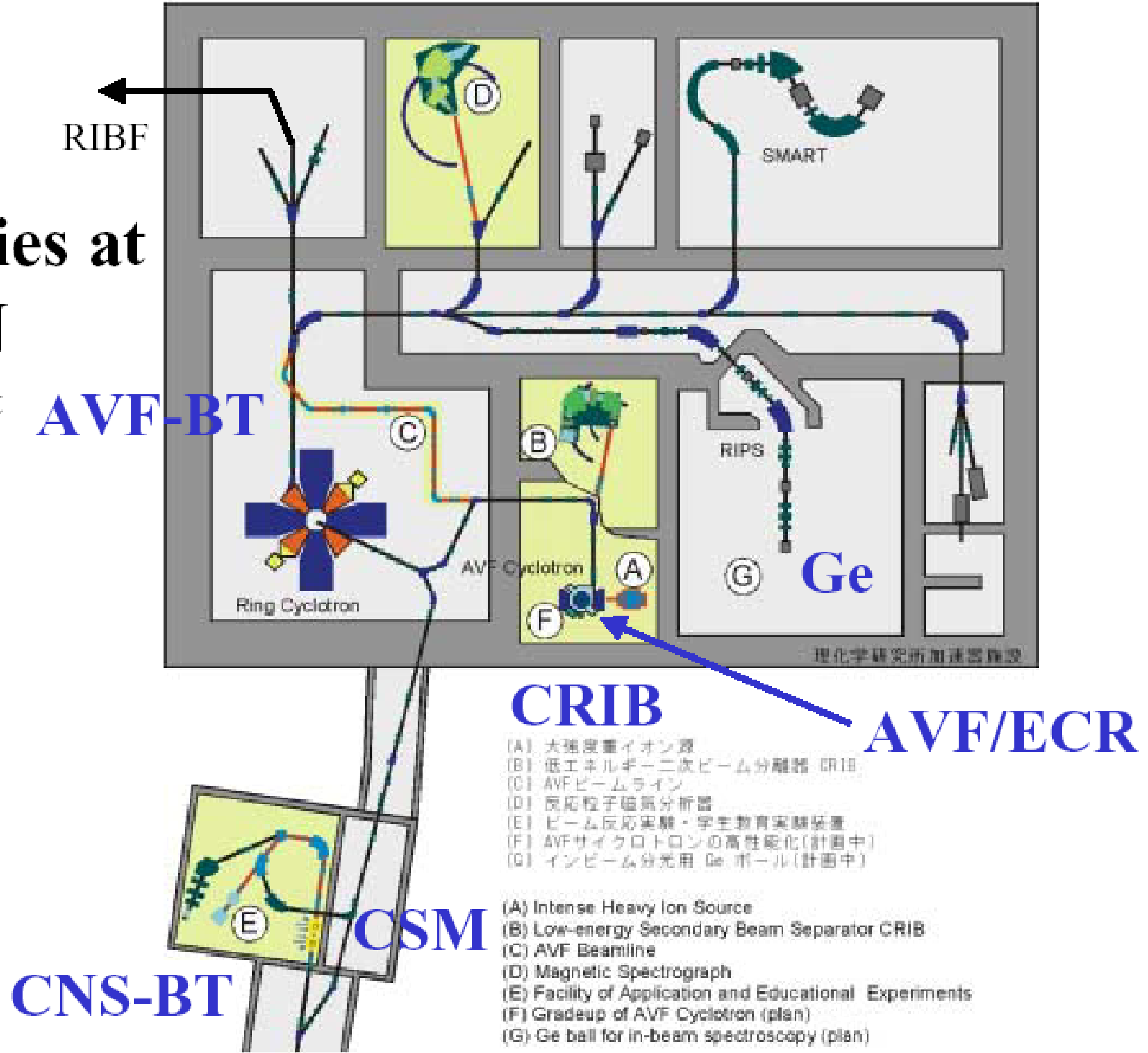


Blackmon et al. @Oak Ridge

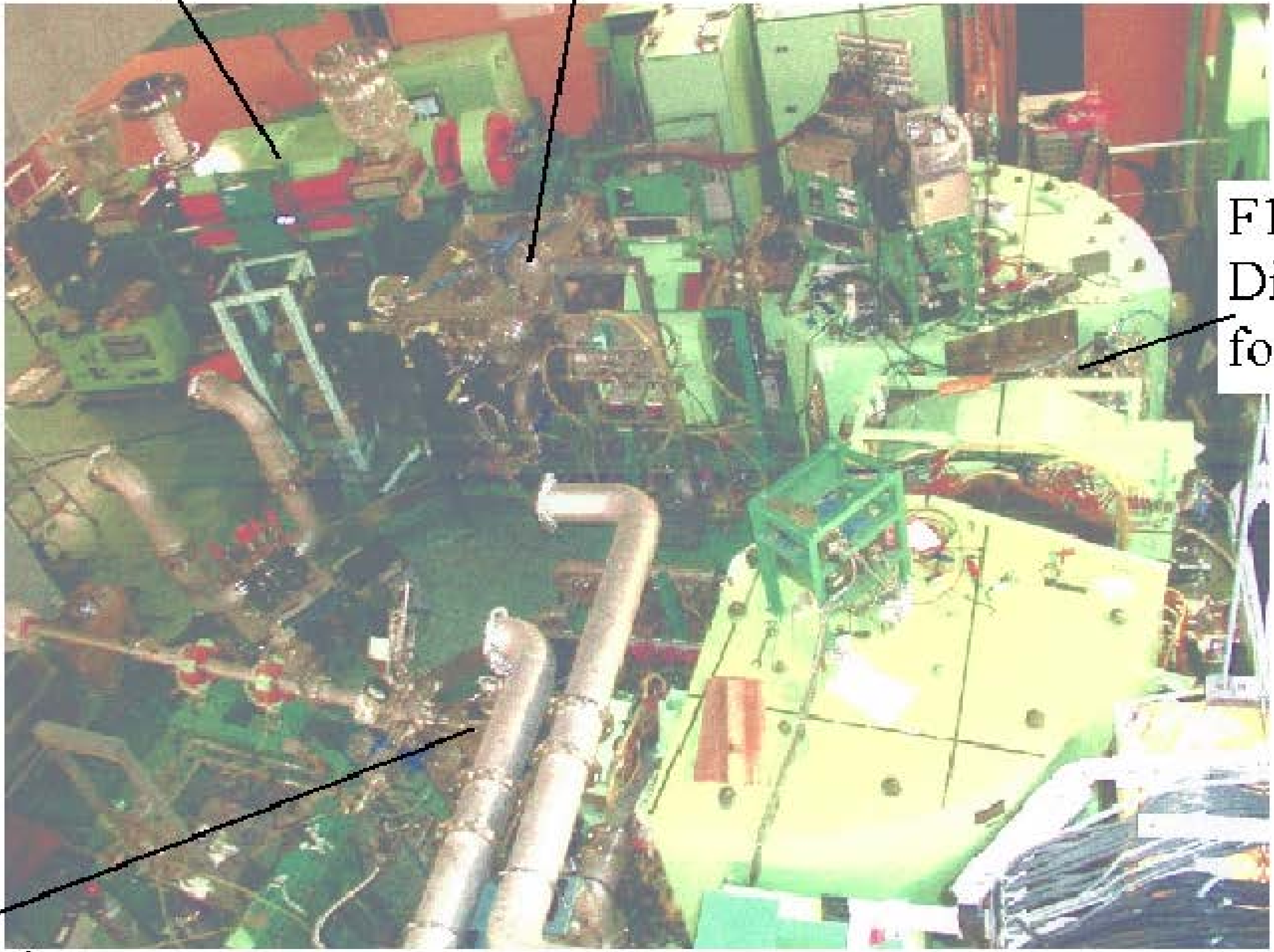
일본 이화학연구소 가속기 시설

CNS Facilities at RIKEN

(Under CNS-RIKEN joint venture)

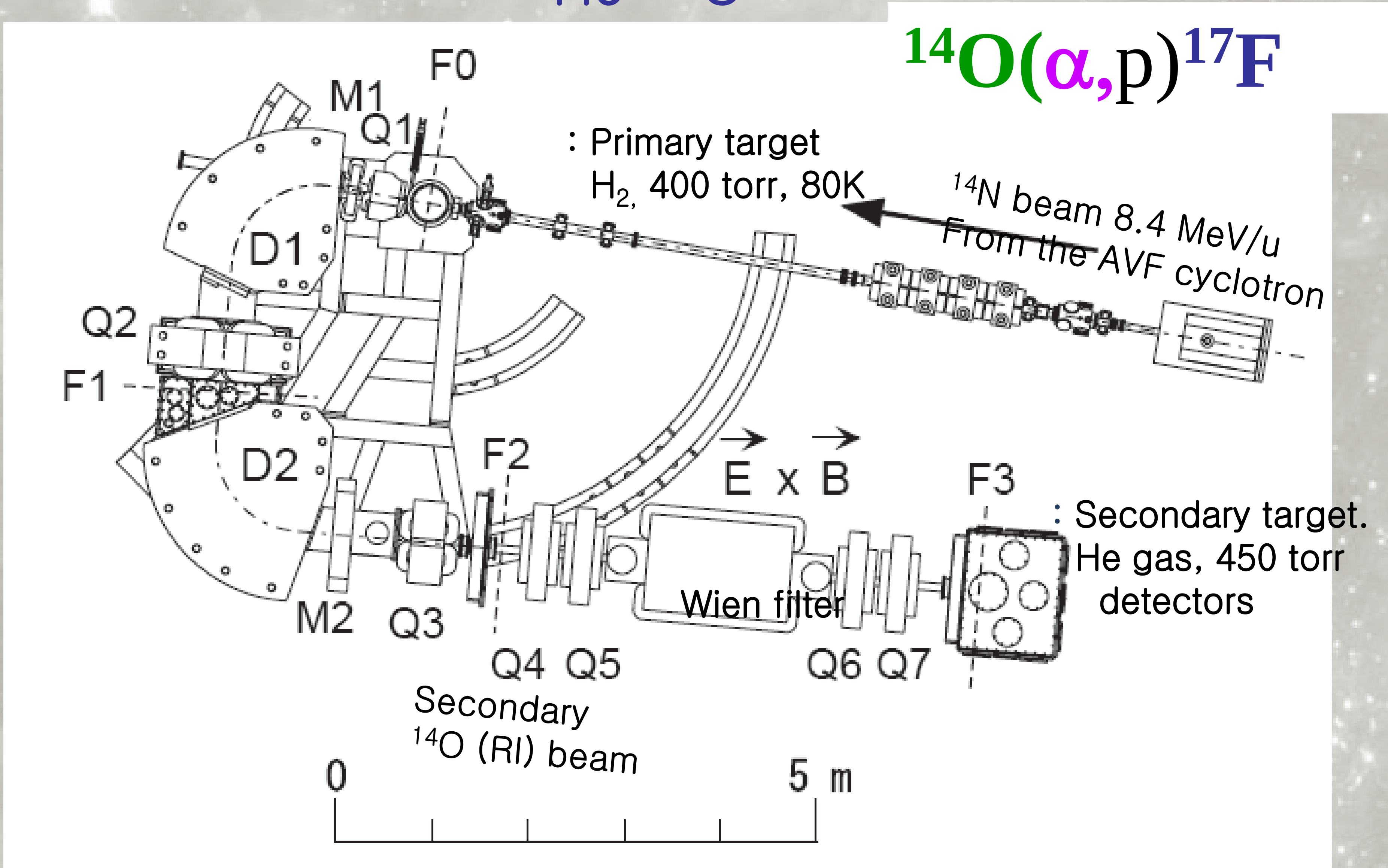


CNS RIB Separator (CRIB)

