Indirect measurement of astrophysical (n,γ) reaction by neutron-rich ion beams

Wei-ping Liu
CIAE
DREB2007
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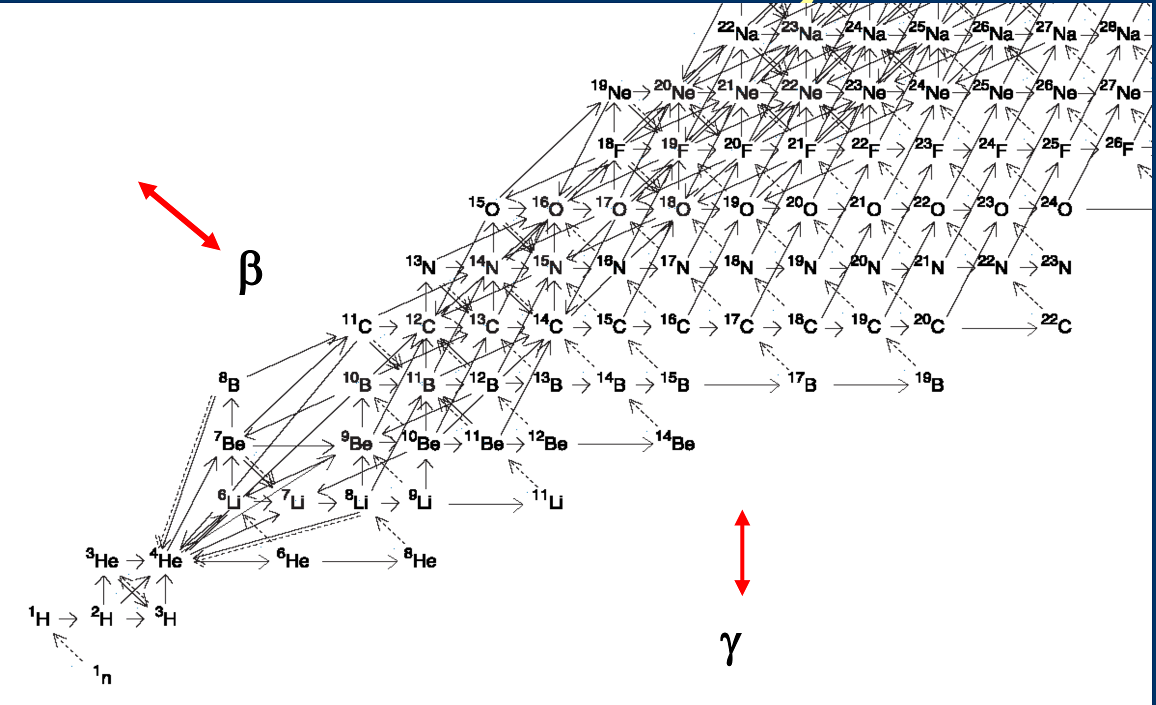
Element synthesis network

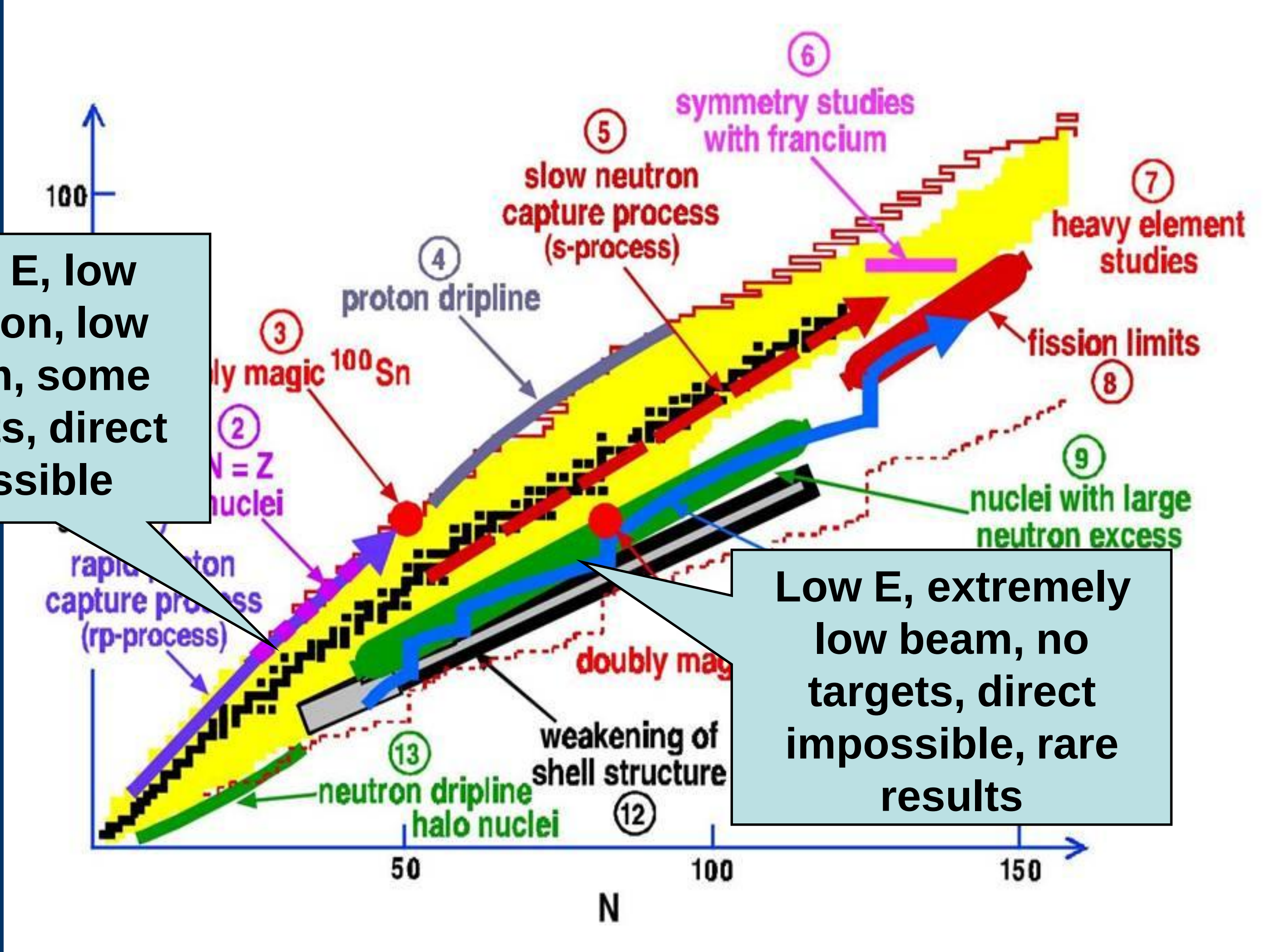


Cross section

$$\frac{dY_i}{dt} = \sum_j N^i_j \lambda_j Y_j + \sum_{j,k} N^i_{j,k} \rho N_A < \sigma V >_{jk,i} Y_j Y_k + \sum_{j,k,l} N^i_{j,k,l} \rho^2 N_A{}^2 < \sigma V >_{jkl,i} Y_j Y_k Y_l$$

Decay half-life

Status of nuclear astrophysics

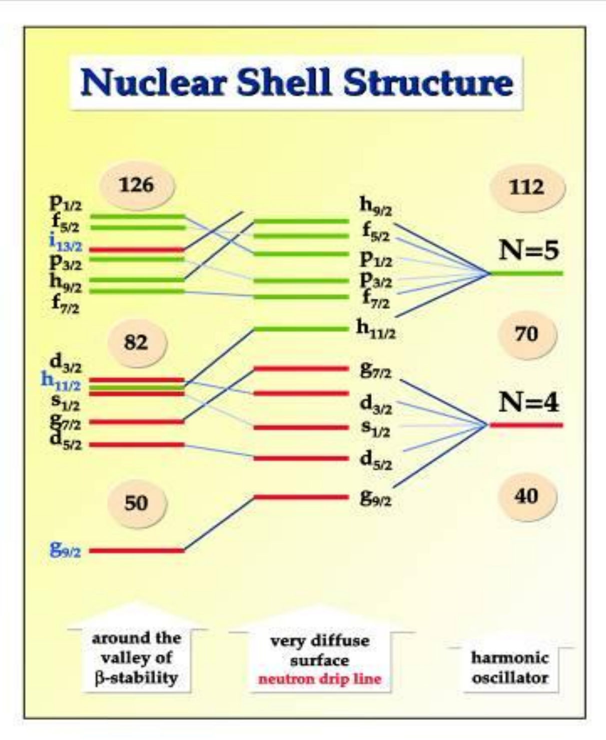


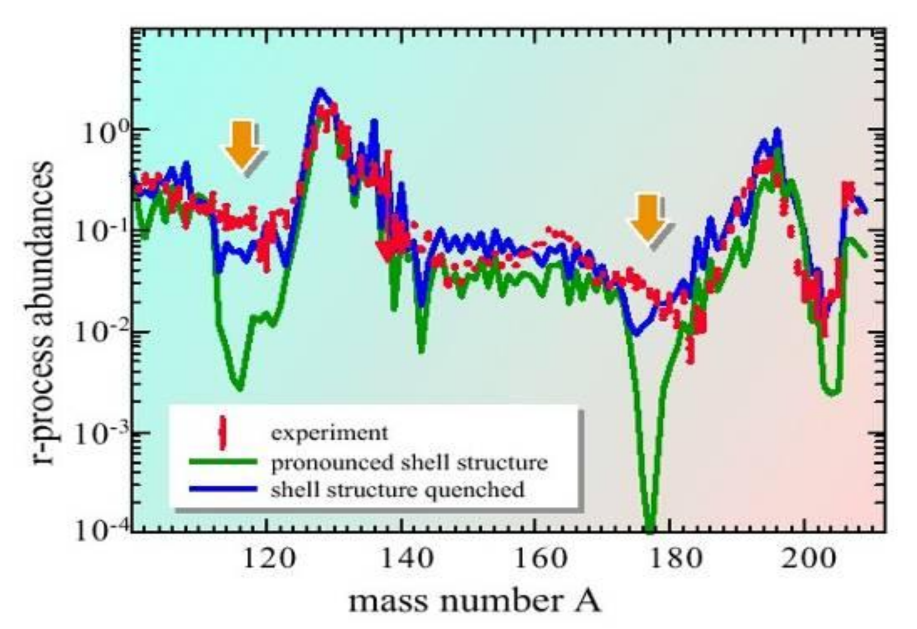
Low E, low section, low beam, some results, direct possible

