# Flow of rp process around $^{56}$Ni

## reaction rates for the $^{56}$Ni(p,$\gamma$)$^{57}$Cu, $^{57}$Cu(p,$\gamma$)$^{58}$Zn, ($^{56}$Ni(n,p)$^{56}$Co, $^{64}$Ge(n,p)$^{64}$Ga) reactions

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# Heavier elements than Fe

Arnould 2003

- heavier elements than Fe

  s process

  r procrss

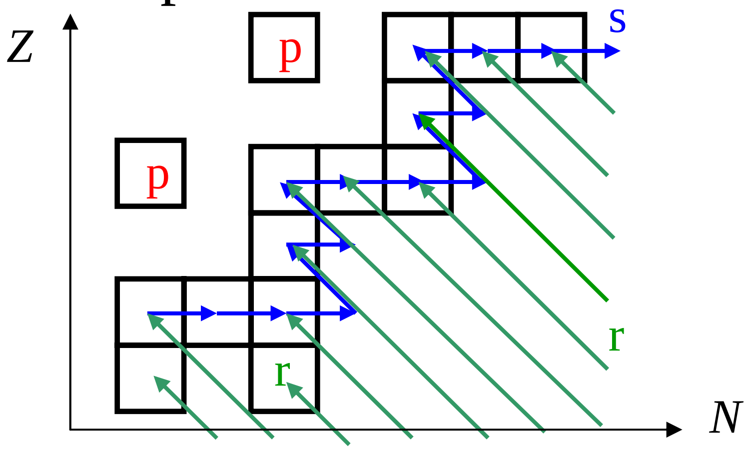
  (n,γ) & $\beta^-$

Arnould, Goriely, Phys.Rep. 384,1
Fig.3

- p nuclides (stable)

  × s process

  × r procrss




s,r process+γ process

proton rich region : $S_p > S_n$

large abundance of $^{92,94}$Mo and $^{96,98}$Ru cannot be explained

# rp process

Schatz et al

Proton-rich region (p,$\gamma$) & $\beta^+$(EC)

Nova, Xray bursts 0.4GK: A<110

Super Nova 1-3GK: up to $^{64}$Ge

waiting points

($^{56}$Ni),$^{64}$Ge, $^{68}$Se, $^{72}$Kr…

long life time

negative or small Q value

for (p,$\gamma$)