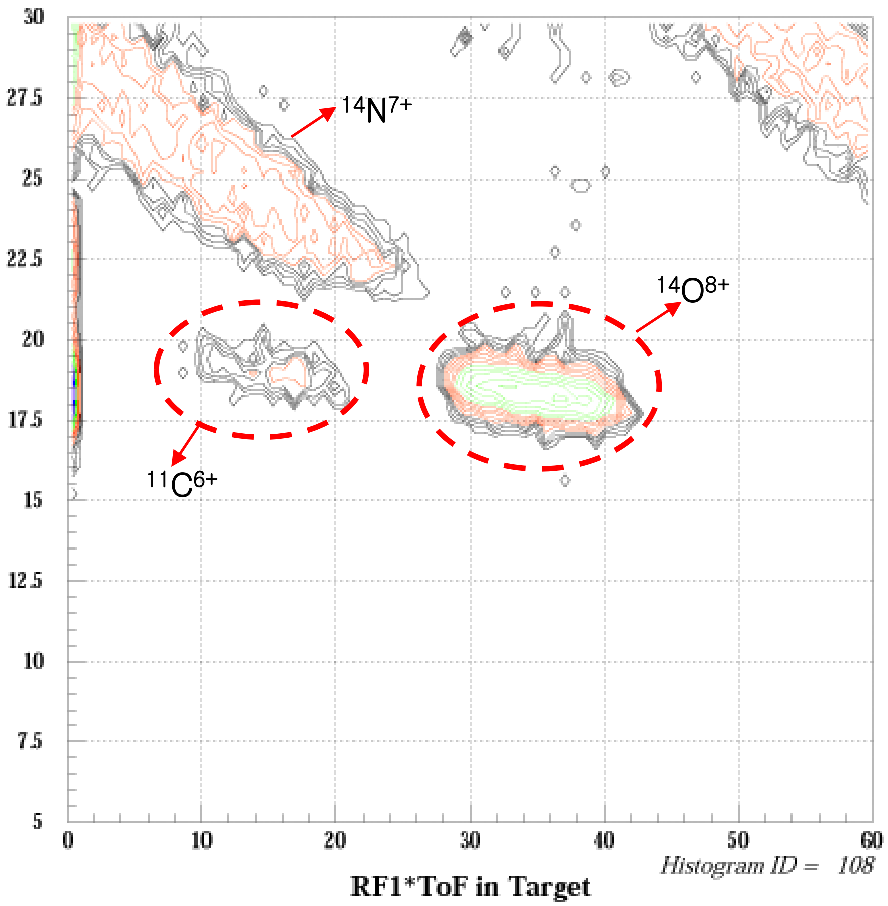


Recent RIB Experiment at CNS

$^{4}He + ^{14}O$



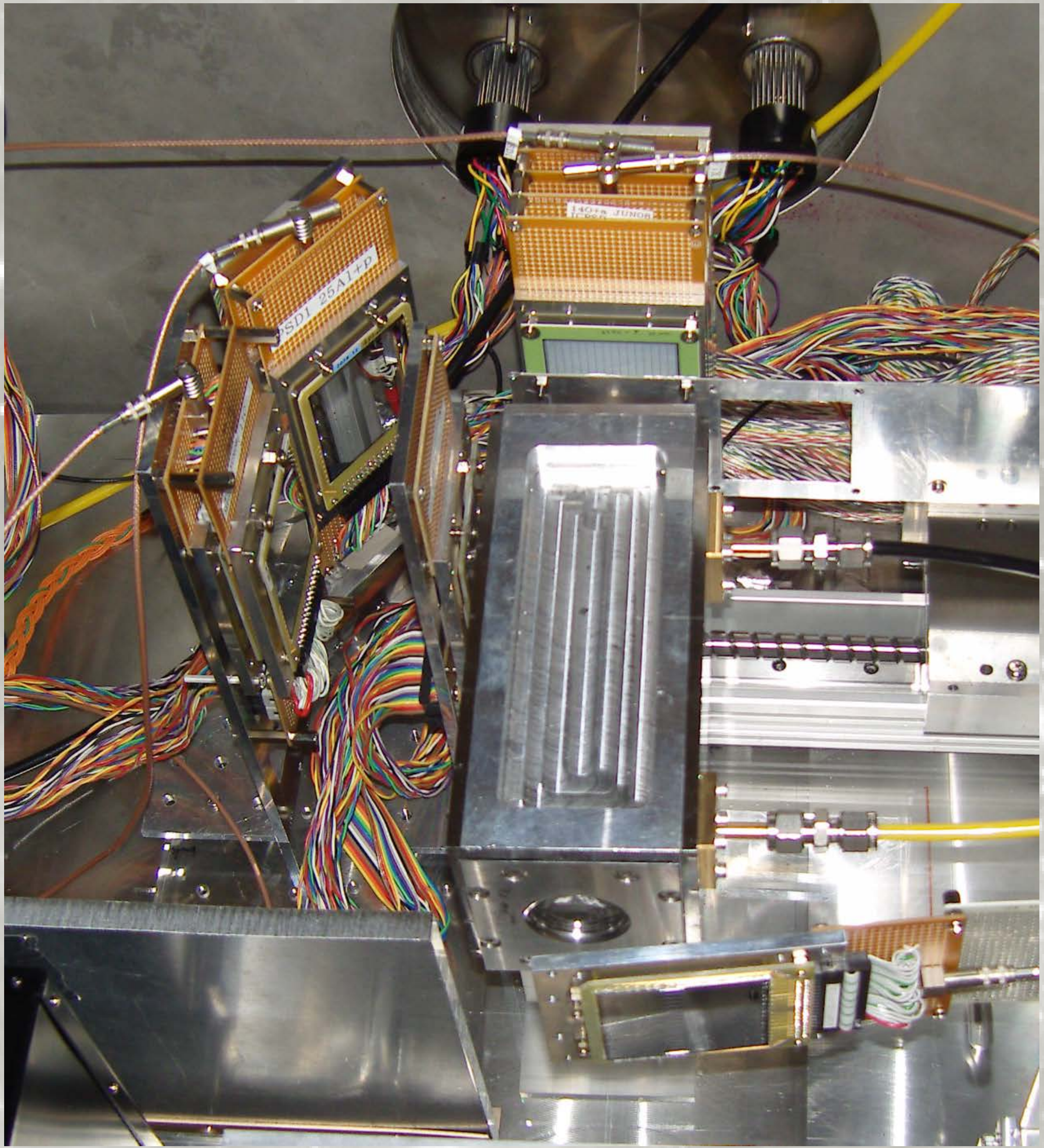
Separation of secondary beam



Two dimensional plot of
RF1 vs TOF at F3

^{14}O beam was distinguished very cleanly.

He target & Detectors



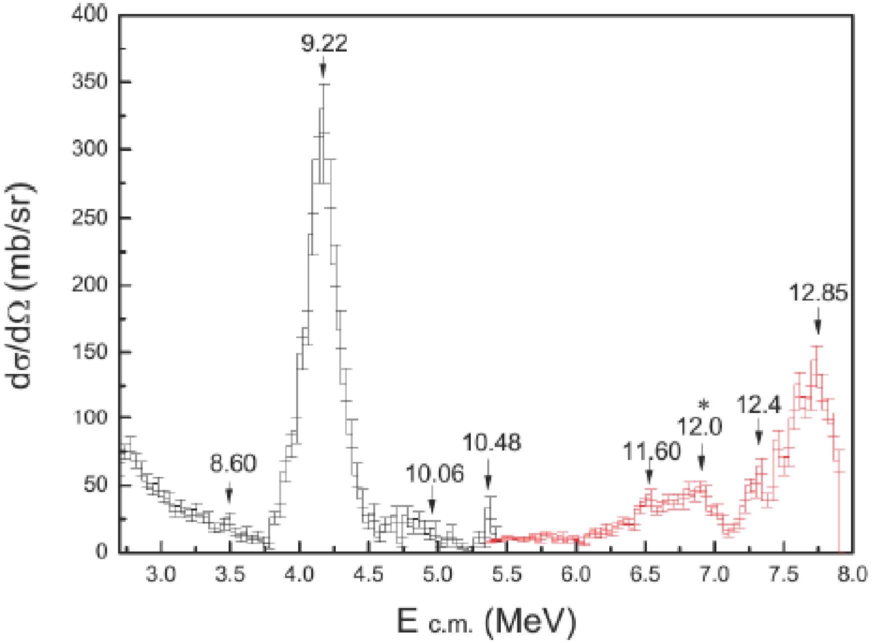


Fig. 5. (Color online) Excitation function of the $^{14}O(\alpha,\alpha)^{14}O$ reaction at the 0 degrees telescope. The level marked by $*$ has not been seen before.

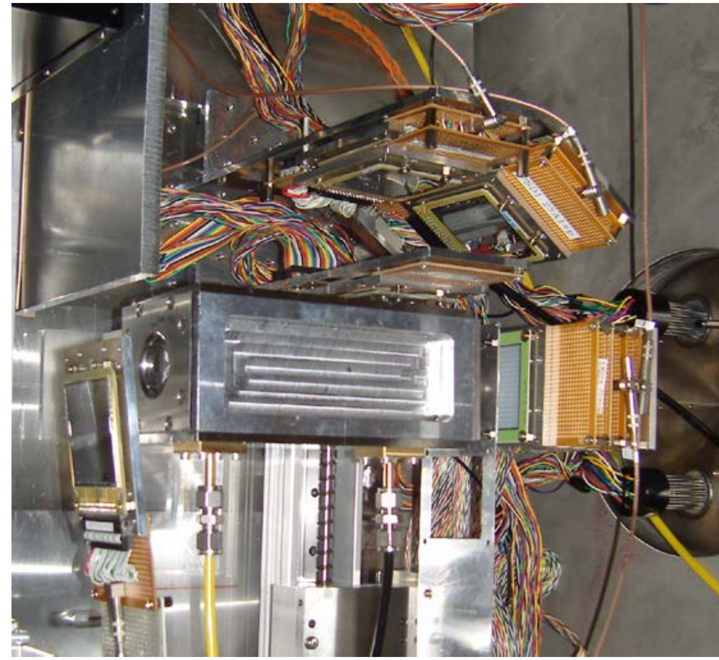
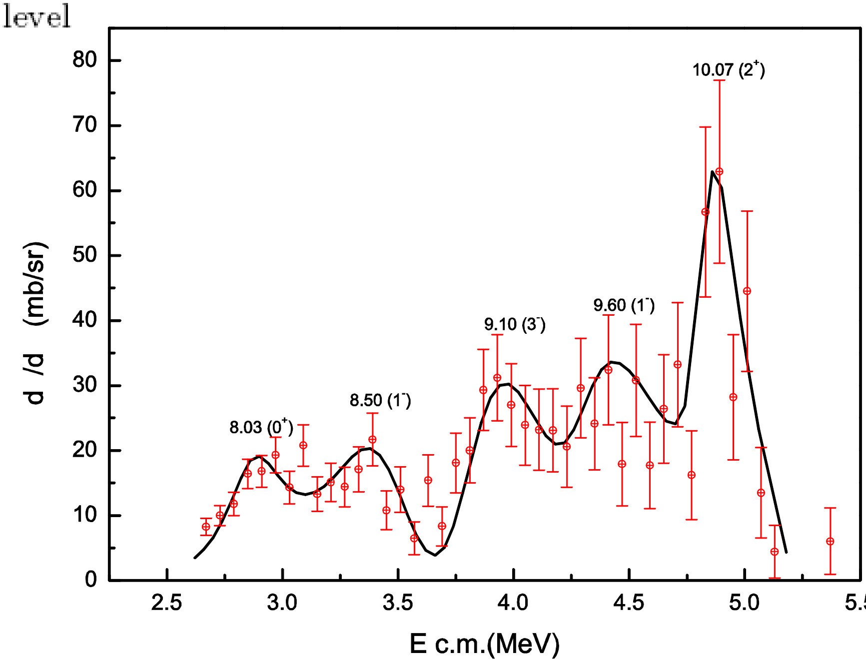


TABLE I. R-matrix fit parameters and the results of shell model calculations.

E_x[MeV]	$E_{c.m.}$[MeV]	Γ_α[keV]	Γ_p[keV]	J^π	E_x^{SM}	$J^\pi(SM)$
8.03 ± 0.09	2.92	40.40 ± 5.90	298.00 ± 38.00	0^+		
8.50 ± 0.07	3.38	84.50 ± 21.00	546.00 ± 60.00	1^-		
9.10 ± 0.10	3.99	27.00 ± 6.00	467.50 ± 59.00	3^-	9.47	3^-
					(9.27	4^+)
9.60 ± 0.09	4.49	620.00 ± 104.00	7.80 ± 6.60	1^-	10.02	1^-
10.07 ± 0.08	4.96	1.50 ± 0.80	90.00 ± 18.00	2^+	10.06	2^+
					(10.10	0^+)



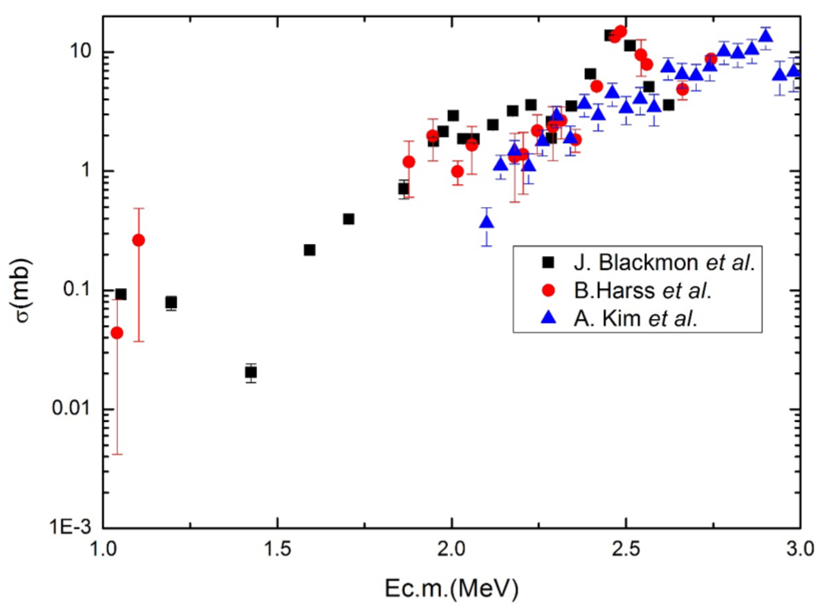
PHYSICAL REVIEW C **92**, 035801 (2015)