Low E, extremely low beam, no targets, direct impossible, rare results

r-process and shell quenching

J. Dobaczewski, PRC 53 (96) 2809





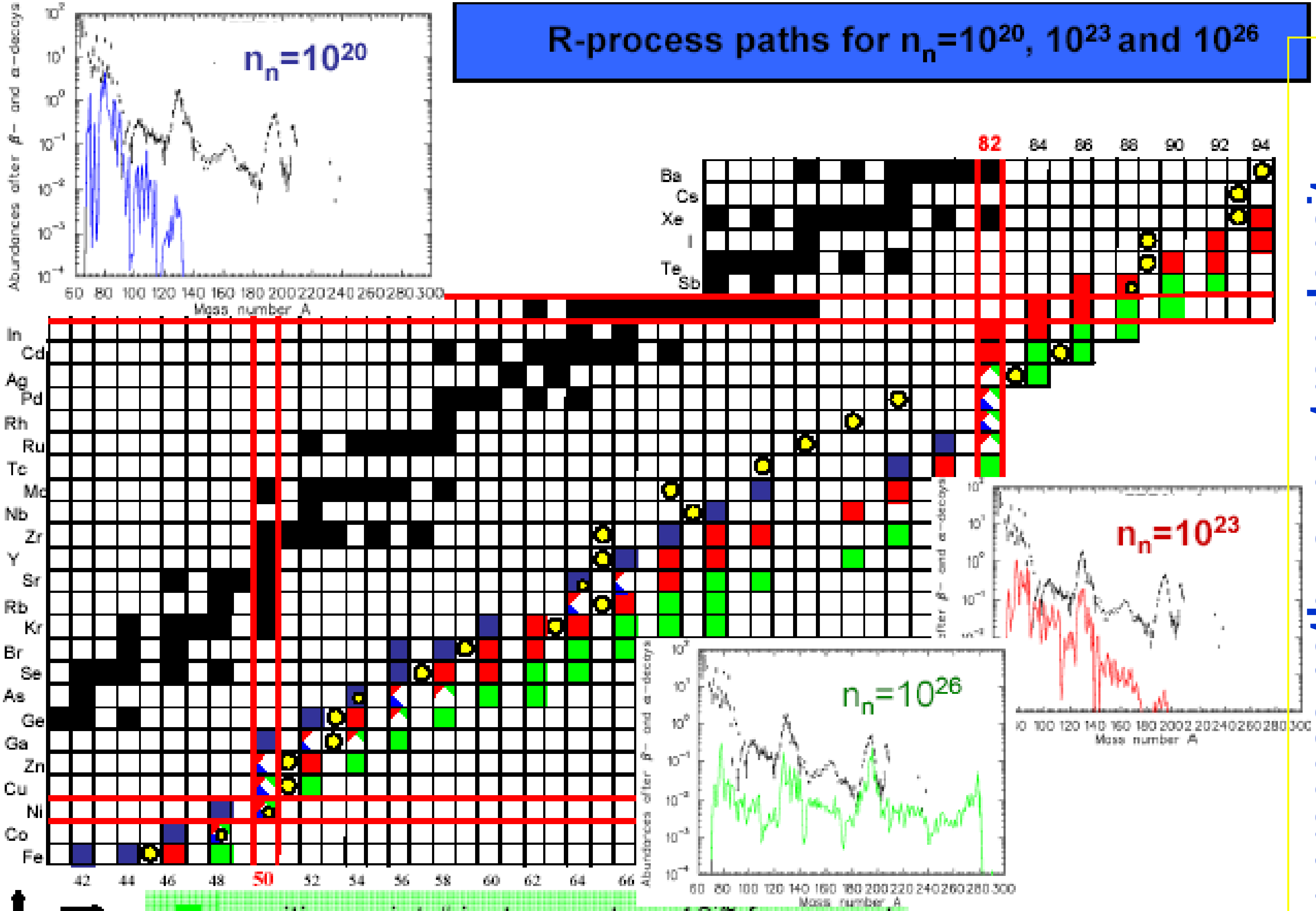
B. Pfeiffer, *et al.*, Z. Physik A357, 253 (1997)

- r-process nuclei is most rarely probed due to its involvement of extremely neutron-richness nuclei
- The shell quenching is predicted in very neutron-rich region due to coupling of pair and surface level, in the same time, it is one of the solution to explain the observed r-process abundance, but so far, its existence has not yet fully verified

physics

- Prominent peaks in the r-process abundance distribution at A=130 and A=195, which corresponds to the r-process path crossing the closed neutron shells at N=82 and N=126 far from stability.
- (γ,n) will determine, the conditions under which (γ,n) (n, γ) equilibrium exists or breaks down.
- Neutron capture rates may also play a role towards the end of the r-process.
- Constraining neutron capture rates on nuclei far from stability poses still a greater challenge.
- Neutron captures can modify the final abundance distribution mainly in the region A>140. Emphasis has to be put on that mass region far from stability.
- See, H. Schatz, NPA758(05)607c, T. Rauscher, NPA758(05)655c

R-process paths for $n_n=10^{20}$, 10^{23} and 10^{26}



🟩 „waiting-points“ isotopes at $n_n=10^{26}$ freeze-out

($T_{1/2}$ exp. : $_{28}$Ni, $_{29}$Cu, $_{47}$Ag – $_{50}$Sn)

★ r-process path vs. neutron density

H. Schatz / Nuclear Physics A 758 (2005) 607c–614c

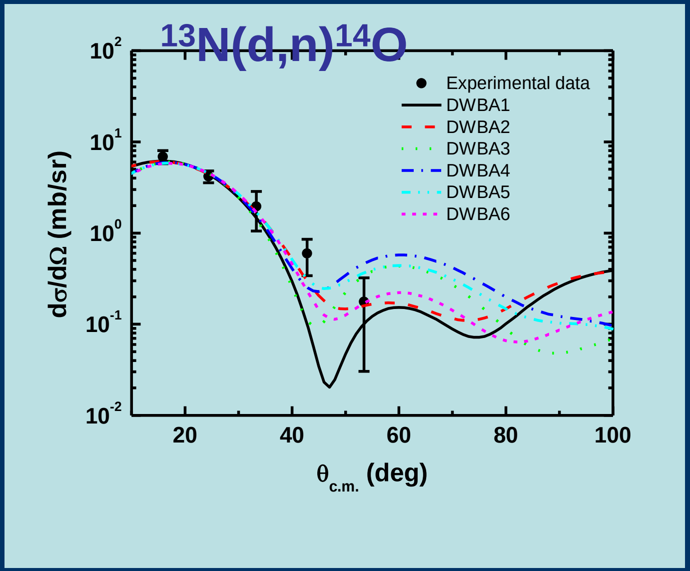
Current progress in in-direct measurement

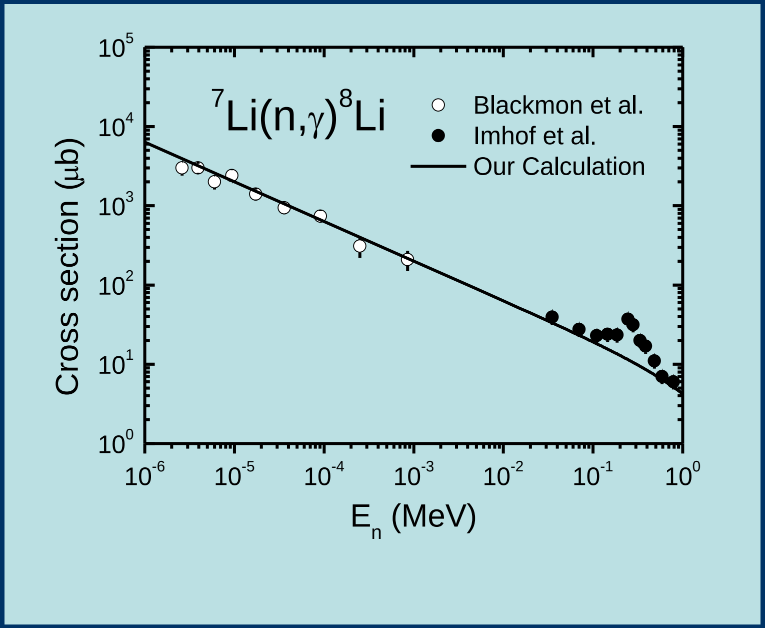
- Direct method, precise have limitation
  - TRIUMF, DRAGON
  - Gran Sasso
- In-direct Method
  - ANC, (p,γ), charge symmetry, CIAE, TAMU, RIKEN
  - Spec-factor, (n,γ), CIAE, GANIL, ORNL
  - Coulomb dissociation, ^{8}B(p,γ)^{9}C, RIKEN, GSI, MSU
  - Break-up reaction, ^{8}B(p,γ)^{9}C, TAMU
  - The study of excited states via thick target, CNS

(p,γ) vs. (n,γ)

- (p,γ)
- One p transfer like (d,n)
- Easy PID, no coin.
- Get ANC
- Peripheral

- (n,γ)
- One n transfer like (d,p)
- Hard PID, coin. with p
- Get spec. factor
- Fix V_0 by known data





From (d,p) to (n,g): the detail

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{exp}} = S_d \sum_{\mathrm{lj}} S_{\mathrm{lj}} \sigma_{\mathrm{lj}}^{DWBA}(\theta)$$