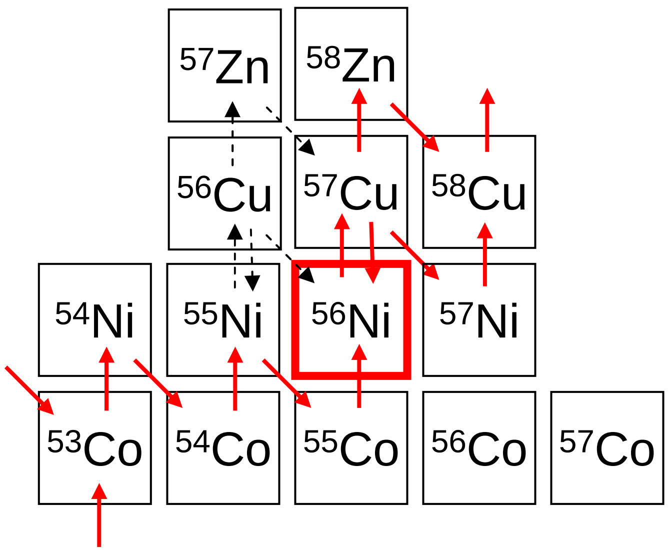
Phys. Rev. Lett. 86 (2001) 3471

# rp process

$^{56}Ni \longrightarrow ^{57}Cu$ reaction rate

$^{56}Ni$ : $T_{1/2}$ = 6 days

$Q_{(p,\gamma)}$ = 0.7MeV

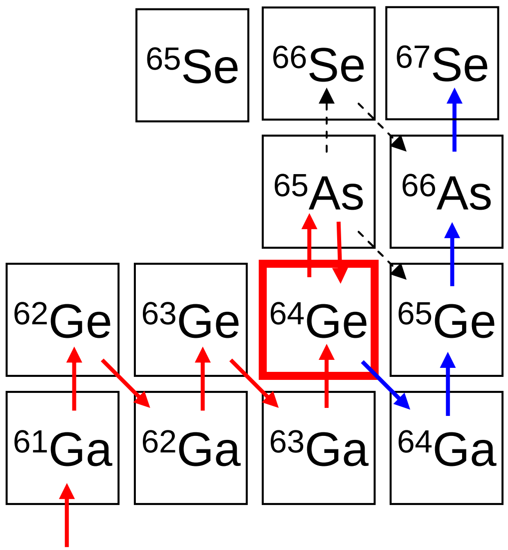



$^{56}Ni$: double magic

$^{64}Ge \longrightarrow ^{65}As$ reaction rate

$^{64}Ge$ : $T_{1/2}$ = 64 s

$Q_{(p,\gamma)}$ = 0.18MeV



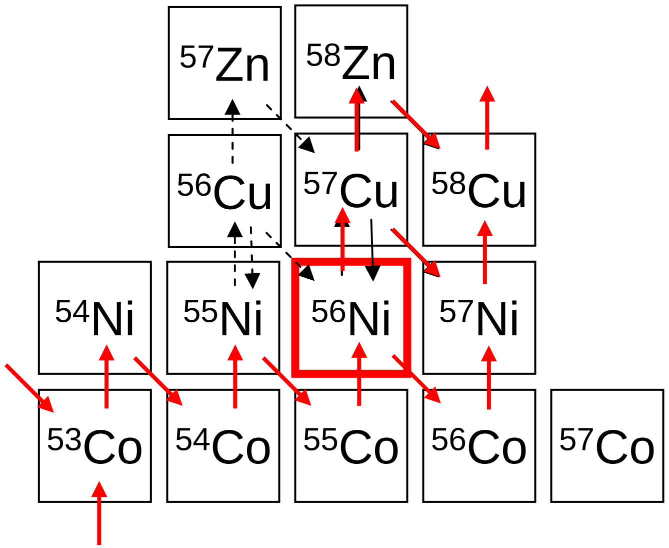

supernova : stop at $^{64}Ge \longrightarrow ^{64}Zn$

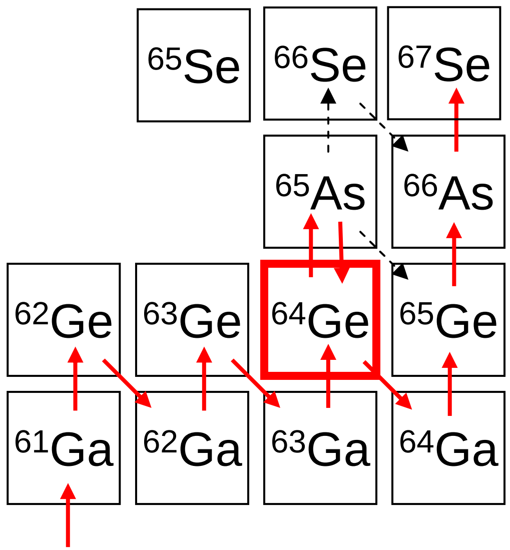
X ray bursts etc.: up to A=110

# νp process

$$p+\bar{\nu}_e \rightarrow n+e^+$$

$$^{56}\mathrm{Ni}+n \rightarrow {}^{56}\mathrm{Co}+p \qquad\qquad {}^{64}\mathrm{Ge}+n \rightarrow {}^{64}\mathrm{Ga}+p$$




Problem on overabundance of P nuclides may be solved

Experimental determination of reaction rates

→precise predictions of p nuclides

Reactions with smaller reaction rates determines reaction rate of the process

$^{56}$Ni(p,γ)$^{57}$Cu, ($^{57}$Cu(p,γ)$^{58}$Zn,) $^{56}$Ni(n,p)$^{56}$Co, $^{64}$Ge(n,p)$^{64}$Ga, $^{68}$Se(n,p),$^{72}$Kr…

# $^{56}Ni(p,\gamma)^{57}Cu$ $S_p$=0.695(19),$T_{1/2}$=196ms

DC component is negligible

- **$^{1}H(^{58}Ni,^{57}Cu\ \gamma)$: Zhou**

  excited states (1.028, 1.106, 2.398 MeV)

  $\Gamma_\gamma$ are not determined.
- $^{2}H(^{56}Ni,p)^{57}Ni$: Rehm

Zhou et al.,Phys. Rev. C53, 982
Fig.2

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- **$^{2}H(^{56}Ni,p)^{57}Ni$: Rehm**

  $C^2S$ of $^{57}Ni$

  same $C^2S$ was used for $^{57}Cu$ assuming the charge symmetry.