Measurement of the $^{14}O(\alpha, p)^{17}F$ cross section at $E_{c.m.} \approx 2.1$–5.3 MeV

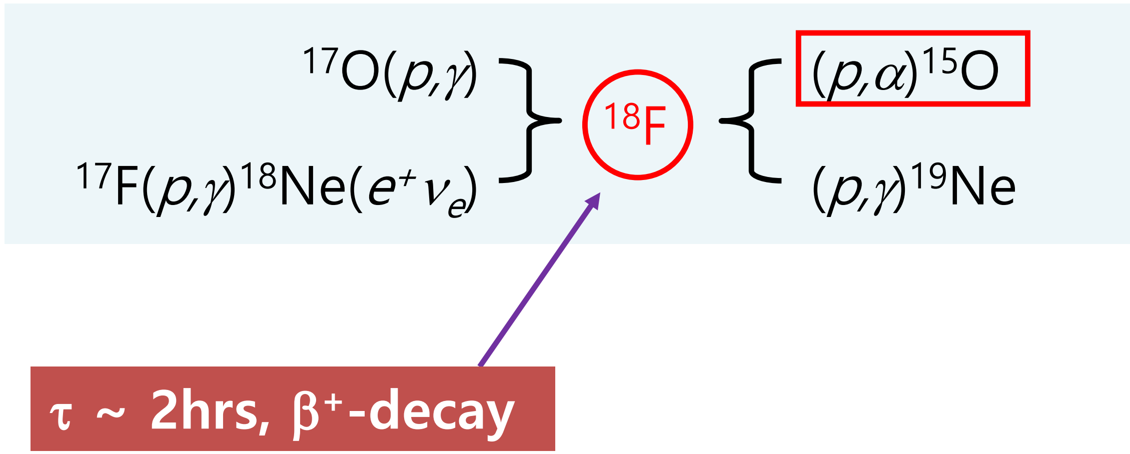
A. Kim,[1,*] N. H. Lee,[1] M. H. Han,[2] J. S. Yoo,[2] K. I. Hahn,[1,2,†] H. Yamaguchi,[3] D. N. Binh,[3] T. Hashimoto,[3] S. Hayakawa,[3] D. Kahl,[3] T. Kawabata,[3] Y. Kurihara,[3] Y. Wakabayashi,[3] S. Kubono,[4,5] S. Choi,[6] Y. K. Kwon,[7] J. Y. Moon,[7] H. S. Jung,[8] C. S. Lee,[8] T. Teranishi,[9] S. Kato,[10] T. Komatsubara,[11] B. Guo,[12] W. P. Liu,[12] B. Wang,[12] and Y. Wang[12]

[1]*Department of Physics, Ewha Womans University, Seoul 120-750, Korea*
[2]*Department of Science Education, Ewha Womans University, Seoul 120-750, Korea*
[3]*Center for Nuclear Study, University of Tokyo, RIKEN Branch, Japan*
[4]*RIKEN Nishina Center, Wako 351-0198, Japan*
[5]*Institute of Modern Physics, Lanzhou, China*
[6]*Department of Physics and Astronomy, Seoul National University, Seoul 151-742, Korea*
[7]*Institute for Basic Science, Daejeon 305-811, Korea*
[8]*Department of Physics, Chung-Ang University, Seoul 156-756, Korea*
[9]*Kyushu University, Fukuoka 812-8581, Japan*
[10]*Yamagata University, Yamagata 990-8560, Japan*
[11]*Tsukuba University, Ibaraki 305-8577, Japan*
[12]*China Institute of Atomic Energy, Beijing, China*

(Received 17 June 2015; published 1 September 2015)



$^{18}F(p,\alpha)^{15}O$ reaction in nova explosion



Important positron annihilation source

$^{18}F(p,a)^{15}O$ reaction rate is dominated by

1. $3/2^{-}$ resonance at E_{cm} = 330keV ⇒ clearly measured.
2. the interference of $3/2^{+}$ states at E_{cm}= 8 and 38 keV and broad resonance at E_{cm}= 665 keV ⇒ still controversial !!

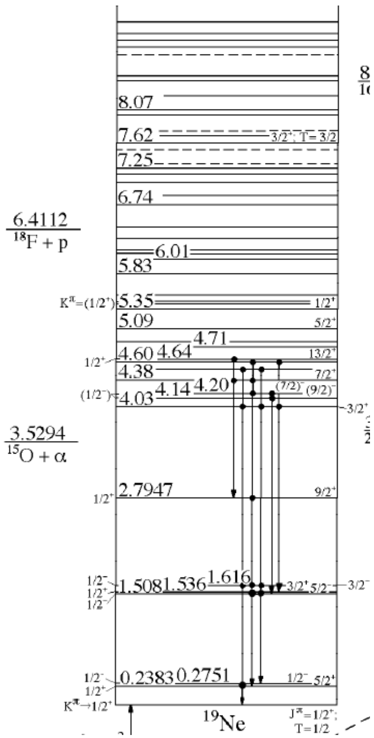
Is γ-Ray Emission from Novae Affected by Interference Effects in the $^{18}F(p, \alpha)^{15}O$ Reaction?

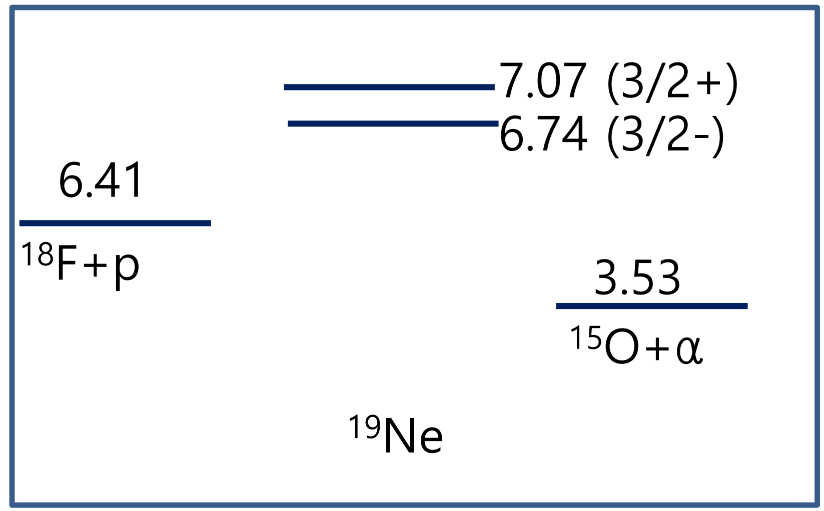
A. M. Laird,[1,*] A. Parikh,[2,3] A. St. J. Murphy,[4] K. Wimmer,[5,6] A. A. Chen,[7] C. M. Deibel,[8,9] T. Faestermann,[10,11] S. P. Fox,[1] B. R. Fulton,[1] R. Hertenberger,[11,12] D. Irvine,[7] J. José,[2,3] R. Longland,[2,3] D. J. Mountford,[4] B. Sambrook,[7] D. Seiler,[10,11] and H.-F. Wirth[11,12]

		Present work		
E_x (MeV)	E_{cm} (keV)	J^π	Γ_p (keV)[b]	Γ_α (keV)[b]
6.014(2)	−397	$3/2^-$	...	...
6.072(2)	−339[c]	$(3/2^+, 5/2^-)$	0.143	6×10^{-4}
6.097(3)	−314	$(7/2, 9/2)^+$	...	...
6.132(3)	−282[c]	$(3/2^+, 5/2^-)$	0.143	7×10^{-4}
6.289(3)	−122	...	...	...
6.416(3)	5[c]	$(3/2^-, 5/2^+)$	4.7×10^{-50}, 1.2×10^{-51}	0.5, 0.126
6.440(3)	29	$(11/2^+)$	...	...
6.459(3)	48[c]	$(5/2^-)$	8.4×10^{-14}	5.5
6.700(3)	289	...		
6.742(2)	331[c]	$(3/2^-)$	2.22×10^{-3}[d]	5.2[d]
6.862(2)	451	$(7/2^-)$	1.1×10^{-5}[d]	1.2[d]

None of three states just above the proton threshold are found to be consistent with 3/2+ assignment!

We need to decide the resonance energy and J^{π} of important states around the proton threshold for the determination of the reaction rate.





Low alpha threshold energy!
Easy to find the resonances around the proton threshold via $^{15}O + \alpha$!

We performed the **$^{15}O + \alpha$ experiment in the range E_x=3.53-12.0 MeV in ^{19}Ne** for understanding the resonances of ^{19}Ne and their astrophysical implications to novae and alpha cluster structure of ^{19}Ne.

⇒These measurements will allow us to measure resonance parameters such as alpha widths, spins, parities and excitation energies of important resonance states above the alpha threshold (E_{th}=3.53MeV).
We aim :

1. First observation of alpha cluster states in ^{19}Ne

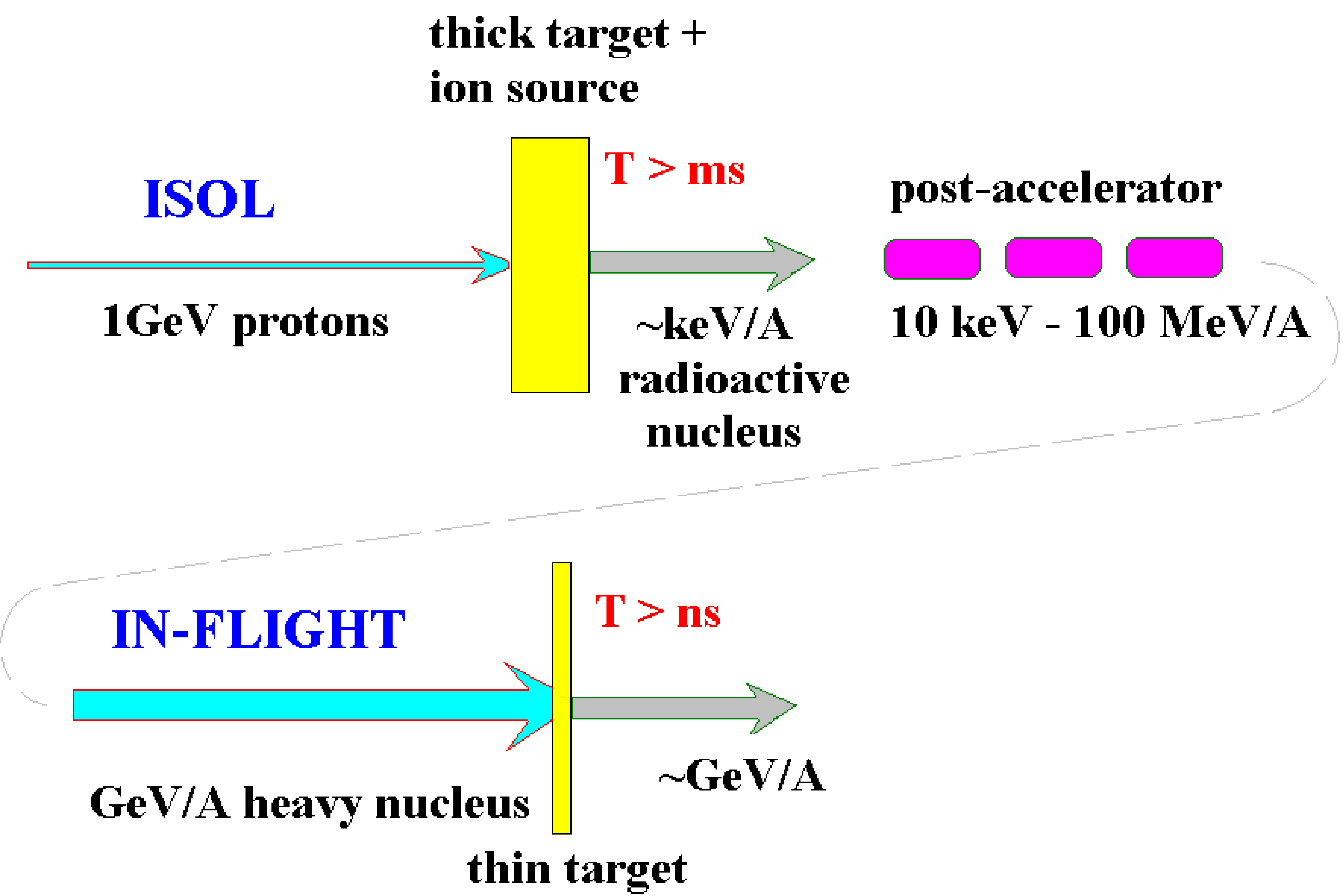
$$E_{exc} = E_0 + \frac{\hbar^2}{2J} l(l+1)$$

Γ_w vs. Γ_α

2. Identification of the existence and their effects of $3/2^+$ states around the proton threshold

$$N_A < \sigma v >= 1.54 \times 10^{11} (AT_9)^{(-3/2)} \times \omega\gamma \times exp(-11.605 \frac{E_r}{T_9})$$

$$\omega\gamma = \frac{2J+1}{(2j_a+1)(2j_b+1)} \frac{\Gamma_\alpha \Gamma_p}{\Gamma}$$