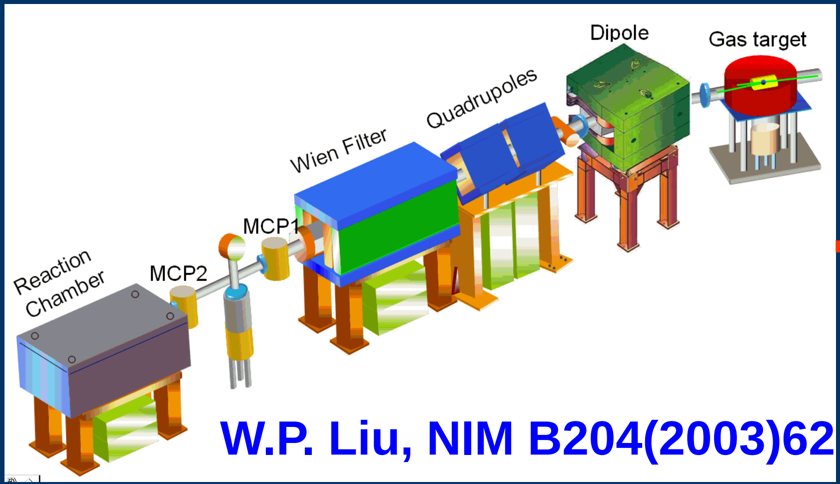
$$\sigma_{n,\gamma} = \frac{8\pi}{9}\left(\frac{E_\gamma}{\hbar c}\right)^3 \frac{e_{eff}^2}{\hbar v} \frac{(2j_f+1)}{(2I_t+1)} \frac{S_{l_f j_f}}{k^2} \left| \int_0^\infty u_{l_f}(r) r^2 w_{l_i}(kr) dr \right|^2$$

Z. H. Li, W. P. Liu et al., The ^{8}Li(d,p)^{9}Li Reaction and the Astrophysical ^{8}Li(n,γ)^{9}Li Reaction Rate, Phys. Rev. C 71 (2005) 052801(R)

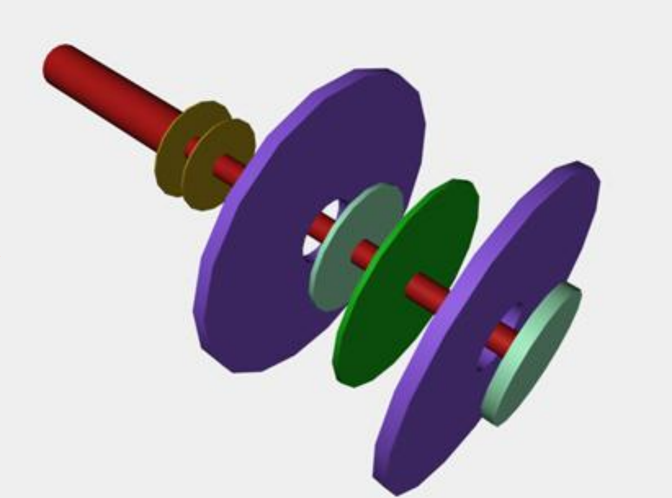
Indirect method for ^{7}Be(p,γ)^{8}B

RIB production

(d,n) or (d,p) measurement



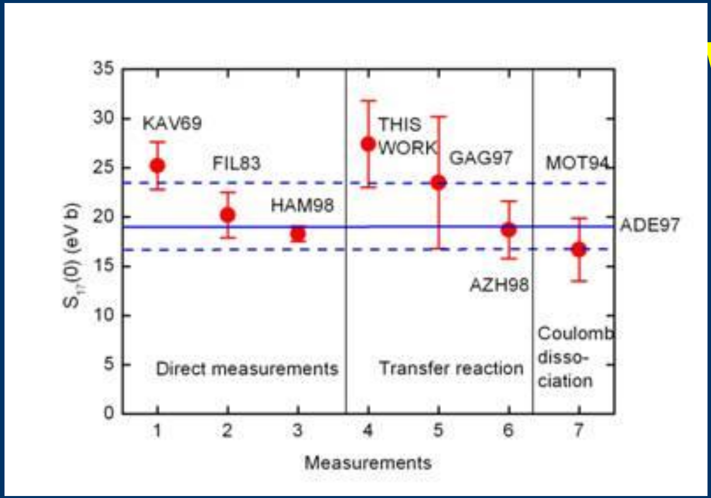
W.P. Liu, NIM B204(2003)62



W.P. Liu, PRL77(1996)611

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{exp}} - \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{CN}} = \sum_{j_i j_f} (C^{\mathrm{d}}_{l_i j_i})^2 (C^{^{12}\mathrm{N}}_{l_f j_f})^2 \frac{\mathrm{d}\sigma^{\mathrm{DW}}_{l_f j_f l_i j_i}/\mathrm{d}\Omega}{b^2_{l_i j_i} b^2_{l_f j_f}},$$

$$\sigma_{\mathrm{t}} = \frac{16\pi}{9}\left(\frac{E_\gamma}{\hbar c}\right)^3 \frac{1}{\hbar v}\frac{e^2_{\mathrm{eff}}}{k^2}\frac{(2j_f+1)}{(2I_1+1)(2I_2+1)} C^2_{\ell_f j_f} \times \left|\int_{R_N}^{\infty} r^2 \mathrm{d}r\, f_{\ell j}(kr) W_{\eta,\ell_f+1/2}(2\kappa r)\right|^2,$$

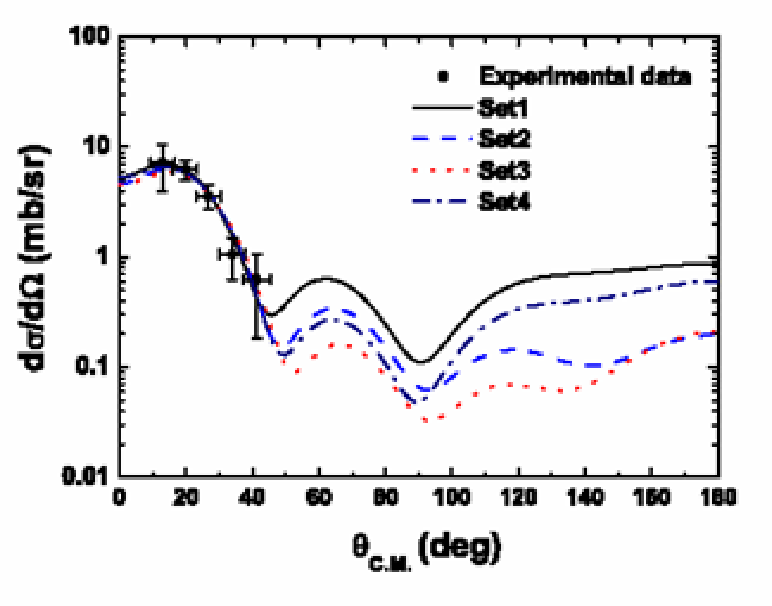


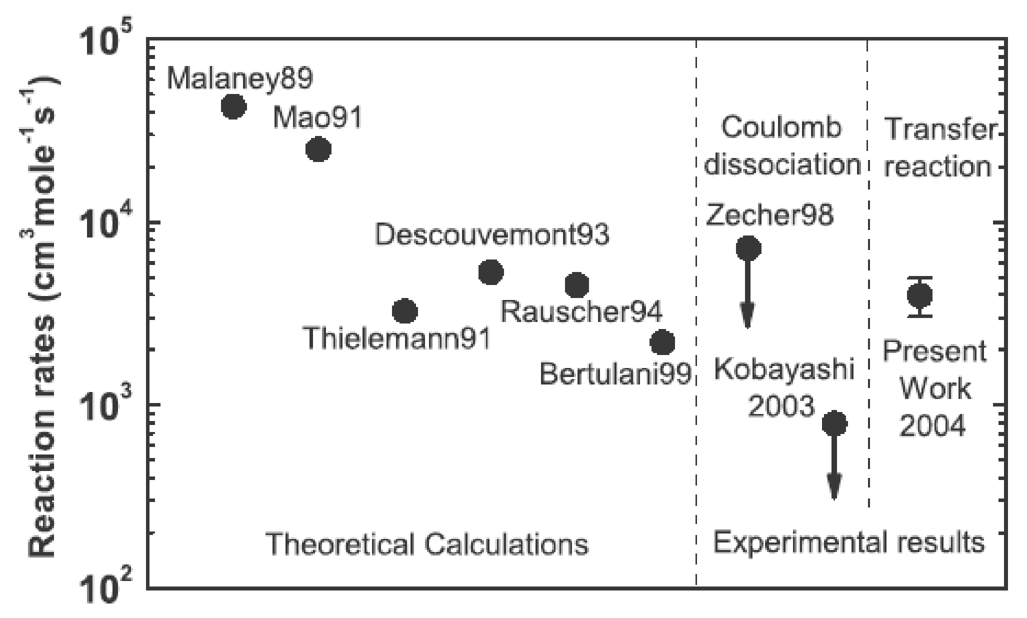
Astrophysical reaction rates

ANC or Spec factor

First measurement of primordial ^{8}Li(n,γ)^{9}Li reaction rate

- Destroy reaction of 8Li: ^{8}Li(n,γ)^{9}Li, ^{8}Li(d,p)^{9}Li in inhomogeneous big bang，APJ429(1994)499
- Half-life of ^{8}Li: 0.83 s，direct (n,γ) exp. impossible