  $C^2S(5/2^-)$= 0.91

  $C^2S(1/2^-)$= 0.90

Rhem et al.,Phys.Rev.Lett. 80,676
Fig.2

Rhem et al.,Phys.Rev.Lett. 80,676
Fig.3

→ 1.028

→ 1.106

Rhem et al.,Phys.Rev.Lett. 80,676
Fig.1

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

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  $C^2S$ of $^{57}Ni$

  same $C^2S$ was used for $^{57}Cu$ assuming the charge symmetry.

More reliable determination is necessary

Rhem et al.,Phys.Rev.Lett. 80,676
Fig.4

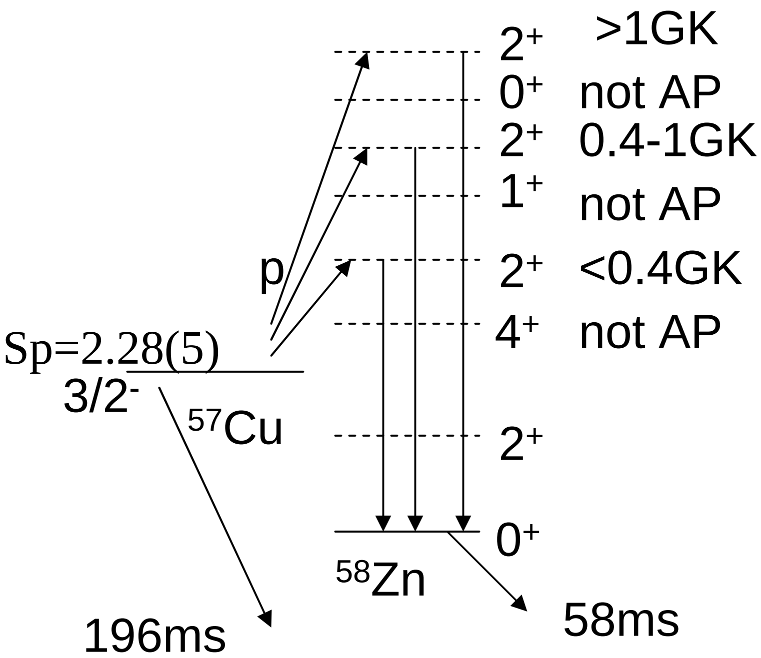
Rhem et al.,Phys.Rev.Lett. 80,676
Table 1

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

FORSTNER, HERNDL, OBERHUMMER, SCHATZ, AND BROWN
PHYSICAL REVIEW C 64 045801

No experimental data

- Forstner, Phys. Rev. **C64**, 045801, 2001
- Experimental determination of $E_x$, $\Gamma_p$ and $\Gamma_\gamma$ is necessary.