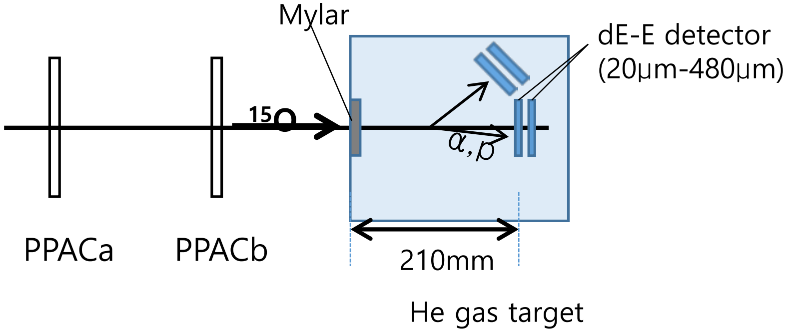

thick target +
ion source
ISOL
T > ms
post-accelerator
1GeV protons
~keV/A
radioactive
nucleus
10 keV - 100 MeV/A
IN-FLIGHT
T > ns
~GeV/A
GeV/A heavy nucleus
thin target

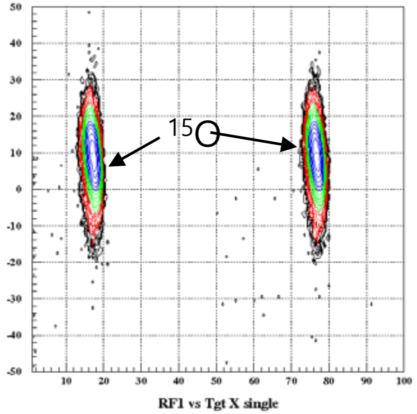
NP1412-AVF20R1

Measurement of alpha elastic scattering on ^{15}O

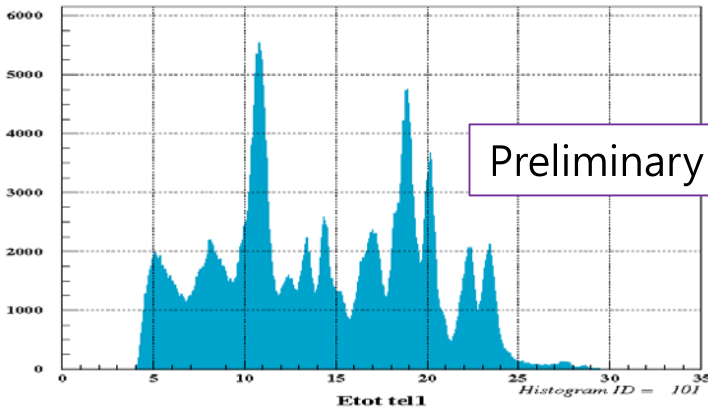
Kevin Insik Hahn

- Beam time : Sep. 20~29, 2015 (9days)
- AVF cyclotron,
- Primary beam : $^{15}N^{7+}$, 7.0MeV/u, 600pnA
- Primary target : H_2 gas, 600 Torr, (90K)
- Secondary beam : $^{15}O^{8+}$
- Secondary target : ^{4}He, 660 Torr





^{15}O beam
purity : 99.9%
intensity : 6×10^5 /s



The experiment was performed successfully, as we identified many resonances of ^{19}Ne.

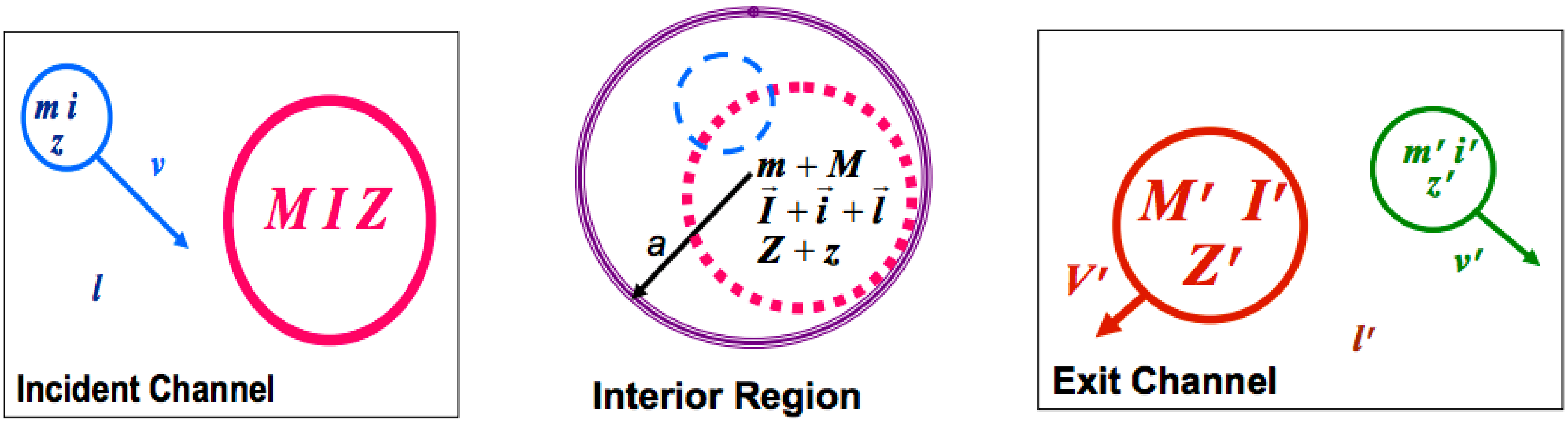
R-Matrix theory in nuclear physics

- 처음 R-Matrix theory는 핵반응에서의 resonances를 설명하기 위하여 만들어짐. 현재는 핵반응으로부터 야기되는 핵산란과 핵반응의 결과들을 설명하기 위하여 쓰임

- 핵물리에서 쓰이는 R-Matrix 이론의 기본적 토대는 Kapur 와 Peierls의하여 만들어졌으며 그후 Wigner와 Eisenbud에 의해서 현재의 R-matrix 이론이 정립됨

  : coupled-channel 슈뢰딩거 방정식을 풀기위하여 space를 internal region과 external region으로 둘로 나누어 생각하여 해법을 찾아냄.

R-Matrix theory in nuclear physics



Nuclear reaction; 여기서 M=mass, I=spin, Z=charge를 의미함

R-matrix는 channel로 표현되는데 이때, channel은 한쌍의 입자와 두 입자간의 상호작용에 관한 정보를 가지고 있어야 한다.

Scattering theory in nuclear physics

- Scattering theory에서 Channel이 가지는 정보는 c=(a,l,s,J)로 정의됨 (a는 mass, charge, spin, Q-value를 포함함; l:orbital angular momentum of pair, parity$(-1)^l$ s: channel spin s= i+I; J: total angular momentum J=l+s)

- Cross section
$$\sigma_{cc'} = \frac{\pi}{k^2} g_{J\alpha} \left| e^{2iw_c} \delta_{cc'} - U_{cc'} \right|^2 \delta_{JJ'}$$

$$g_{J\alpha} = \frac{2J+1}{(2i+1)(2I+1)}$$ (spin statistical factor)

$$K_\alpha^2 = (\hbar k_\alpha)^2 = \frac{2m M^2}{(m+M)^2} E$$ (center of mass)

$$U_{cc'} = \Omega_c W_{cc'} \Omega_{c'}$$ (scattering matrix)

(constant $\Omega_c = e^{i(w_c - \varphi_c)}$)

$$W = P^{1/2}(I - RL)^{-1}(I - RL^*)P^{-1/2}$$ (related to R- matrix term)

SAMMY

Scattering theory에서 계산을 위해 많은 파라미터들이 필요했기 때문에 SAMMY코드 안에 실제 핵반응 실험과 관련된 변수를 넣어주어야 함(질량, 양성자수 스핀값 등)

또한 두 입자로부터 생성될 수 있는 total angular momentum값을 구하여 spin group을 정의

예) ^{15}O ($1/2^-$) + alpha(0^+)

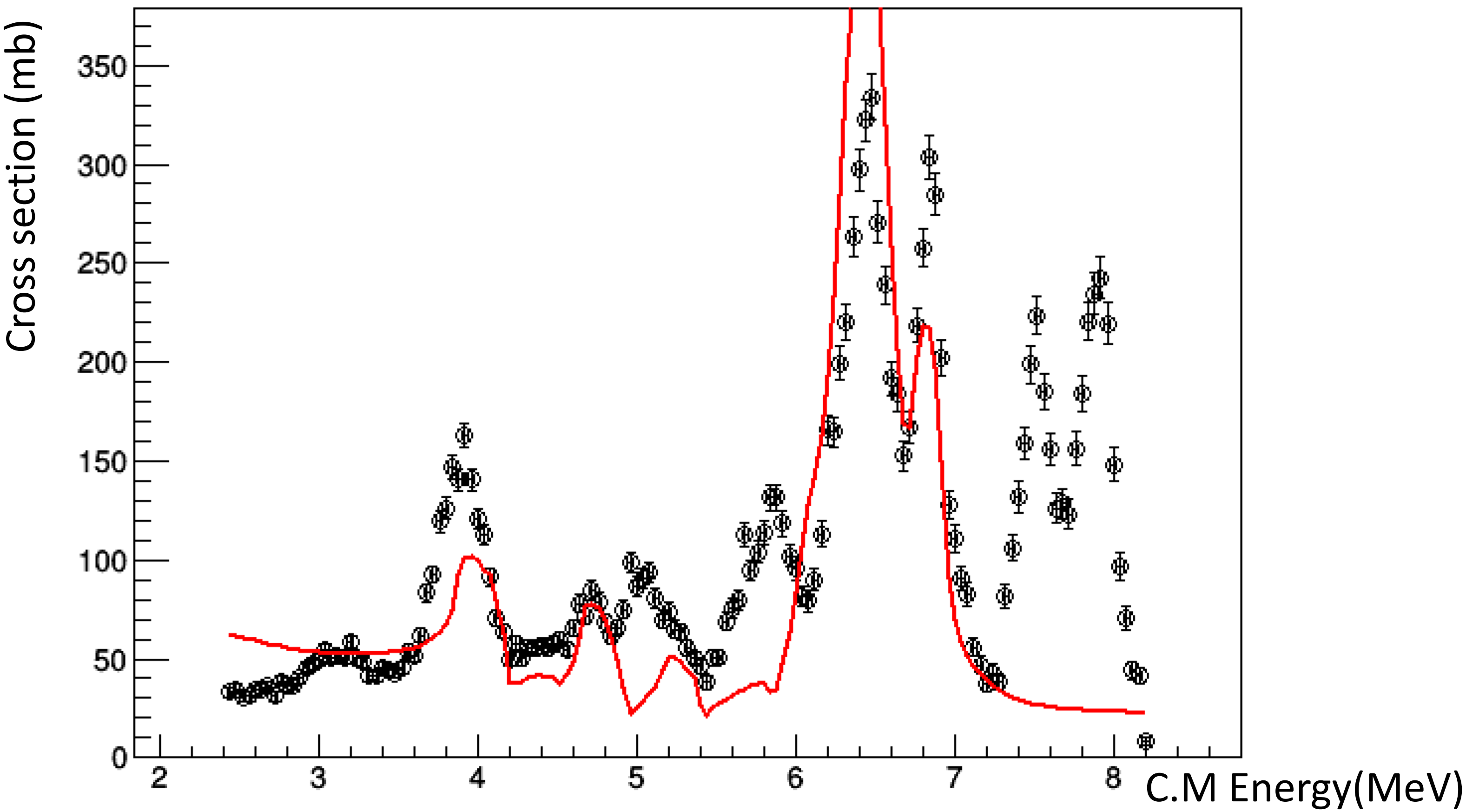
(Incidence channel spin = -1/2+0;

Total angular momentum = l+s)

Orbital momentum	Incidence channel spin	Total angular momentum
0	-1/2	$1/2^-$
1	-1/2	$1/2^+$
	-1/2	$3/2^+$