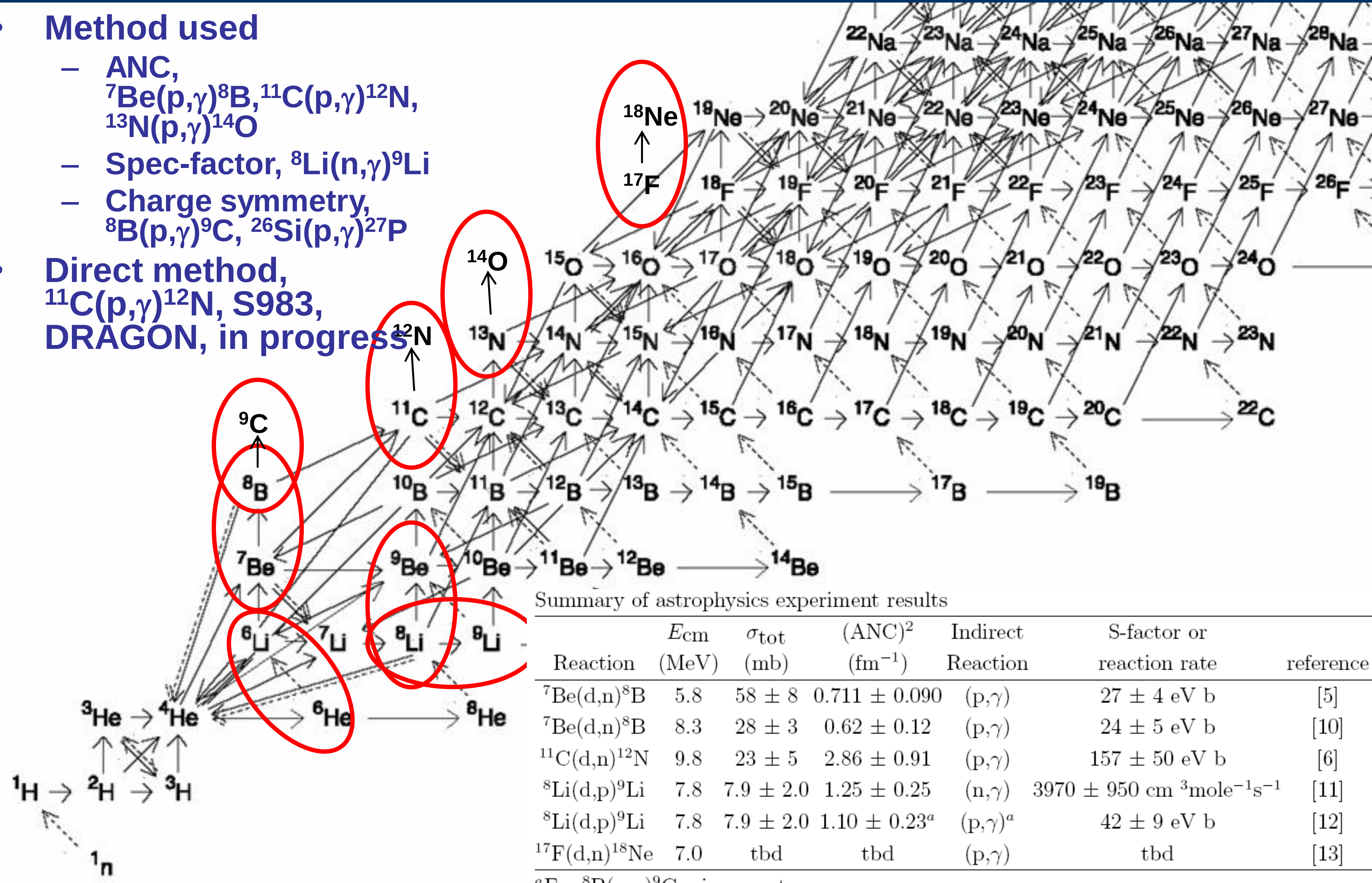




Z. H. Li, W.P. Liu et al.，
PRC 71, 052801(R) (2005)

Summary of reaction studied

- **Method used**
  - **ANC, ^{7}Be(p,γ)^{8}B, ^{11}C(p,γ)^{12}N, ^{13}N(p,γ)^{14}O**
  - **Spec-factor, ^{8}Li(n,γ)^{9}Li**
  - **Charge symmetry, ^{8}B(p,γ)^{9}C, ^{26}Si(p,γ)^{27}P**
- **Direct method, ^{11}C(p,γ)^{12}N, S983, DRAGON, in progress**



Summary of astrophysics experiment results

Reaction	Ecm (MeV)	σ_{tot} (mb)	(ANC)^2 (fm^{-1})	Indirect Reaction	S-factor or reaction rate	reference
^{7}Be(d,n)^{8}B	5.8	58 ± 8	0.711 ± 0.090	(p,γ)	27 ± 4 eV b	[5]
^{7}Be(d,n)^{8}B	8.3	28 ± 3	0.62 ± 0.12	(p,γ)	24 ± 5 eV b	[10]
^{11}C(d,n)^{12}N	9.8	23 ± 5	2.86 ± 0.91	(p,γ)	157 ± 50 eV b	[6]
^{8}Li(d,p)^{9}Li	7.8	7.9 ± 2.0	1.25 ± 0.25	(n,γ)	3970 ± 950 cm ^{3}mole^{-1}s^{-1}	[11]
^{8}Li(d,p)^{9}Li	7.8	7.9 ± 2.0	1.10 ± 0.23^a	(p,γ)^a	42 ± 9 eV b	[12]
^{17}F(d,n)^{18}Ne	7.0	tbd	tbd	(p,γ)	tbd	[13]

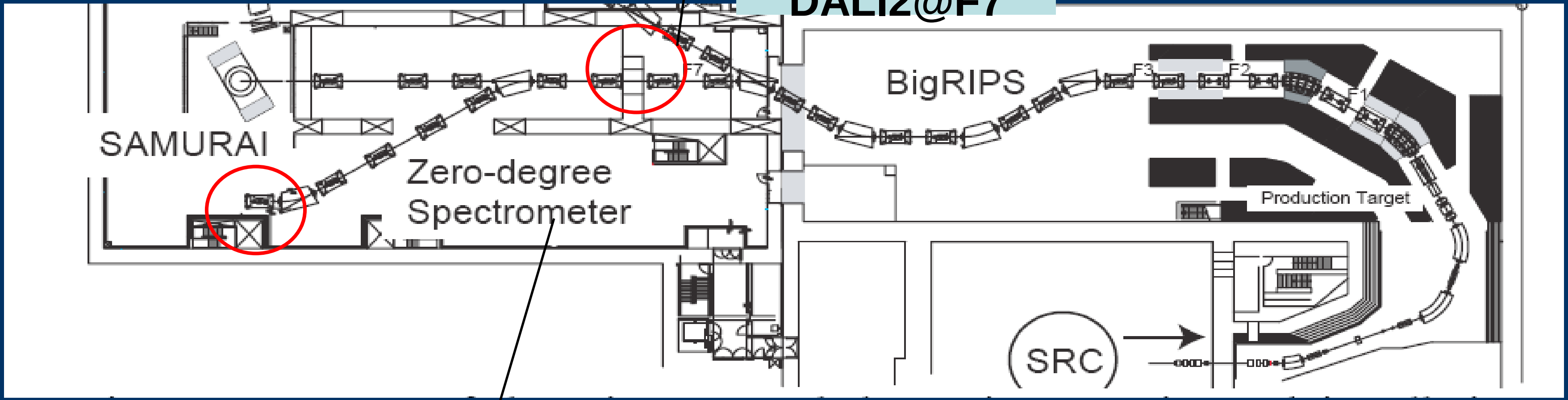
^{a}For ^{8}B(p,γ)^{9}C mirror system.

Think about experiment in RIKEN

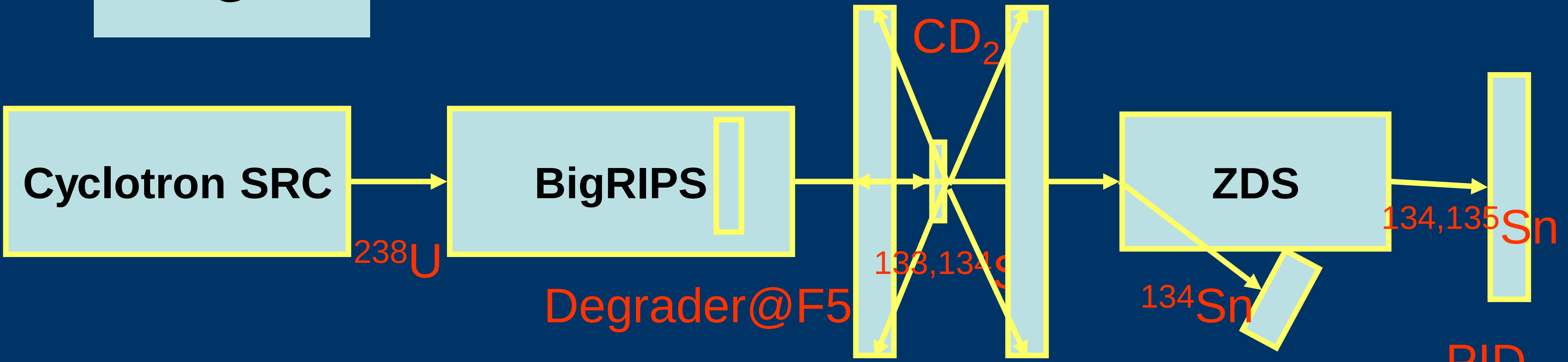
- A natural extension of our method to heavier nuclei
- RRC-SRC provide 345 MeV/u, 2 pnA, ^{238}U beam
- BigRIPS to select a cocktail secondary beam using in-flight fission r-process path nuclei, ^{134}Sn 200 MeV/A in 100-1000 pps
- De-grade beam energy, to 20-40 MeV/u to keep the good transfer reaction domain
- CD_2 or liquid D target in focu plain of BigRIPS surranded by ring silicon detector CPAC and NaI array DALi to tag proton and/or gamma from $(d,p_{0,1})$
- ZDS as a recoil mass separator to identify the residuals and in coincidence with proton
- d,p) angular distribution →spectroscopic factor →microscopic calculation →(n,γ) cross section
- (d,p_0) and (d,p_1) for even-even nuclei→$E(2^+)$ and $B(E2)$