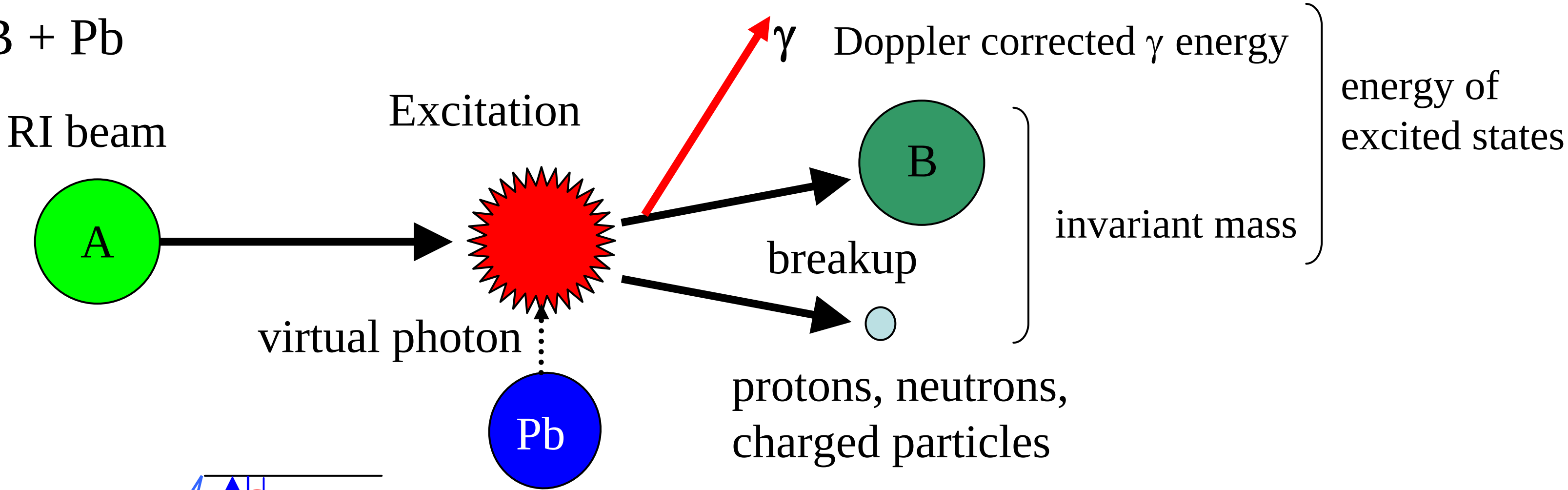


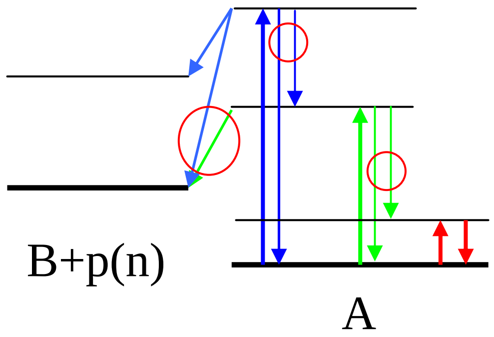

Forstner, Phys. Rev. **C64**, 045801
Table 5

Forstner, Phys. Rev. **C64**, 045801
Fig. 3

# Coulomb dissociation method

- The Coulomb dissociation method is powerful tool to deduce radiative capture cross sections relevant to nuclear astrophysics.
- RIB + Pb




$$\frac{d\sigma_{CD}}{dE} = \sum_{\pi\lambda} \sigma^{\pi\lambda}_{(p,\gamma)} n_{\pi\lambda} \frac{(2I_p+1)(2I_{Be}+1)}{2(2I_B+1)} \frac{2\mu c^2 E}{(E+Q)^3}$$

A+Pb⟶B+p+Pb

↓ Virtual photon theory

A+γ⟶B+p

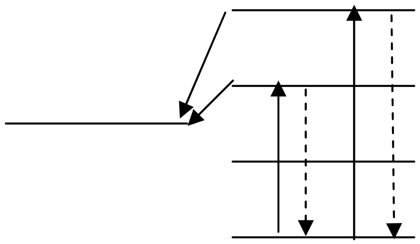
↓ Detailed valance

B+p ⟶ A+γ

# Coulomb dissociation studies on (p,γ) reactions

$$\langle \sigma v \rangle = \left( \frac{2\pi}{\mu kT} \right)^{\frac{3}{2}} \hbar^2 \omega \frac{\Gamma_p \Gamma_\gamma}{\Gamma} \exp\left( -\frac{E_R}{kT} \right)$$

$\Gamma_p >> \Gamma_\gamma$

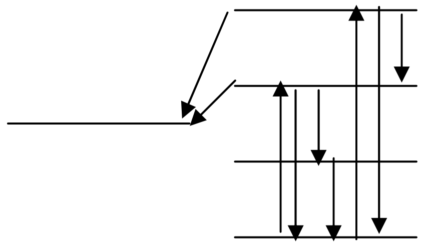


$$\langle \sigma v \rangle \approx \left( \frac{2\pi}{\mu kT} \right)^{\frac{3}{2}} \hbar^2 \omega \Gamma_\gamma \exp\left( -\frac{E_R}{kT} \right)$$