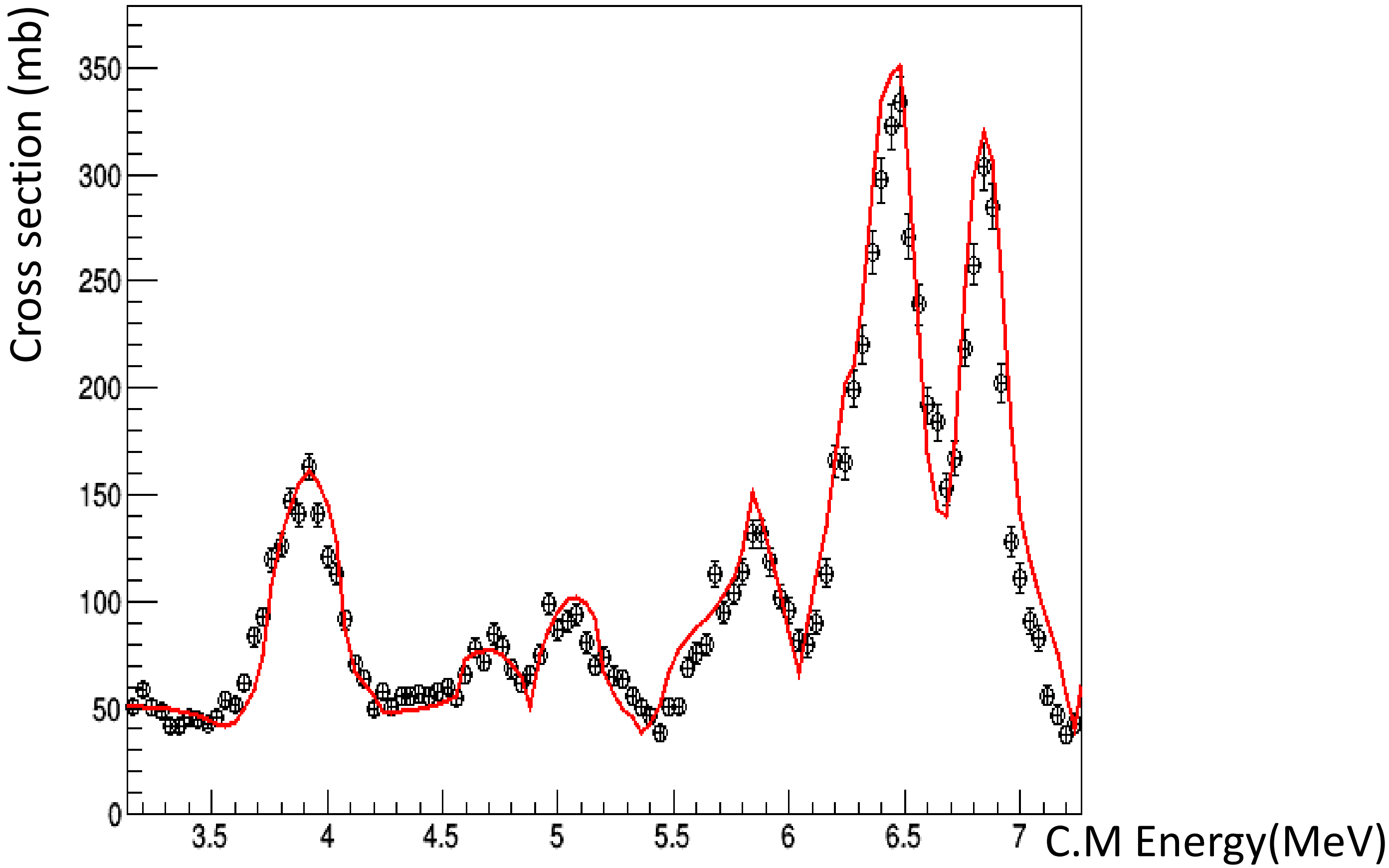
```
print INP
"Oxygen15-alpha resonance scattering
15O        15.0031    5976500. 30000000.
KEY-WORD PARTICLE-PAir definitions
PRINT ALL INPUT PARAMETERS
chi squared is wanted
differential data are in ascii file
do not suppress any intermediate results
generate odf file automatically
do not solve bayes equations
print debug information
print theoretical values
broadening is not wanted
twenty

Name=15O+a0     Pa=alpha
 Pb=15O         Zb=  8    Mb= 15.00306     Sb= -0.5
Name=18F+p0     Pa=proton
 Pb=18F         Zb=  9    Mb= 18.00090     Sb=  1.0

   5.6750     0.010000
DIFFERENTIAL ELASTIC SCATTERING
    1          180.0
                1.0
  1       1     0 -0.5       1.0
    1  15O+a0        0      -0.5
  2       1     0  0.5       1.0
    1  15O+a0        1      -0.5
  3       1     0  1.5       1.0
    1  15O+a0        1      -0.5
  4       1     0 -1.5       1.0
    1  15O+a0        2      -0.5
```

SAMMY-Fitting results



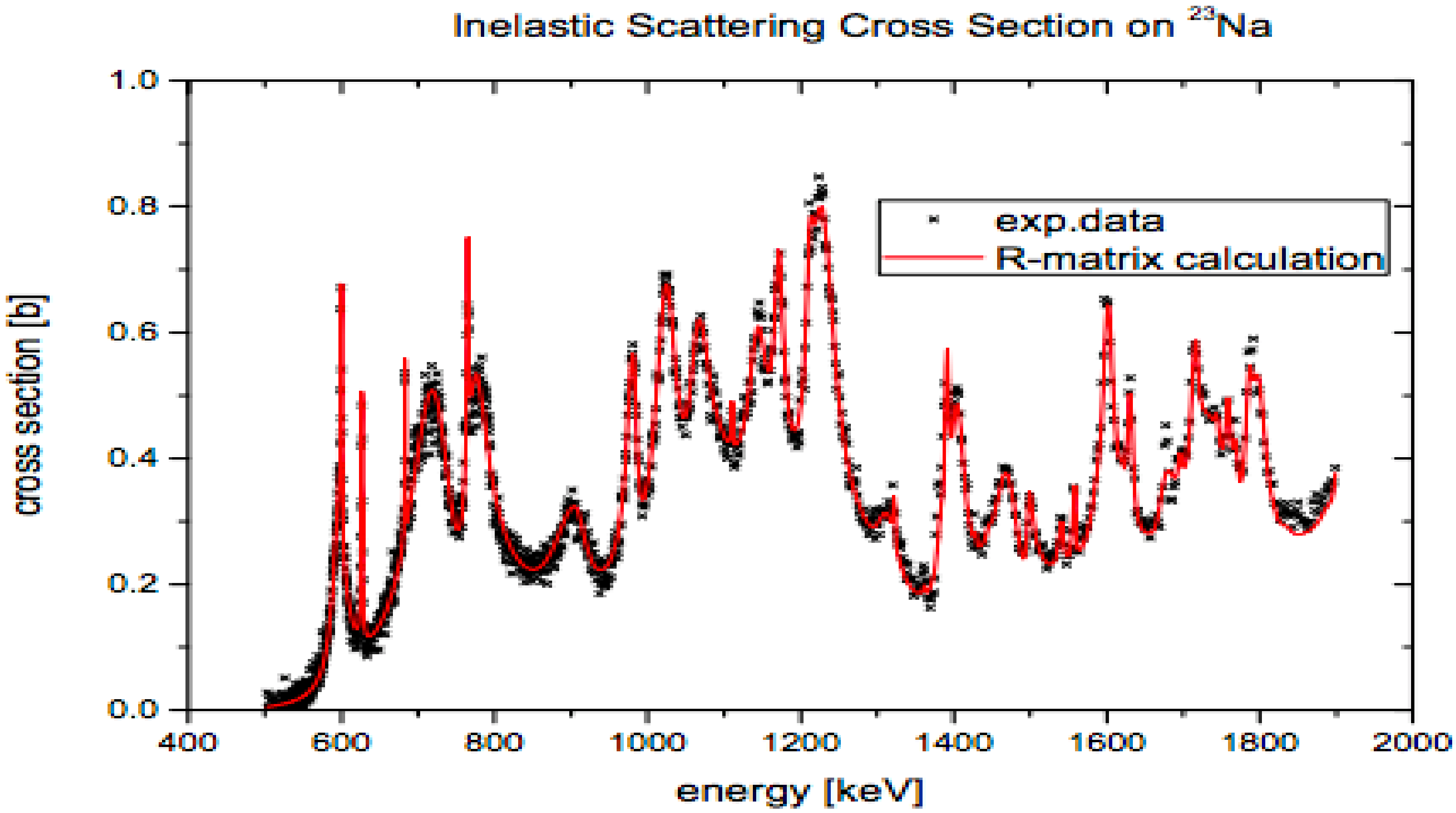
입력값이 계산값과 잘 일치하지 않은경우 fitting 결과

SAMMY-Fitting results ($^{15}O+\alpha$)



입력값이 계산값과 잘 일치하는 경우 fitting 결과

SAMMY-Fitting results (좋은 예)



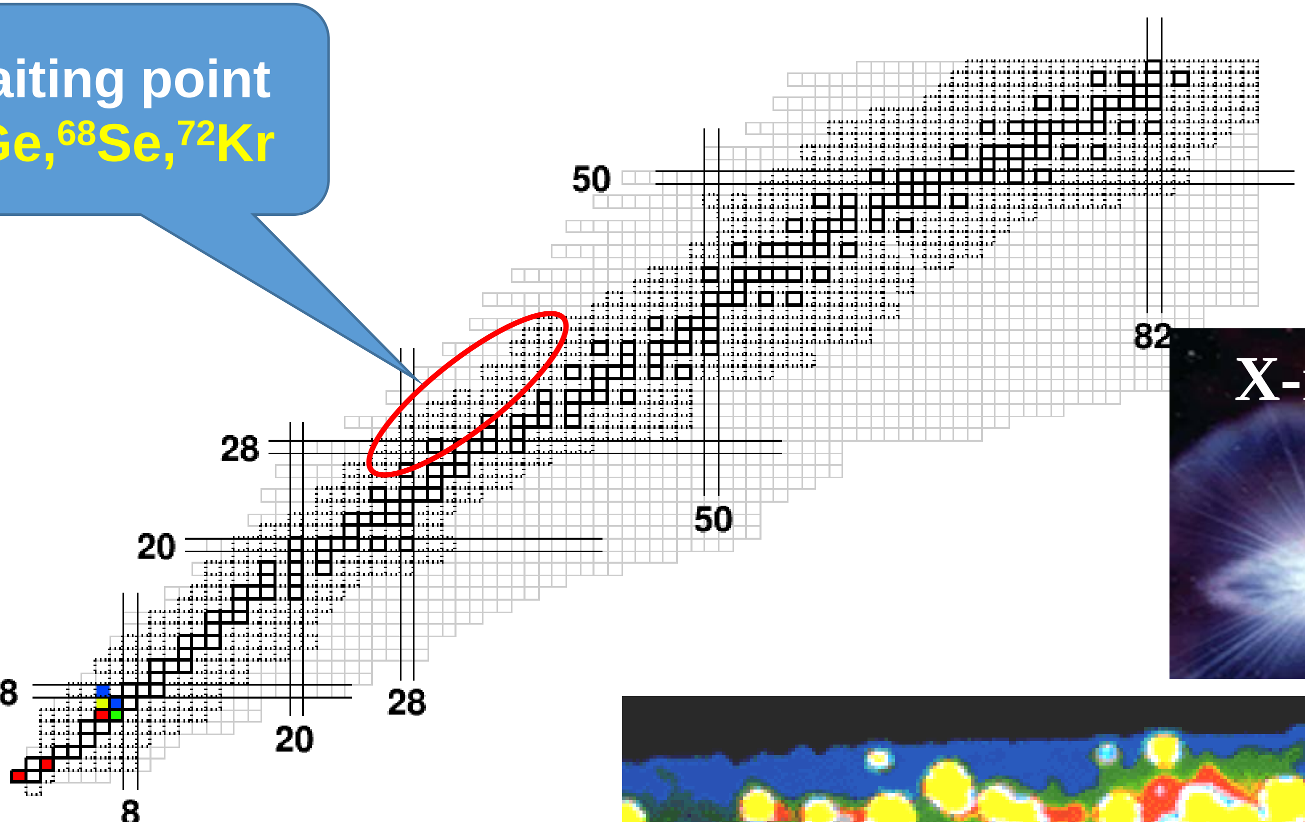
입력값이 계산값과 잘 일치하는 경우 fitting 결과

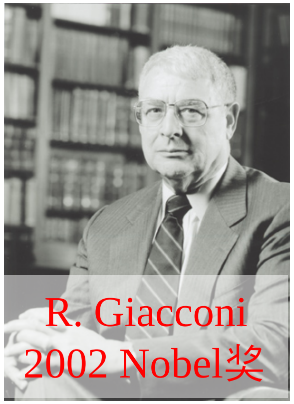
Impact on the studies of nuclear astrophysics