General layout

CD_2, CPAC and DALI2@F7



PID@F11



Cyclotron SRC

^{238}U

BigRIPS

Degrader@F5

CD_2

^{133,134}S

p, CPAC

γ, DALI-2

ZDS

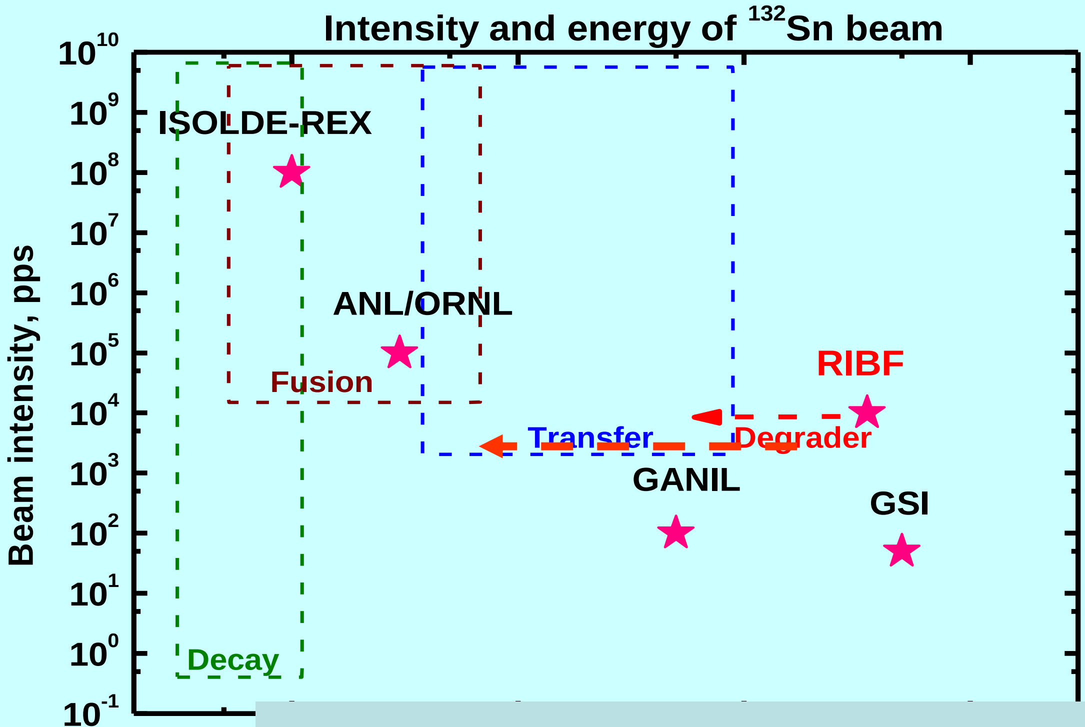
^{134}Sn

^{134,135}Sn

PID

^{238}U 2pnA Pb target

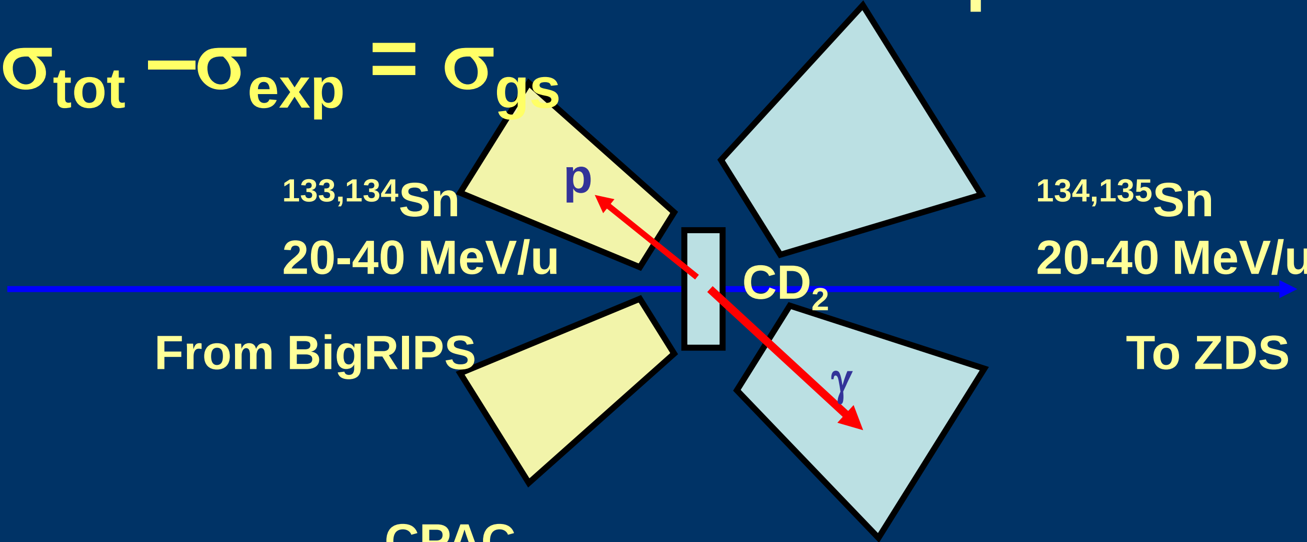
Energy freedom of RIKEN beam



- Higher primary beam energy (345 MeV/u ^{238}U) and in-flight fission to enhance production
- Using degrader in F5 to lower ^{133,134}Sn beam energy from 200 MeV/u to 40 MeV/u

Detector setup

$$\sigma_{tot} - \sigma_{exp} = \sigma_{gs}$$



^{133,134}Sn
20-40 MeV/u

From BigRIPS

p

CD_2

γ

^{134,135}Sn
20-40 MeV/u

To ZDS

CPAC
$140^o<\theta_{lab}<160^o$
$0<E_p<10$ MeV

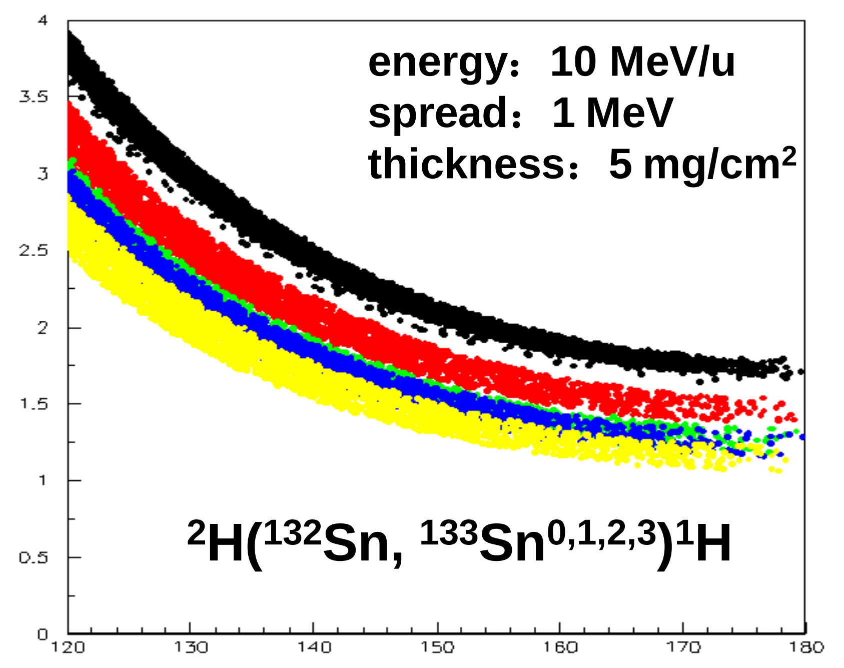
DALI-2
Rest of angular range
$0<E_\gamma<2$ MeV

- $140^o<\theta_{lab}<160^o$, 20 degree
- $0<E_p<10$ MeV
- Si double strip (100 μm, x, y) + Si (300 μm)
- 50x50 mm^2 size, with 3 mm wide strip, 16 strip each side, 10 units

- 160 NaI(TI)
- 16-164 degree
- $\varepsilon=20\%$ for 1 MeV γ with $\beta=0.5$
- $\Delta E/E= 15\%$ for 1 MeV γ

Experimental challenge

- The difficulty due to larger energy and angular spread should be addressed carefully with regard to experimental setup, and BigRIPS de-grading combination
- Because above difficulty, the high resolution of ZDS may not be used, the non-ZDS PID solution should be an alternative.
- Gamma detection with DALI-2 is necessary, in the sense of providing cross check for proton energy group
- To increase counting rate, ^{133}Sn instead of ^{134}Sn, should be considered as a first step