$E_x$ (inv. mass)

reaction rate

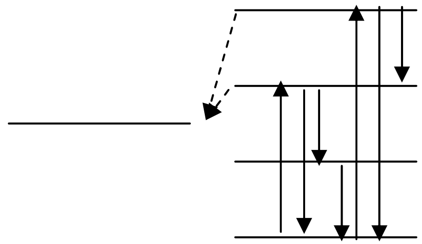
$\Gamma_p \approx \Gamma_\gamma$



$E_x$ (inv. Mass & $E_\gamma$)

reaction rate

$\Gamma_p << \Gamma_\gamma$



$$\langle \sigma v \rangle \approx \left( \frac{2\pi}{\mu kT} \right)^{\frac{3}{2}} \hbar^2 \omega \Gamma_p \exp\left( -\frac{E_R}{kT} \right)$$

Energy ($E_\gamma$)

$\Gamma_\gamma$

reaction rate → difficult ?

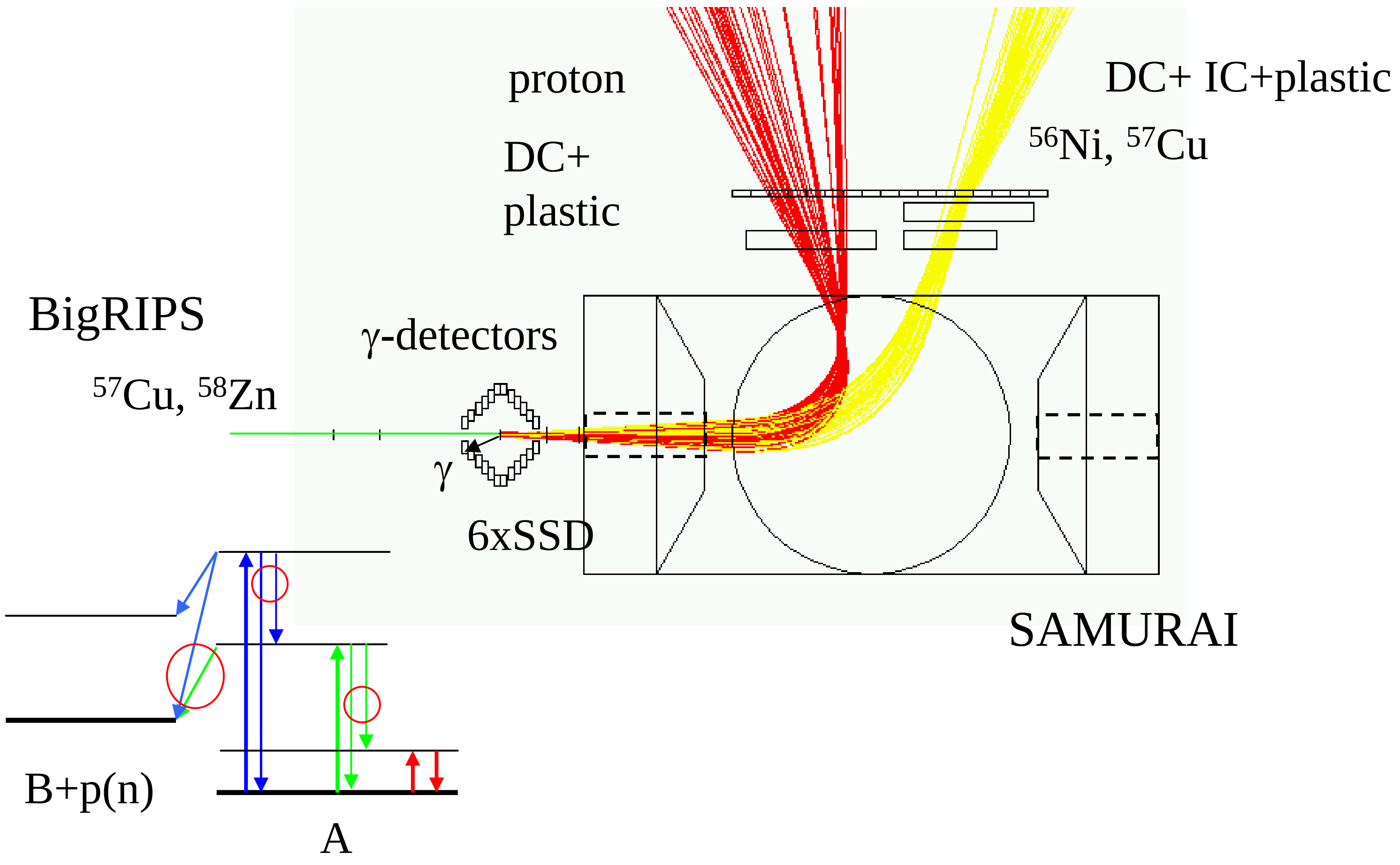
CB cross section is too small.