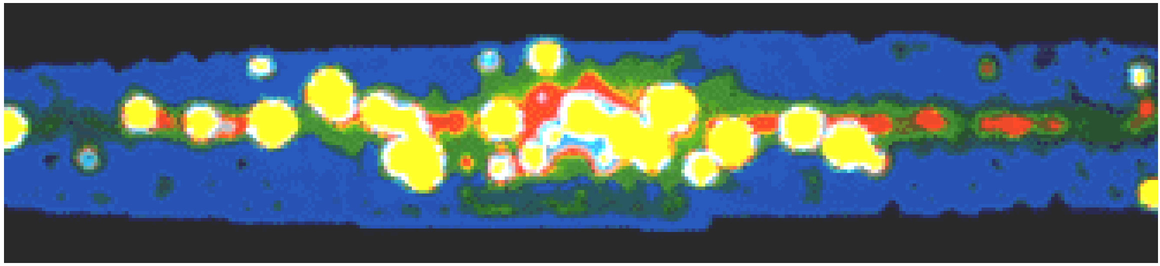
rp-process in X-ray burst

Nuclear inputs:
Masses, Half-lifes,
Reaction rates

Waiting point
^{64}Ge, ^{68}Se, ^{72}Kr



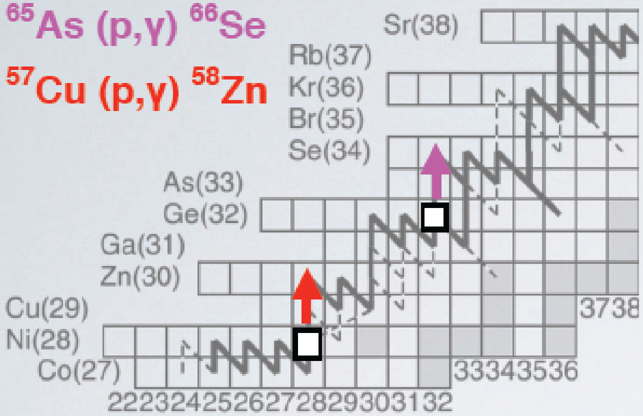




Selected reactions

$^{65}As\ (p,\gamma)\ ^{66}Se$

$^{57}Cu\ (p,\gamma)\ ^{58}Zn$



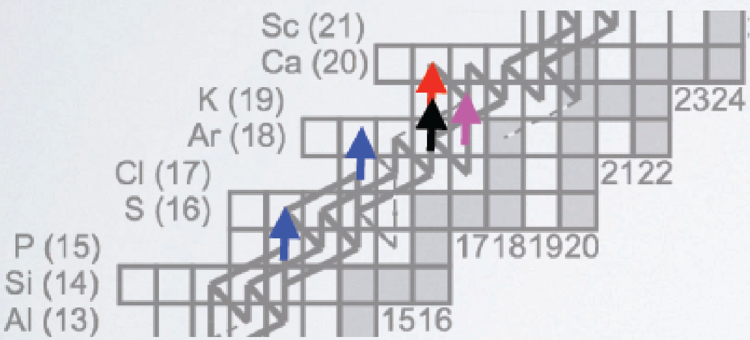
Reaction flow from *H. Schatz et al., Phys. Rev. Lett. 86, 3471, (2001)*

- Breakout form the (p,γ)-(γ,p) equilibrium at the waiting point nuclei **^{56}Ni** and **^{64}Ge** via two-proton capture.

$$\lambda_{^{64}Ge\longrightarrow ^{65}As\longrightarrow ^{66}Se} = F(N_p, T, j_i, G_i) \times \exp\left(\frac{Q_{^{64}Ge\longrightarrow ^{65}As}}{kT}\right) \times \lambda_{^{65}As\rightarrow ^{66}Se}$$

- Dramatic effect on energy production, light curves and final yields

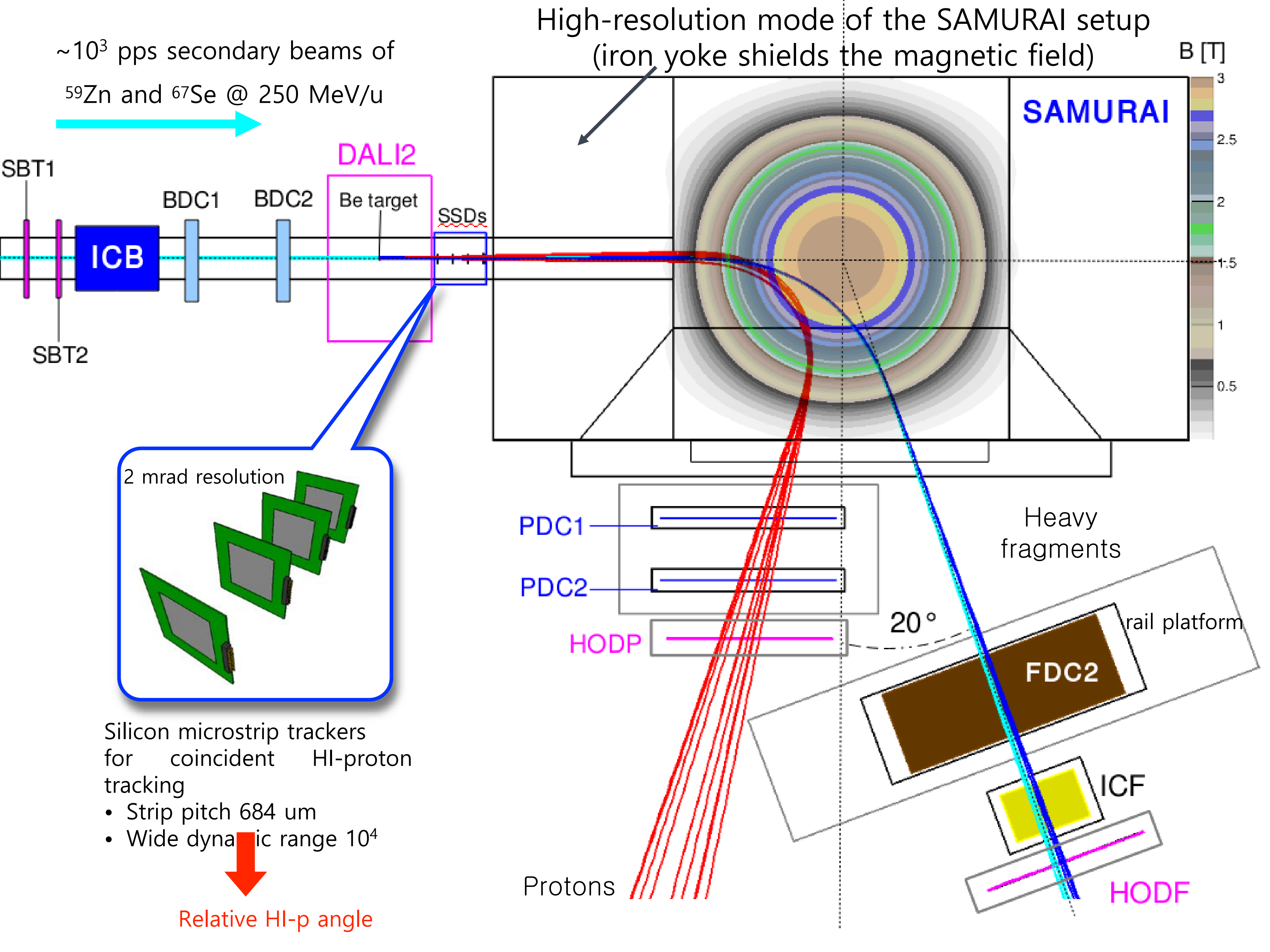
- Proceeding reaction flow into the heavier mass region (where is the endpoint of the rp-process?)



- **^{27}P (p,γ) ^{28}S** and **^{31}Cl (p,γ) ^{32}Ar**
  Significant effect on the XRB light curves. Dominated by **direct proton capture.**
  (proposal by B.C.Rasco, LSU)

- **^{34}Ar(p,γ)^{35}K(p,γ)^{36}Ca** and **^{35}Ar(p,γ)^{36}K**
  Influence on nuclear energy generation and predicted light curves e.g. multi-peak XRB.
  (proposal by Z. Elekes, Atomki)

- Additional proposal to study ^{8}B(p,γ)^{9}C **direct-capture reaction rate** (by L.Trache, IFIN-HH):
  - Explosive hydrogen burning in massive stars
  - Hot pp chain pp-IV, bypass of the 3α-process


~10^3 pps secondary beams of
59Zn and 67Se @ 250 MeV/u
High-resolution mode of the SAMURAI setup
(iron yoke shields the magnetic field)
B [T]
3
2.5
2
1.5
1
0.5
SAMURAI
SBT1
SBT2
ICB
BDC1
BDC2
DALI2
Be target
SSDs
2 mrad resolution
PDC1
PDC2
HODP
Heavy fragments
20 °
rail platform
FDC2
ICF
HODF
Protons
Silicon microstrip trackers for coincident HI-proton tracking
• Strip pitch 684 um
• Wide dynamic range 10^4
Relative HI-p angle

Rare Isotope Science Project (RISP)

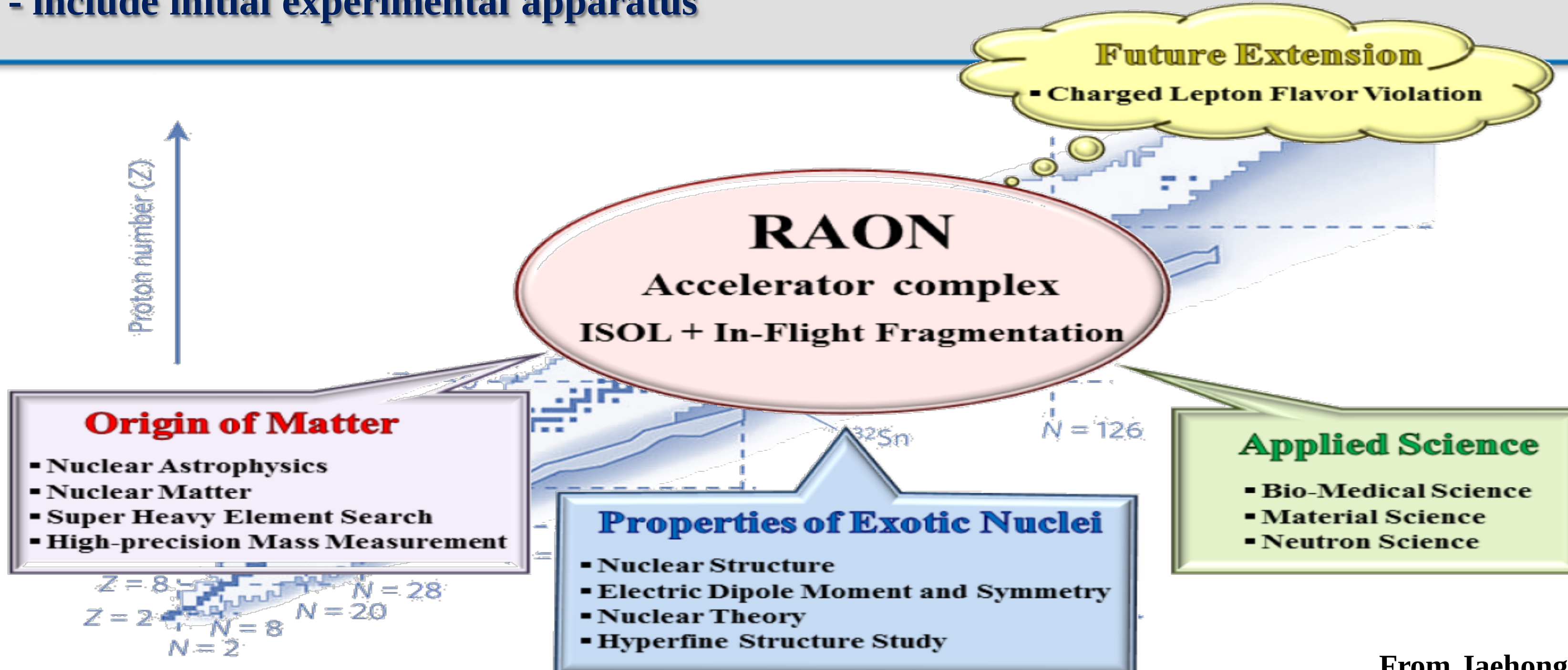
○ Goal : To build a heavy ion accelerator complex for rare isotope science researches in Korea

○ Project period : 2011.12 - 2021.12

○ Total Budget : ~$ 1.44 billion

(Facilities ~ $ 0.46 bill., Bldgs & Utilities ~ $ 0.98 bill.)

- include initial experimental apparatus



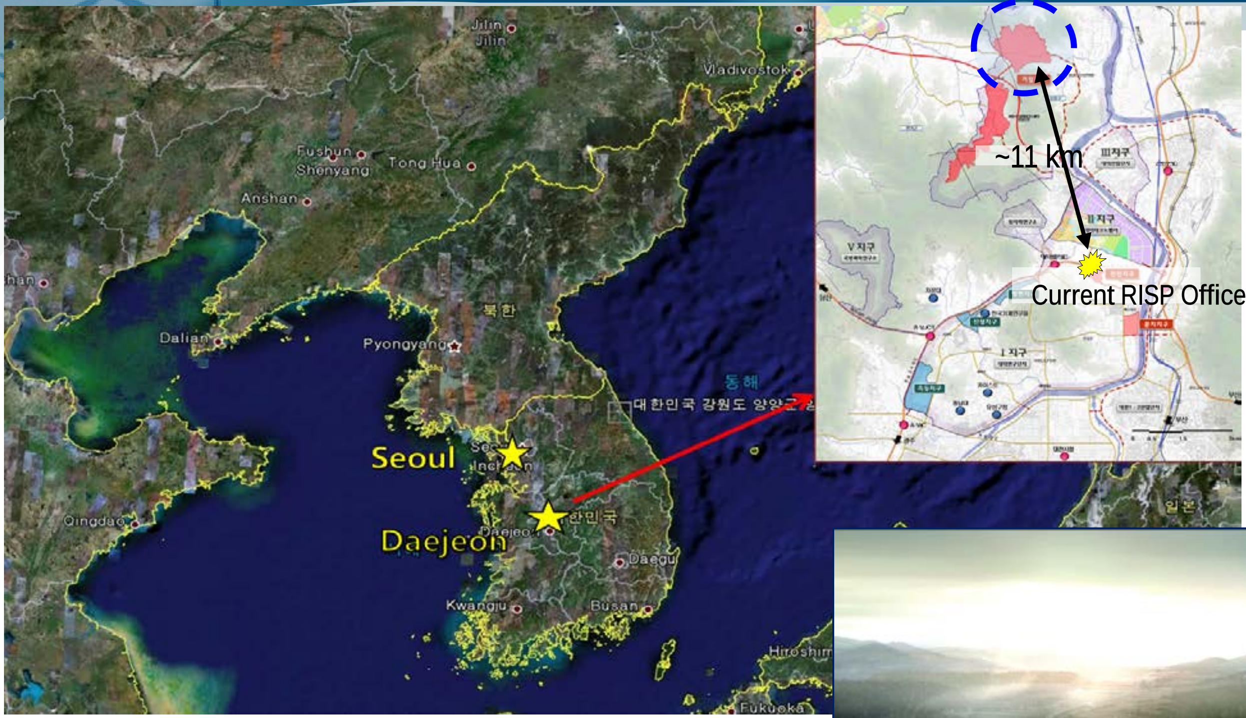
From Jaehong Kim
Project Integration Division

RISP - RAON

- The construction and civil engineering for the RI beam accelerator facility called RAON (Rare isotope Accelerator complex for ON-line experiments) has begun.
- The ground breaking for accelerators and experimental buildings was done on Feb. 13th this year. A full scale ground breaking ceremony is scheduled in the near future.