energy：10 MeV/u
spread：1 MeV
thickness：5 mg/cm^2

^{2}H(^{132}Sn, ^{133}Sn^{0,1,2,3})^{1}H

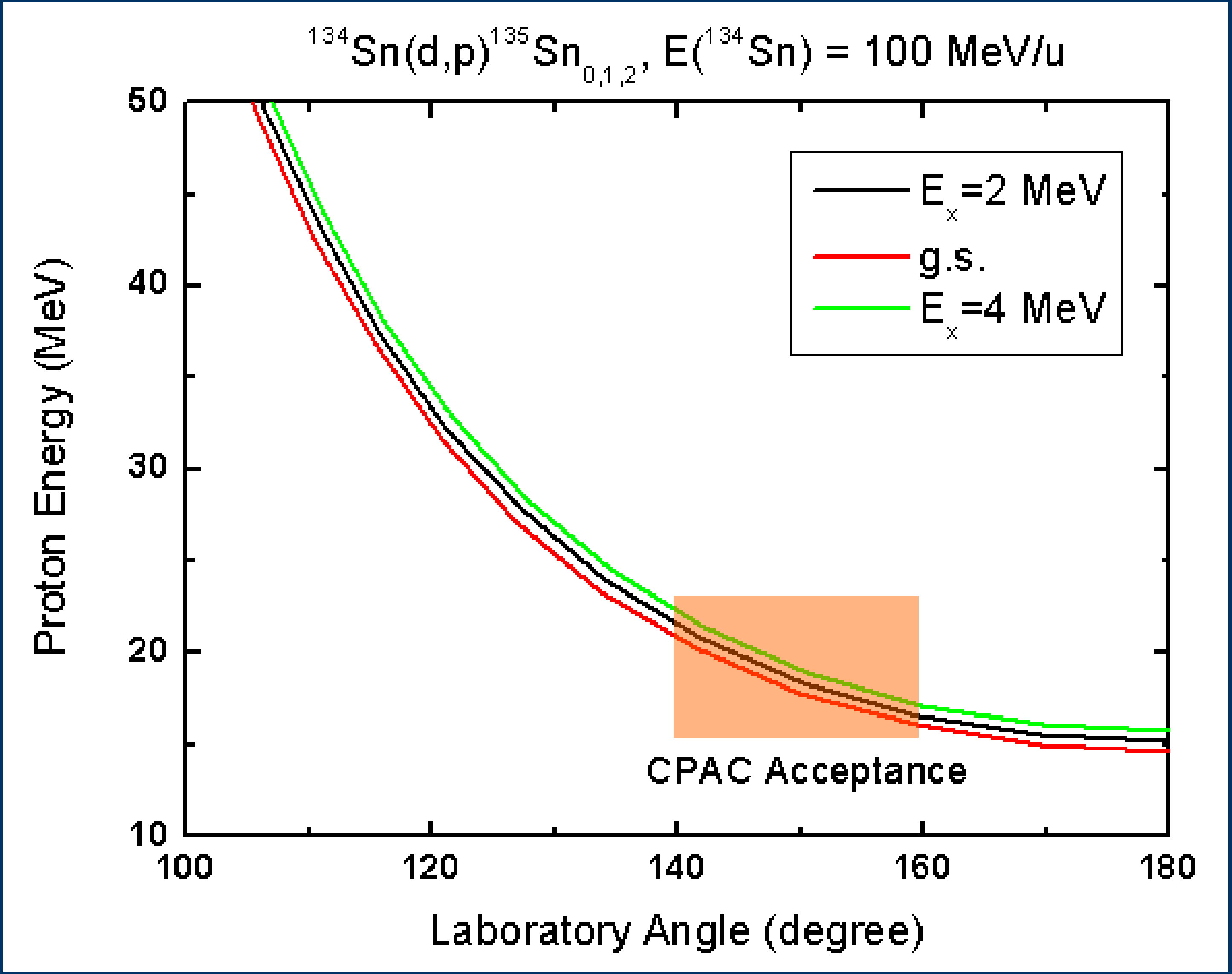
Conclusion

- In-direct reaction is an effective way to measure astrophysics reactions
- Progress have been made in CIAE in ^{8}Li(n,γ)^{9}Li
- SHARP experiment, if overcome the challenges, will provide unique information on r-process and shell evolution
- SHARP experiment will provide an unprecedented opportunities to explore astrophysical r-process
- It will use relatively simple yet clear direct reaction and experimental approach, the essential is well established and tested to be very effective and feasible

Thanks to the following people in SHARP Collaboration

- CIAE: simulation and detector (Z. H. Li), design (Y. B. Wang), theory (Z. Y. Ma, Z. H. Li), general (H.Q. Zhang and X. X. Bai), charge particle detection (C. J. Lin), Gamma alternative (L. H. Zhu), r-process (Y. S. Chen)
- RIKEN: physics, experiment, most of local assistance, BigRIPS tuning, DAQ, more detectors (A. Aoi, H. Otsu) (More participants to be confirmed)
- PKU team, physics, theory, detector, experiment (Y. L. Ye, H. Hua, T. Zheng, Z. H. Li, J. Meng)
- CNS: physics, detector, experiment, S. Kubono, S. Hayakawa, Y. Wakabayashi, H. Yamaguchi
- IMP: nuclear structure, simulation verification and detector assistance (H. S. Xu, Y. H. Zhang et al.)
- Kyushu Univ.: physics, detector, experiment, T. Teranishi, N. Iwasa

CPAC acceptance



Counting rate estimation

- ^{238}U intensity 2 enA, 100 hr beam time, proton coverage 30%, gamma efficiency 10%, recoil efficiency 50%(fully stripped), cross section 10 mb, target thickness 10^{22} atom/cm^2 (xxx mg/cm^2)
- So 5% statistical uncertainty can be achieved for sepc. factor

^{134}Sn, pps	10	100	1000
Proton counts	75	750	7500
Gamma counts	25	250	2500

About cocktail beam

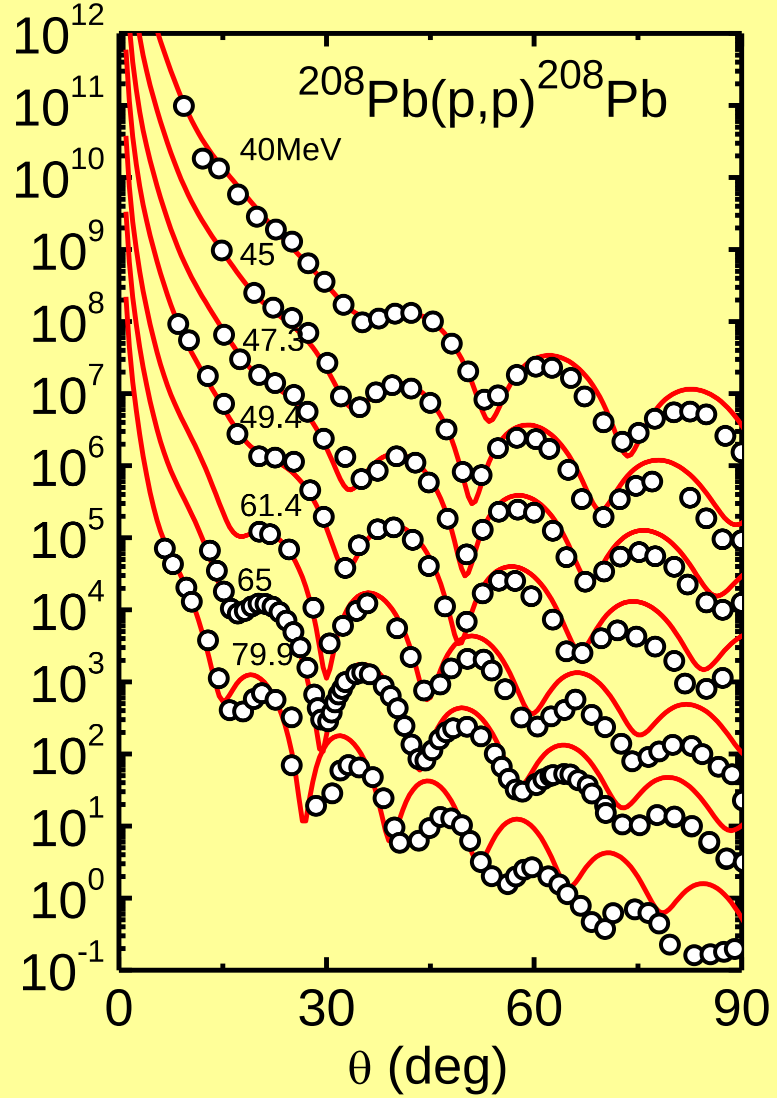
- One RIPS and ZDS setting for ^{134}Sn
- Shows the feasibility of effective beam usage

n =82 chain, even-even				
nuclei	^{130}Cd	^{132}Sn	^{134}Te	^{136}Xe
pps	100	10000	100000	100000

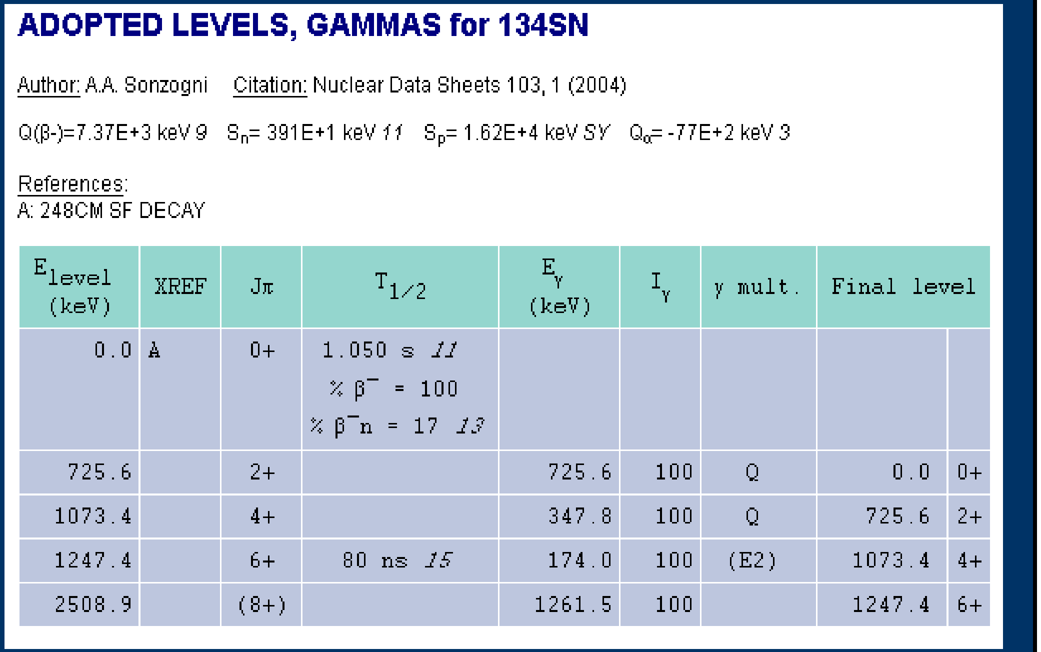
Z =50 chain, even-even				
nuclei	^{128}Sn	^{130}Sn	^{132}Sn	^{134}Sn
pps	10000	10000	10000	100

Where to get optical potential

- **Microscopic calculation by Z. Y. Ma**
- **The optical potential of a nucleon: the nucleon self-energy in the nuclear medium**
- **Real part of RMOP-nucleon self-energy cal. by G matrix**
- **Imaginary part of RMOP is obtained by the G matrix**
- **Can extend to n-rich region**