Alternative method ?

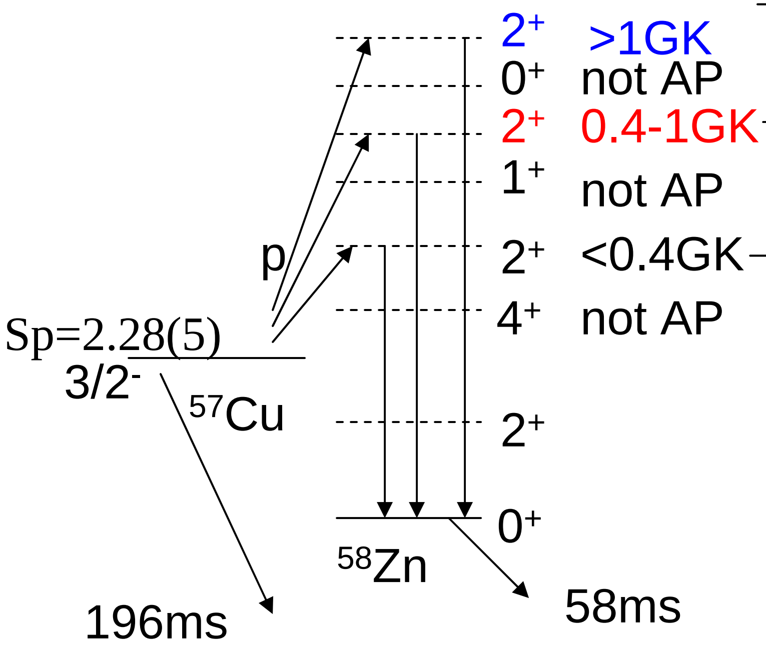
# Experimental setup in RIBF

We are planning to perform measurements of reactions in the rp and r processes in RIBF.

- rp process ($\gamma$,p)



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




$\rightarrow \Gamma_p >> \Gamma_\gamma$ Excitation energy, reaction rate

$\rightarrow \Gamma_p \approx \Gamma_\gamma/10$ Excitation energy, reaction rate branching ratio

$\rightarrow \Gamma_p << \Gamma_\gamma$ Excitation energy

The reaction rate will be determined from an experiment of the Coulomb dissociation of $^{58}Zn$.

Forstner, Phys. Rev. **C64**, 045801 Fig. 3

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

Rehm et al., Phys. Rev. Lett. **80**, 676, 1998

Rhem et al.,Phys.Rev.Lett. 80,676
Table 1

g.s. $3/2^-$

1.028 and 1.106 MeV states $\Gamma_p << \Gamma_\gamma$

$\Gamma_p << \Gamma_\gamma$: CD ×

2.398 MeV states: M1/E2 mixture → CD

angular distribution → M1/E2 ratio ?

branching ratio

2.520 MeV states: E2 → CD

Rhem et al.,Phys.Rev.Lett. 80,676
Fig.4

Reaction rate for T>1.2GK can be determined.

For T<1.1GK, ?

# To determine $\Gamma_p$ from experiments

- $\Gamma_p$<<1 eV: Transfer reaction

$$\Gamma_p = C^2 S \Gamma_p^{SP}$$

*S*: determined from experiments
→ stripping reaction

•(d,n) in reverse kinematics
energy and scattering angle of neutron should be measured, precisely to select ex. states.
thermal neutron? scattering ?
efficiency?