- **Site preparation :**

  Acc. & Exp. bldg site ('16.07.~'17.01.), Support bldg site('16.08.~'17.06.)



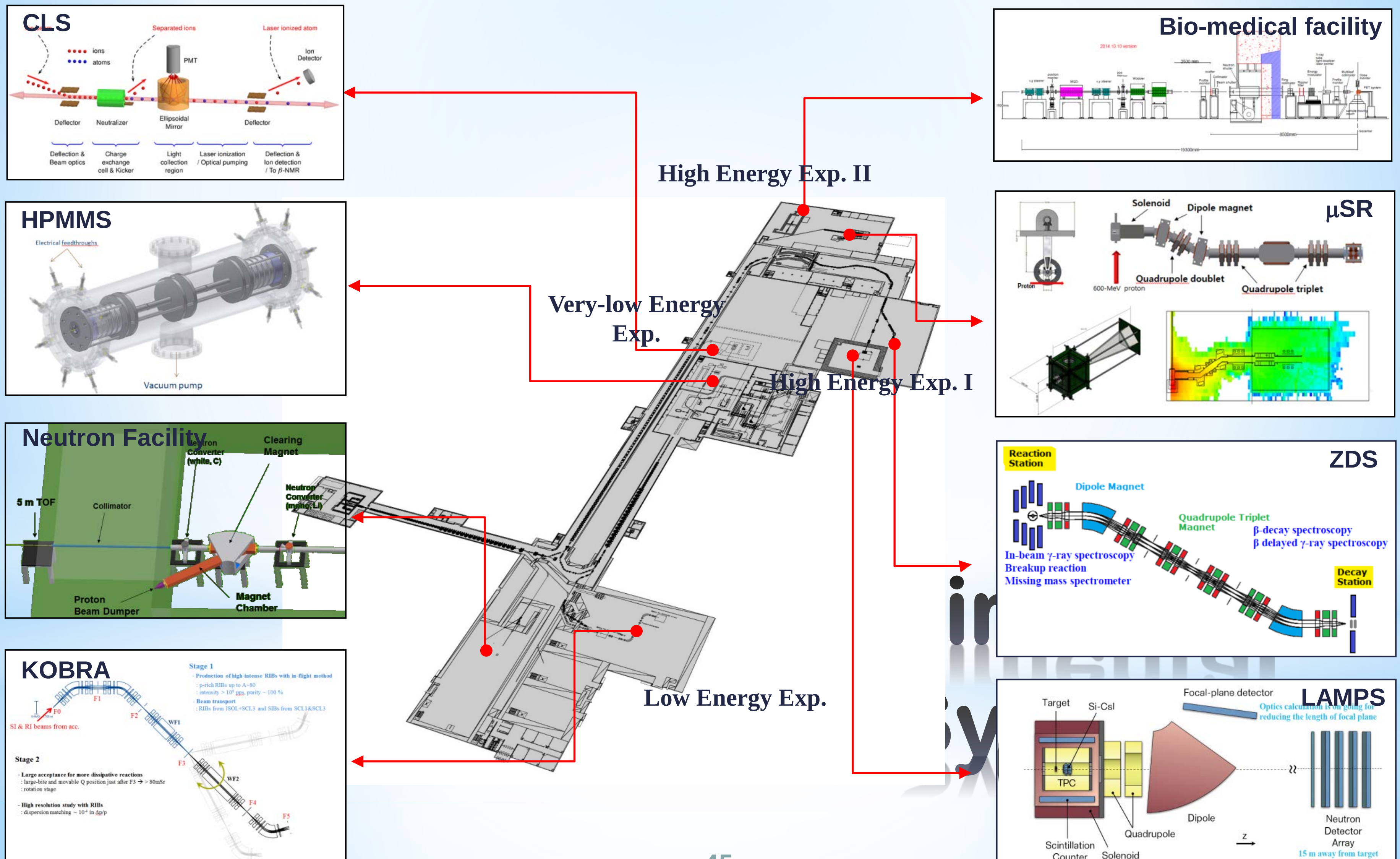
RAON Site :

Sindong in Daejeon

Bird's-eye view

A construction company was selected in September, 2016.

Area (Lot/Bldg): 952,066 m² / 130,846 m²



From Jaehong Kim
Project Integration Division

Experimental Facilities at RAON

Field	Facility	Exp. hall	Characteristics	Remark
Pure science	Recoil spectrometer – KOBRA	Low E	High resolution, Large acceptance function, RIBs production with in-flight method	Mass resolution; ~ 200 Large acceptance; ~ 80 msr
	Large acceptance Spectrometer – LAMPS(L&H)	Low & High E (I)	High efficiency for charged particle, n, and γ	TPC ; 3π sr, Neutron wall, Si-CsI array, dipole spectrometer
	High resolution Spectrometer	High E (I)	High resolution, Precise scattering Measurement to the focal plan, Rotatable	Momentum resolution ; 1.5×10^4
	Zero-degree Spectrometer	High E (I)	Charge and mass separation, Good mass resolution	Momentum resolution ; 1200~ 4100
	High precession mass measurement system	Ultra low E	Penning trap, Multi-reflection Time of flight	Mass resolution ; 10^{-5}~ 10^{-8}
	Collinear laser Spectroscopy	Ultra low E	High Resolution Laser Spectroscopy System	Spectral resolution ; ≤ 100 MHz
Applied science	β-NMR/μ-SR	Low / High E (II)	High intensity ^{8}Li & muon production	^{8}Li & muon > 10^8 pps
	Bio-medical facility	Low & High E (II)	Irradiation system for stable & radio ion beam	Uniformity ; < 5%
	Neutron science Facility	Low E	Fast neutron generation & measurement system of fission cross section	Uncertainty ; < a few %

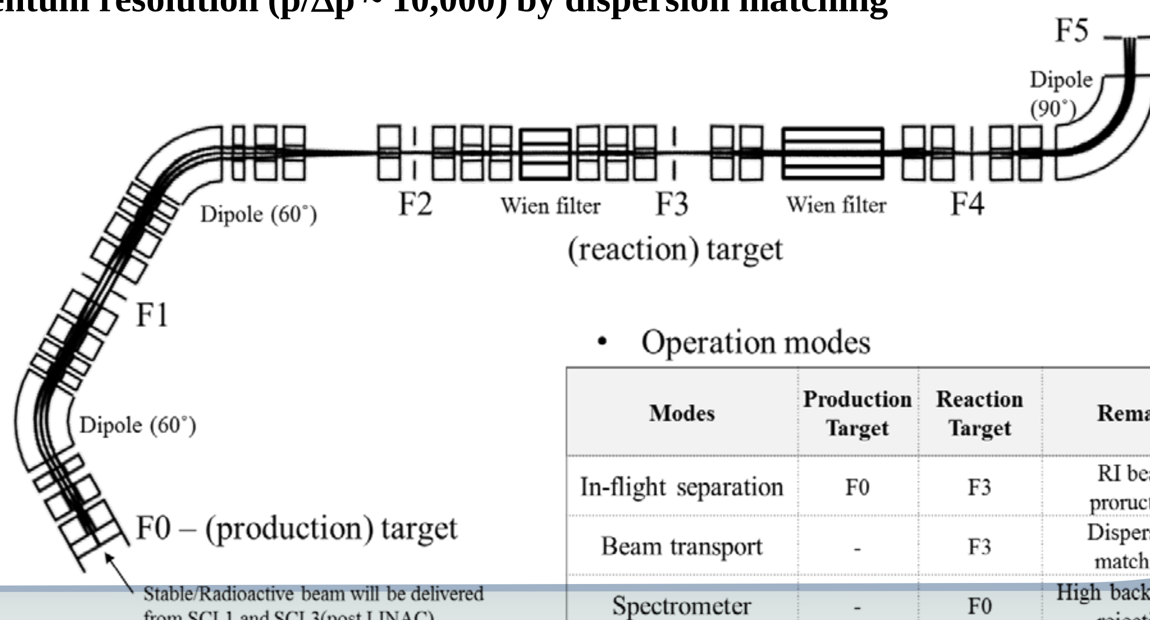
(KOrea Broad acceptance Recoil spectrometer and Apparatus)

Characteristics of the KOBRA

from Y. K. Kwon

- **Versatile two-stage device**
- **RI beams production (stage1)**
  - **- low energy in-flight method**
  - **- Quasi Projectile Fragmentation**
  - **- Polarized RI beam (beam swinger)**
- **High performance spectrometer (stage2)**
  - **- Rotatable**
  - **- Large acceptance (>50mSr) by movable Q magnets just after F3**
  - **- High momentum resolution (p/Δp ~ 10,000) by dispersion matching**

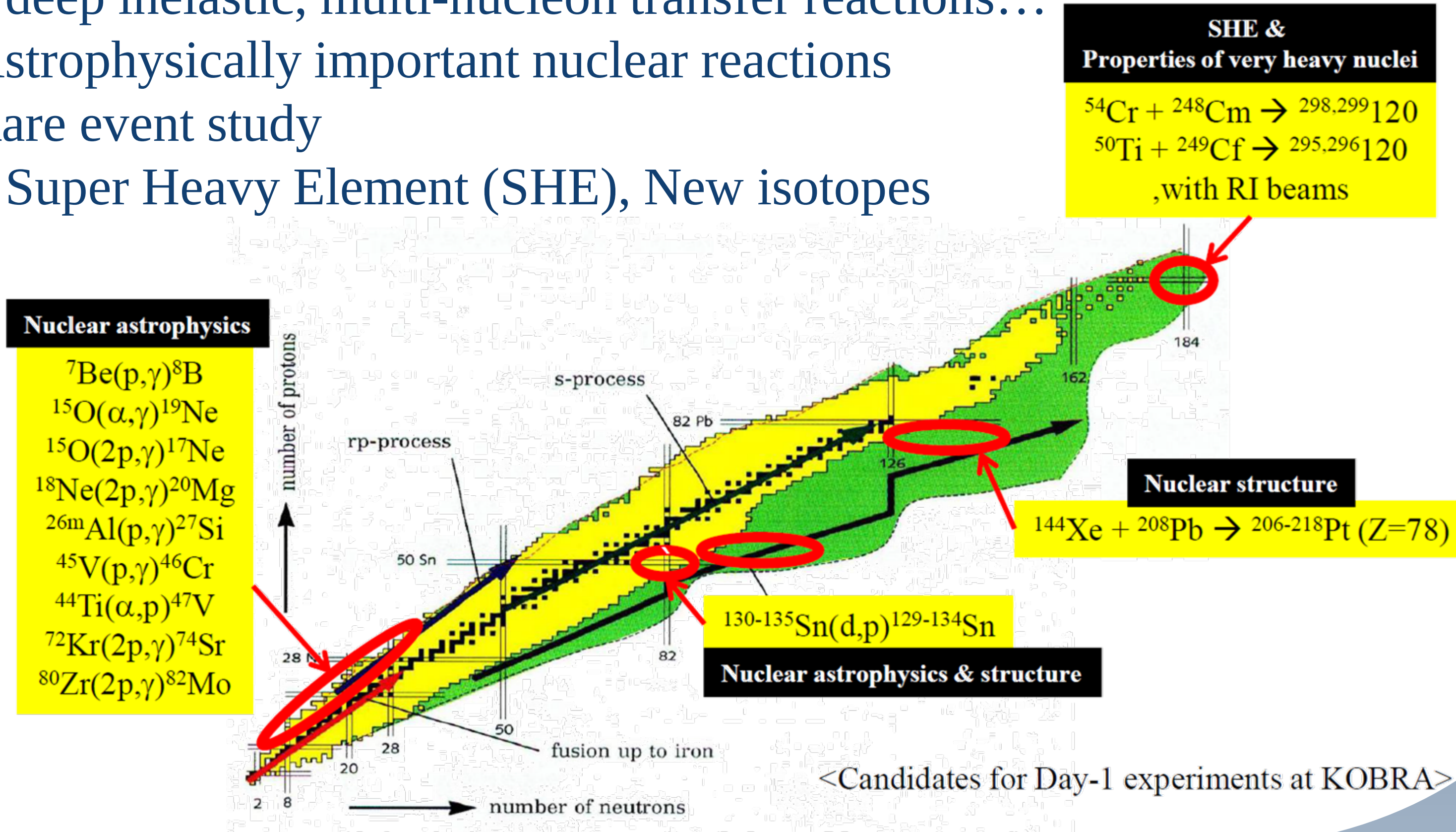
Commissioning in 2019 !