Data on ^{134}Sn



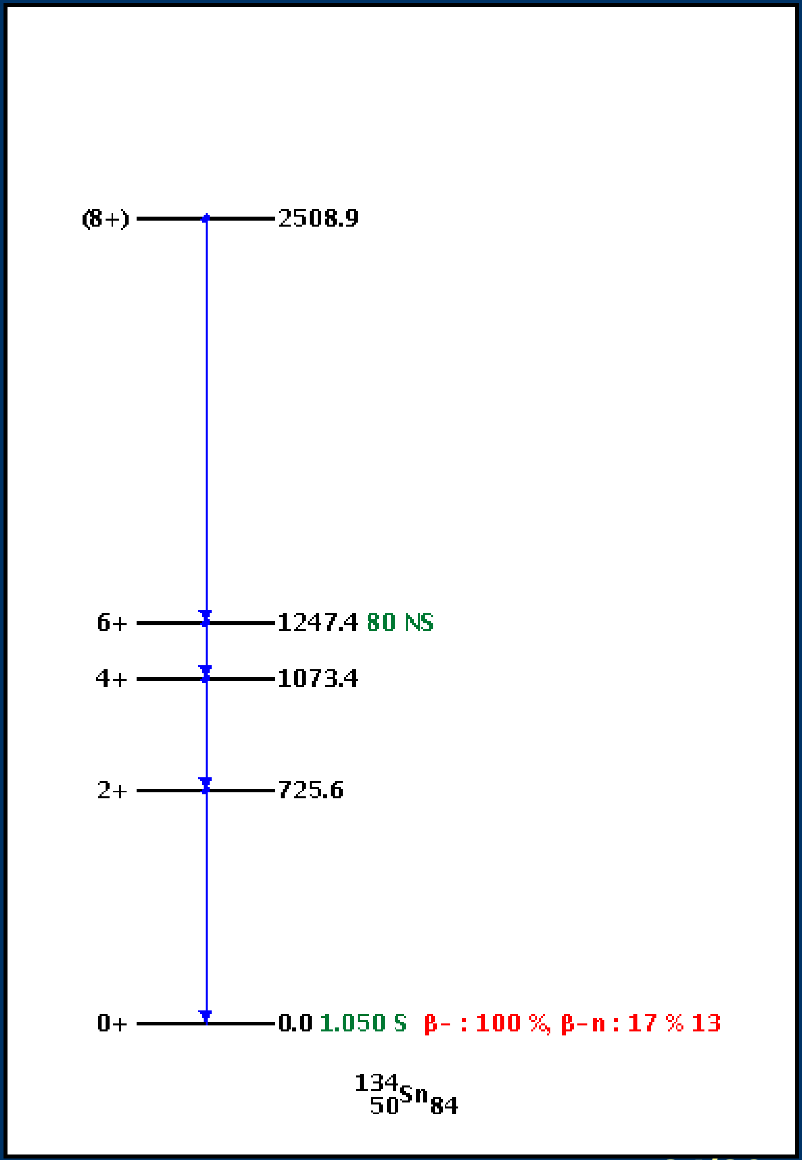
ADOPTED LEVELS, GAMMAS for 134SN

Author: A.A. Sonzogni Citation: Nuclear Data Sheets 103, 1 (2004)

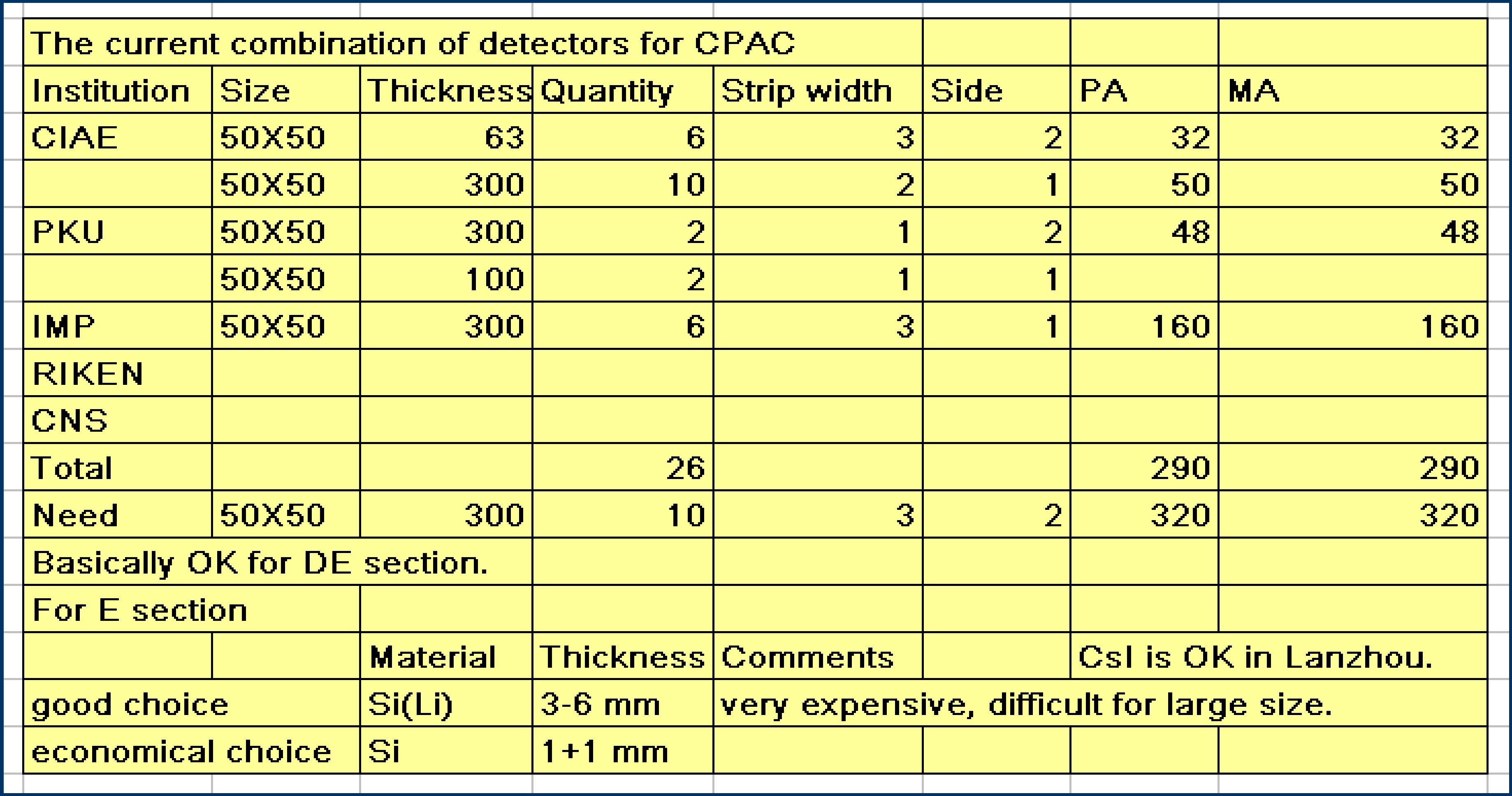
$Q(\beta^-)$=7.37E+3 keV *9* S_n= 391E+1 keV *11* S_p= 1.62E+4 keV *SY* Q_α= -77E+2 keV *3*

References:
A: 248CM SF DECAY

E_{level} (keV)	XREF	Jπ	$T_{1/2}$	E_γ (keV)	I_γ	γ mult.	Final level	
0.0	A	0+	1.050 s *11* $\% \beta^- = 100$ $\% \beta^- n = 17$ *13*					
725.6		2+		725.6	100	Q	0.0	0+
1073.4		4+		347.8	100	Q	725.6	2+
1247.4		6+	80 ns *15*	174.0	100	(E2)	1073.4	4+
2508.9		(8+)		1261.5	100		1247.4	6+