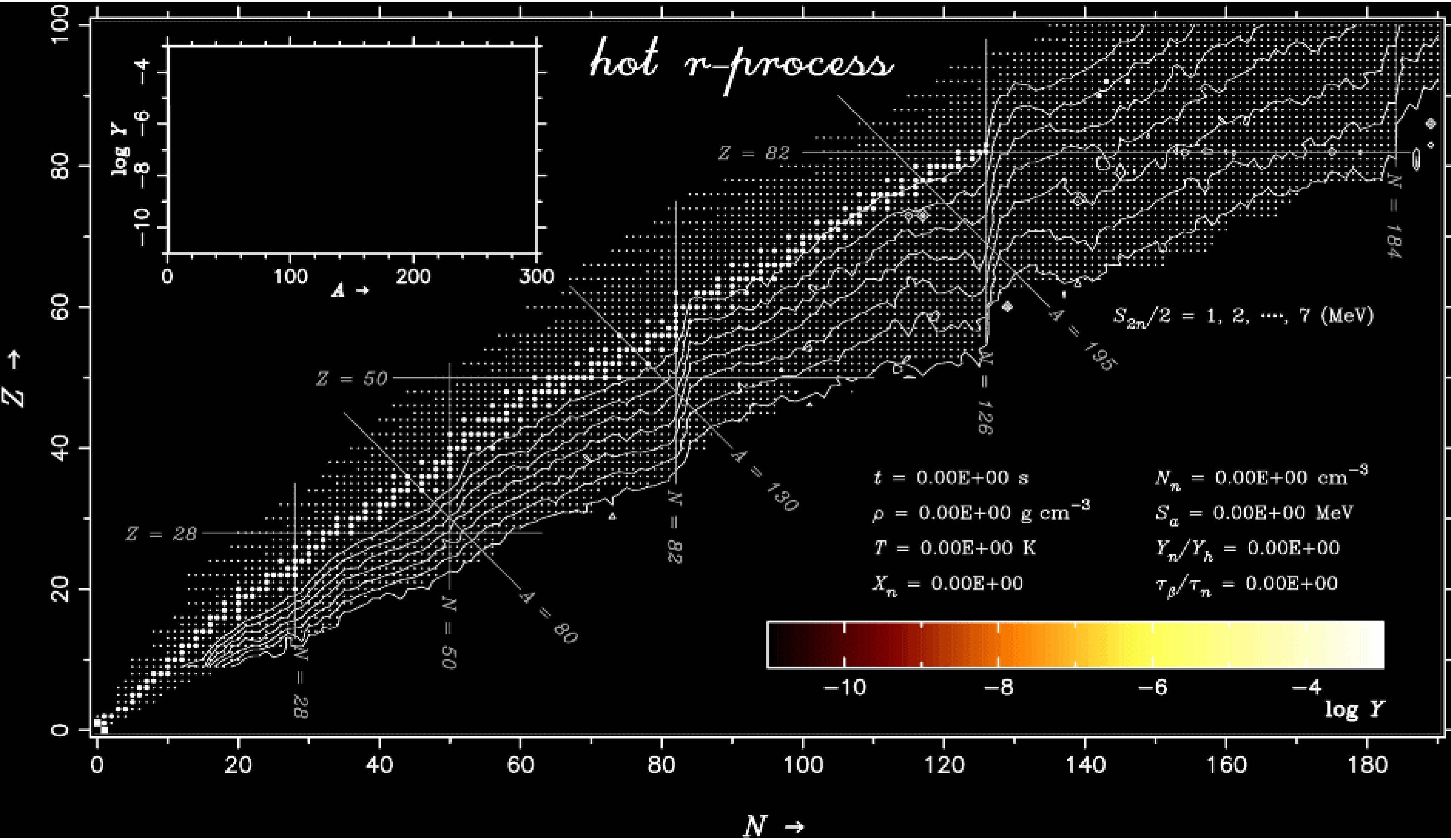
- Operation modes

Modes	Production Target	Reaction Target	Remark
In-flight separation	F0	F3	RI beam proruction
Beam transport	-	F3	Dispersion matching
Spectrometer	-	F0	High background rejection

- **Main Research Subject**
  - Nuclear structure of exotic nuclei
    - shell evolution, shape coexistence, isomers, etc
  - Nuclear reactions
    - deep inelastic, multi-nucleon transfer reactions…
  - Astrophysically important nuclear reactions
  - Rare event study
    - Super Heavy Element (SHE), New isotopes

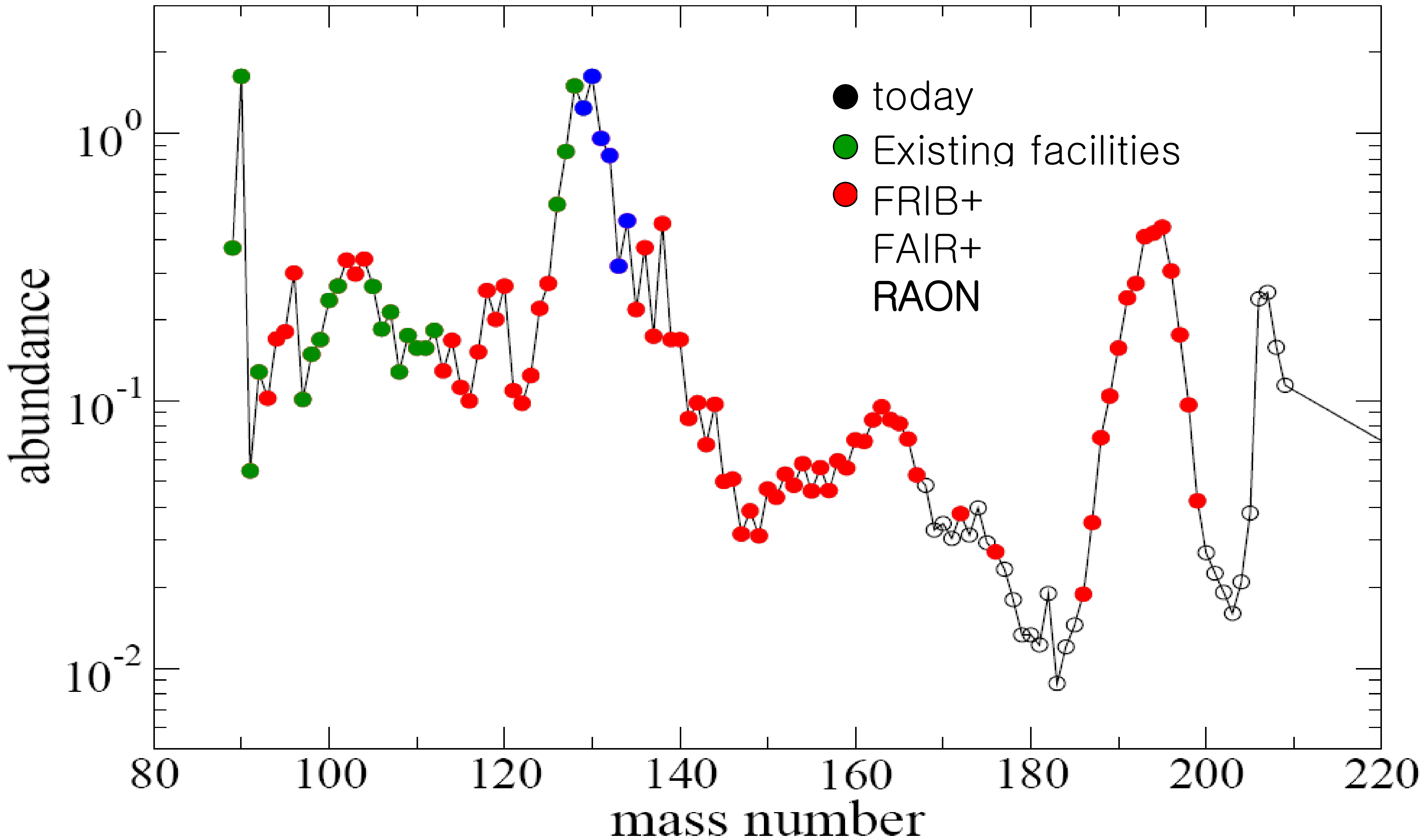


<Candidates for Day-1 experiments at KOBRA>



by S. Wanajo (Tokyo)

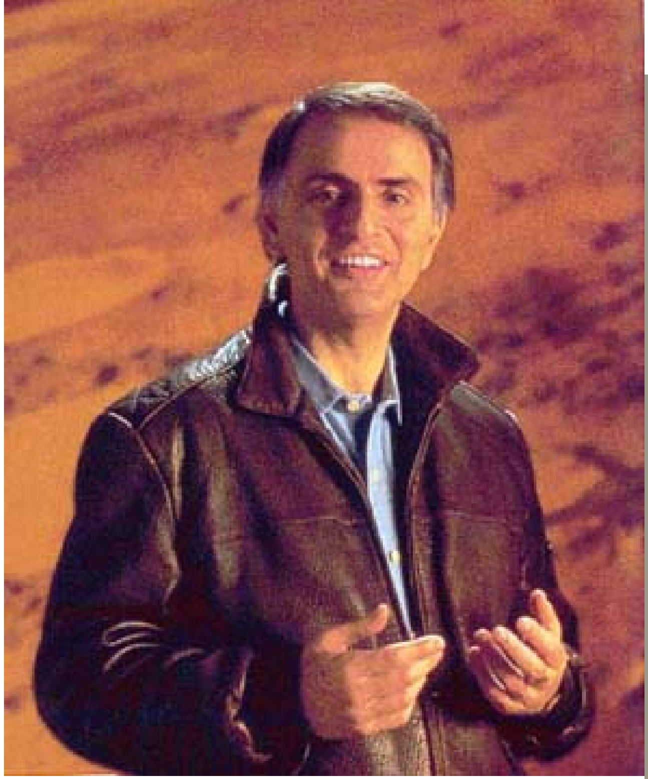
New Era due to RIB Facilities

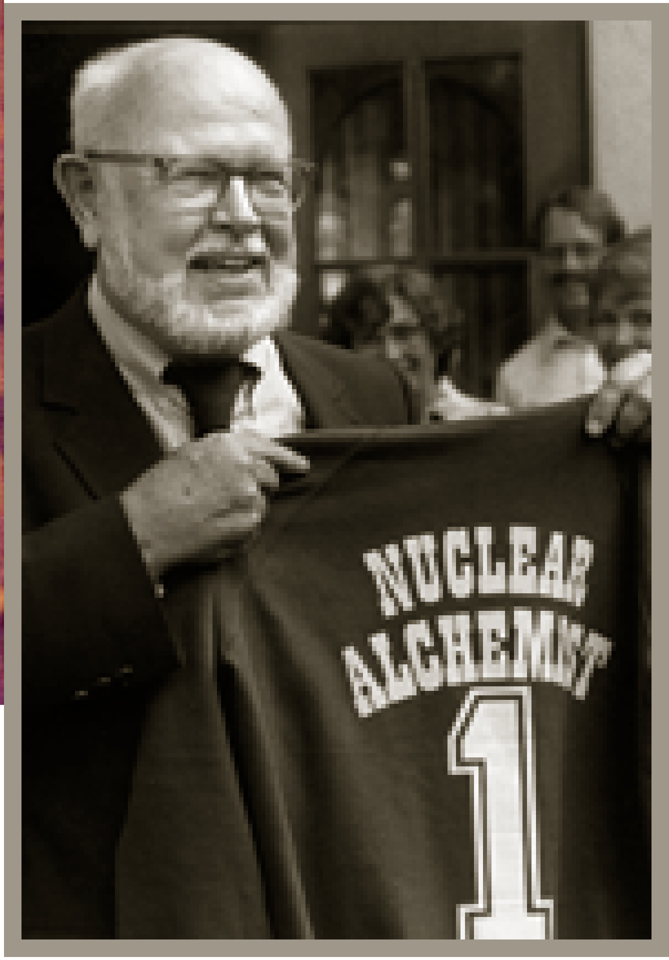


From Langanke

Summary

- Nuclear astrophysics studies have been very successful and there are many more interesting studies to be done.
- Measurements using RI beams will give us a deeper understanding of the Universe
  - Indirect measurement with RIB
    - Coulomb dissociation, ANC, etc
  - Direct measurements with RIB
    - More intense radioactive beams
  - Element abundance, star evolution
  - X-ray burst, novae, supernovae
- KoBRA is one of the first experimental facilities at RAON for nuclear astrophysics and nuclear structure studies using low energy RI beams.





We are all made of stardust that were created by nuclear reactions

감사합니다.