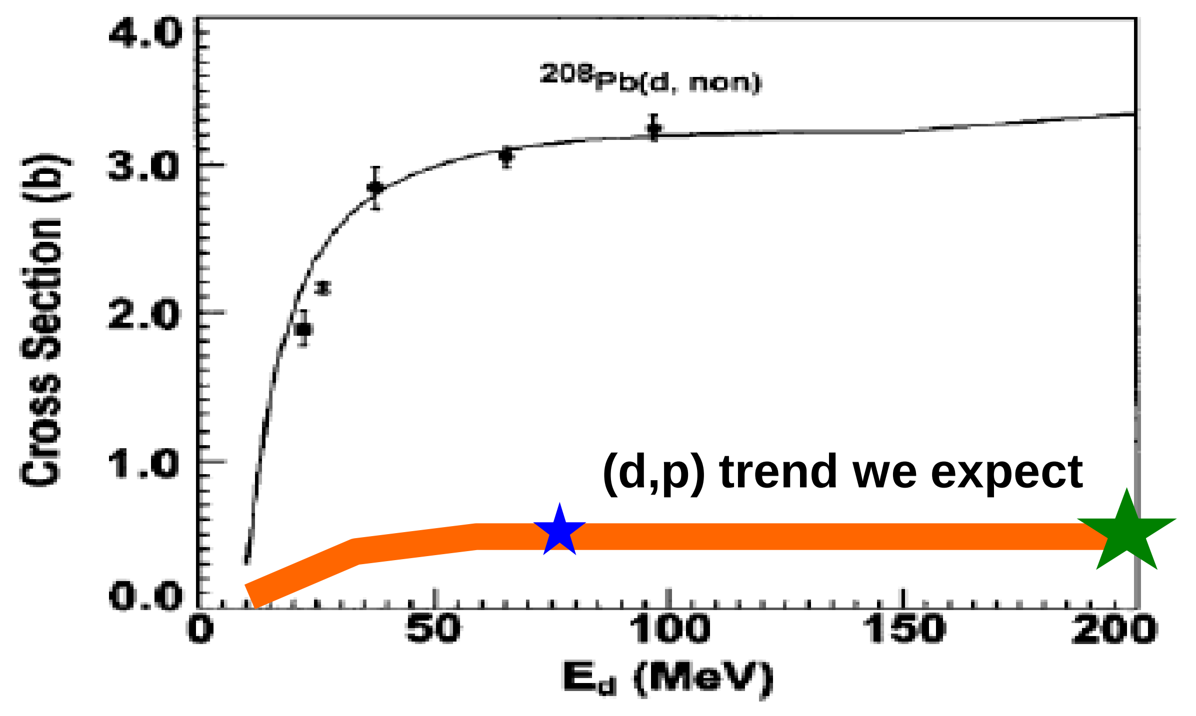


Readiness of CPAC



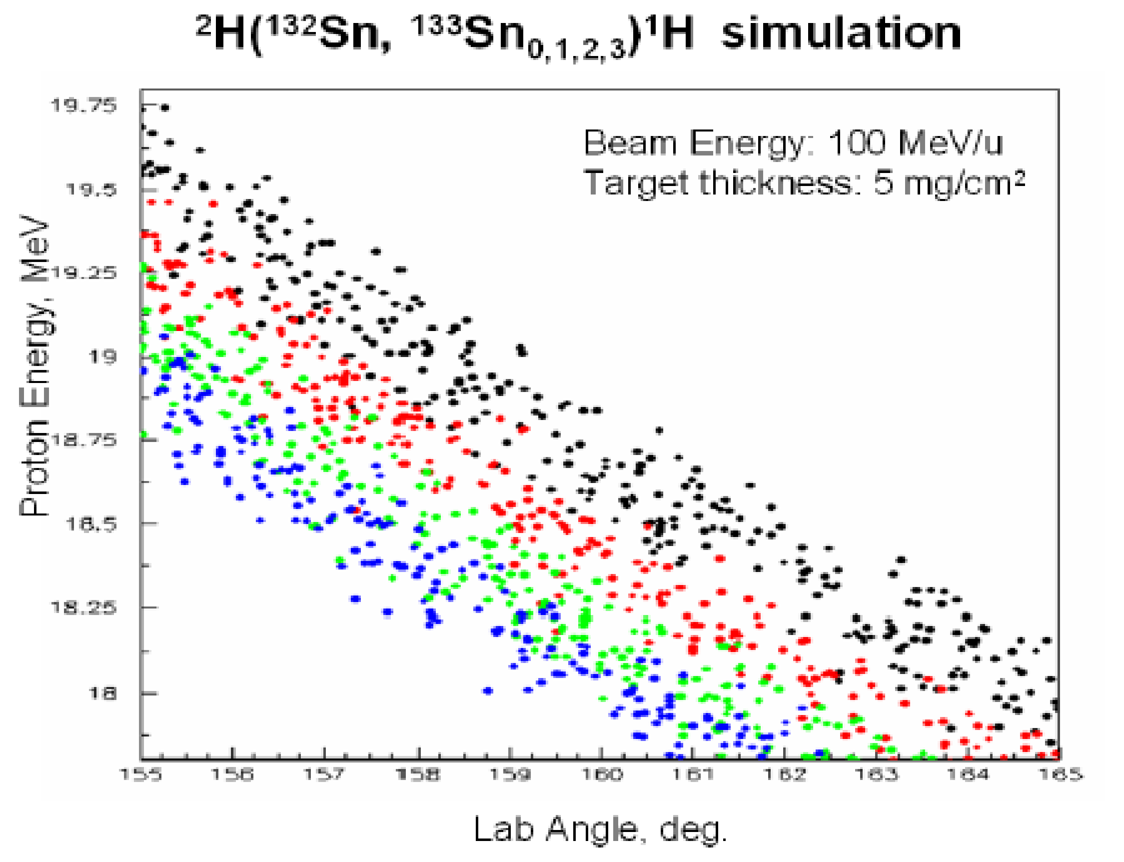
The current combination of detectors for CPAC							
Institution	Size	Thickness	Quantity	Strip width	Side	PA	MA
CIAE	50X50	63	6	3	2	32	32
	50X50	300	10	2	1	50	50
PKU	50X50	300	2	1	2	48	48
	50X50	100	2	1	1		
IMP	50X50	300	6	3	1	160	160
RIKEN							
CNS							
Total			26			290	290
Need	50X50	300	10	3	2	320	320
Basically OK for DE section.							
For E section							
		Material	Thickness	Comments		CsI is OK in Lanzhou.	
good choice		Si(Li)	3-6 mm	very expensive, difficult for large size.			
economical choice		Si	1+1 mm				

Cross section issues



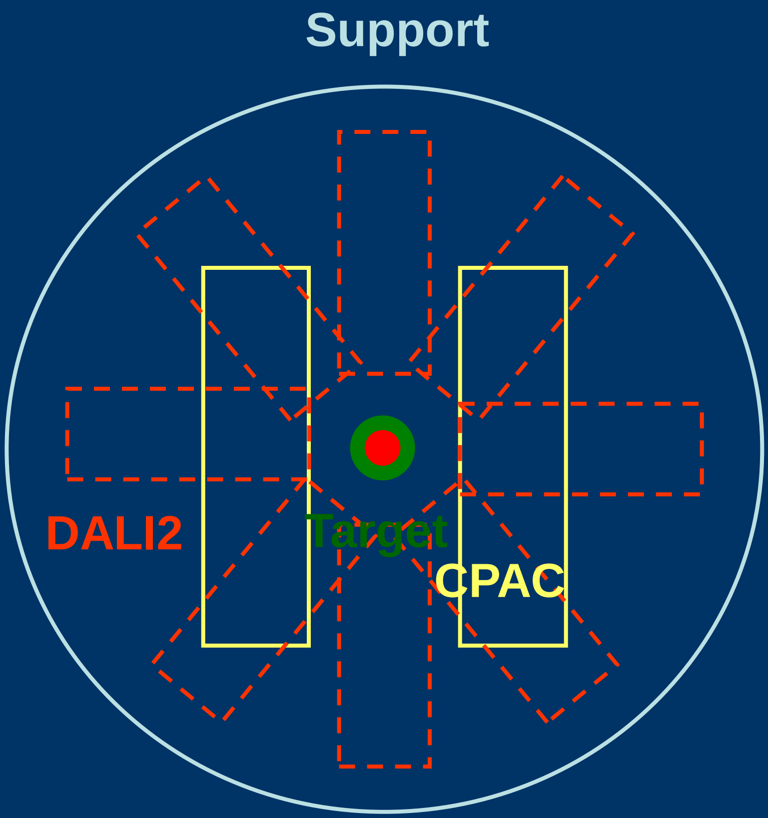
We can expect the (d,p) part, that is in the order of 30 mb at 35 MeV/u, one should conservatively expect the cross section should still be order of 10 mb at 100 MeV/u.

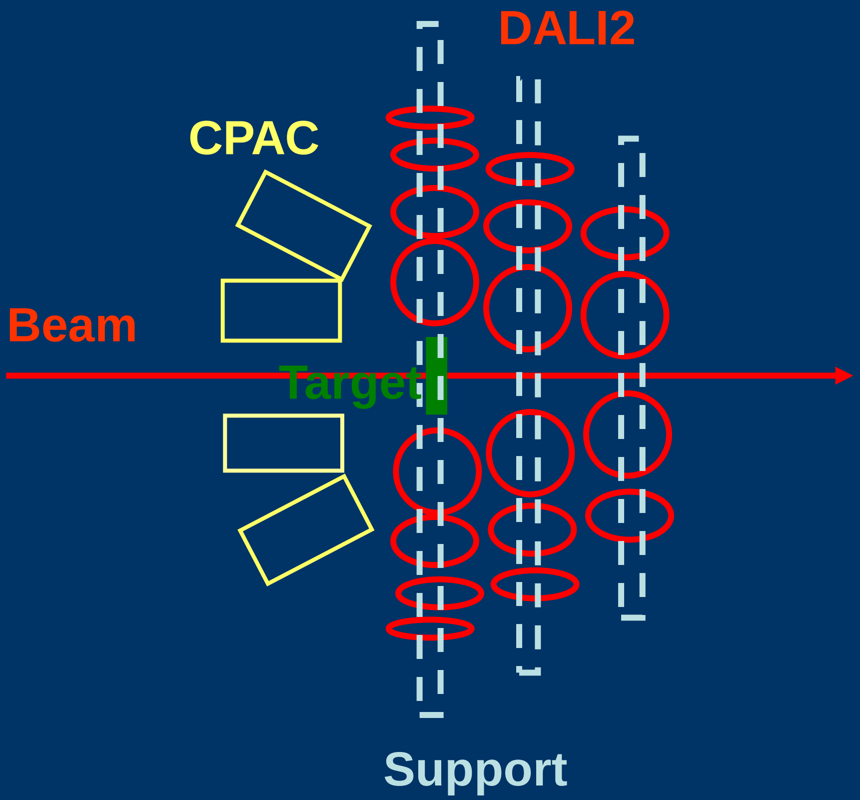
Simulation of resolution



This simulation was based on the experimental data of the excitation energy of ^{133}Sn, with 0.854, 1.561 and 1.656 MeV respectively. Such case can be a rough estimation for ^{134}Sn(d,p)^{135}Sn

Schematic detector setup





Way to PID ^{135}Sn

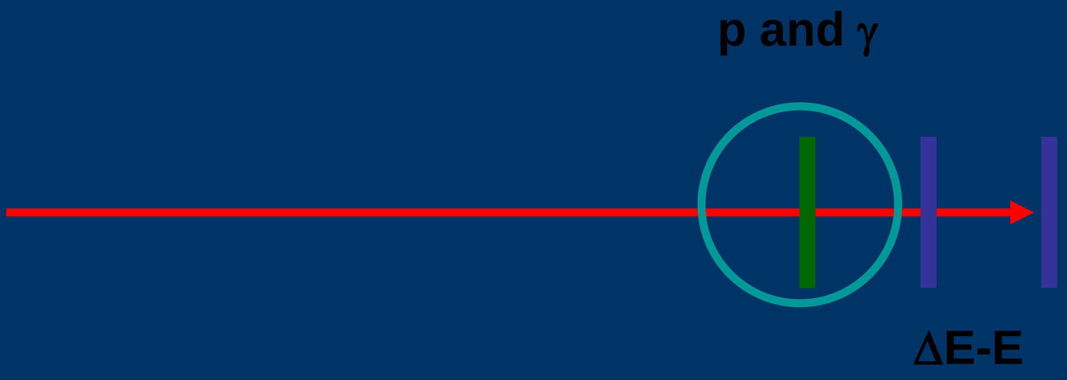
- ZDS DP/P 2000-4000, well resolving peak and tails
- Light PID between p and d to further resolve the possible tails of ^{134}Sn

The ORNL experiment

- **Recently, ORNL measured ^{132}Sn(d,p)^{133}Sn reaction in HRIBF at beam energy of 4.8 MeV/u without particle identification of recoils and measurement of gamma-ray.**
- **We are prepared to measure, e. g., ^{134}Sn(d,p)^{135}Sn, a real r-process data and with good particle identification of recoils and measurement of gamma-ray.**

Beam energy

- Lower beam energy, to 10-20 MeV/u as PAC suggested, and keep detector arrangement basically unchanged
- Feasibility experiment, in GANIL, Solin et al., is 10 MeV/u for Z=18 Ar isotopes (d,p), we are now in Z=50 Sn isotopes, how much more struggling
- (New info, Solin propose to do ^{133}Sn in 10 MeV A, also ORNL is done ^{132}Sn.)
- Give us some confidence in 10 MeV/u, but should be keep in mind that their beam quality is better than us (not intensity!)



Good events = (p and γ in energy window)⊗ Z(ΔE-E)