Rehm et al.
$^{56}$Ni+d→ $^{57}$Cu+n ×
→ $^{57}$Ni+p ○

- $^{56}$Ni+d→$^{57}$Cu+n+γ at ～50*A*MeV

Rehm $^{56}$Ni+d→$^{57}$Ni*+p 8*A*MeV
$\sigma_{tot}$～20mb
→$^{57}$Cu+n+γ at 40*A*MeV
assuming 1mb ?
5mm Liq. (Sol.) $D_2$ target
(energy deposit: 17AMeV)
beam 100 cps, gamma eff.～20%
$^{57}$Cu eff.～80% → 35 counts/day?

Separation of the 1.028 and 1.106 MeV state ?

feeding from higher excited states?

# ($^{3}$He,d) reaction in reverse kinematics

- ($^{3}$He,d) reaction

  Iliadis and Wiescher, PRC69, 064305 (2004)

$$\frac{d\sigma}{d\Omega} = N \frac{2J_f + 1}{2J_i + 1} \frac{1}{2j+1} \boxed{C^2 S} \frac{d\sigma^{\mathrm{DWBA}}}{d\Omega}$$

  $N$ = 4.42 for ($^{3}$He,d) by P.D. Kunz

  Hale *et al*. PRC70, 045802(2004)

  $^{23}$Na($^{3}$He,d)$^{24}$Mg→(p,γ), (p,α)

  Reverse kinematics & RI ?

- $^{3}$He($^{56}$Ni,d$^{57}$Cu)→$^{56}$Ni(p,γ)$^{57}$Cu

  1028, 1106 keV states

  $\Gamma_p << \Gamma_\gamma$

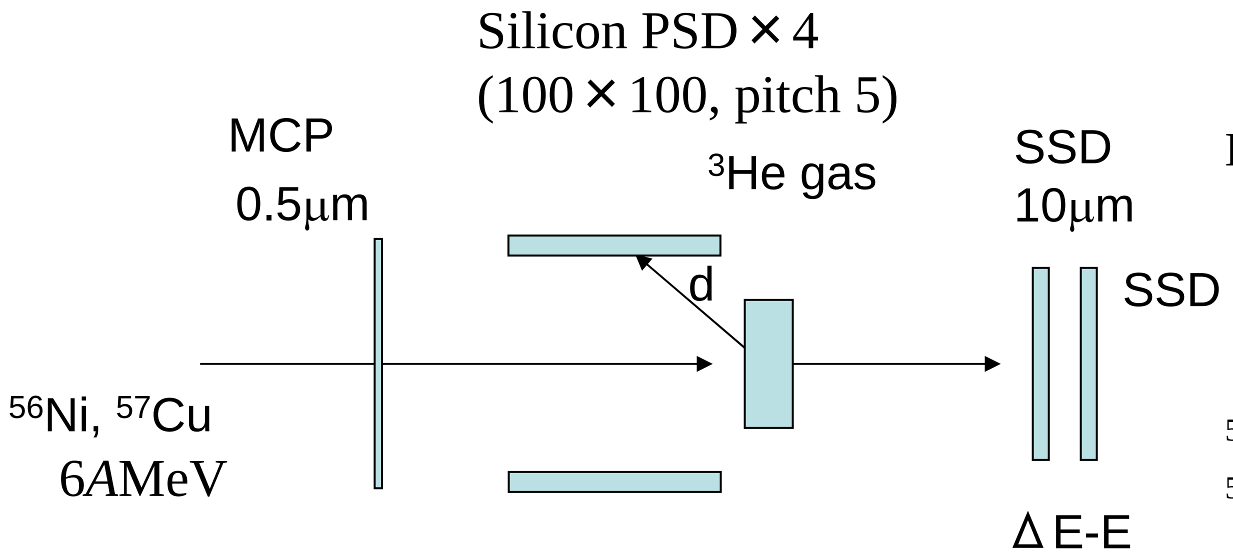
  $C^2S$～0.9 estimated by Rehm

  $\sigma^{\mathrm{DWBA}}$～10mb @5 *A* MeV

# A example of experimental setup

reaction:
($^3$He,p), ($^3$He,d), ($^3$He,2p)…

Back scattering
($^3$He,d), ($^3$He,2p)




$^{56}$Ni($^3$He,d)$^{57}$Cu
$^{56}$Ni($^3$He,2p)$^{57}$Ni

$E_{in}$=5 AMeV

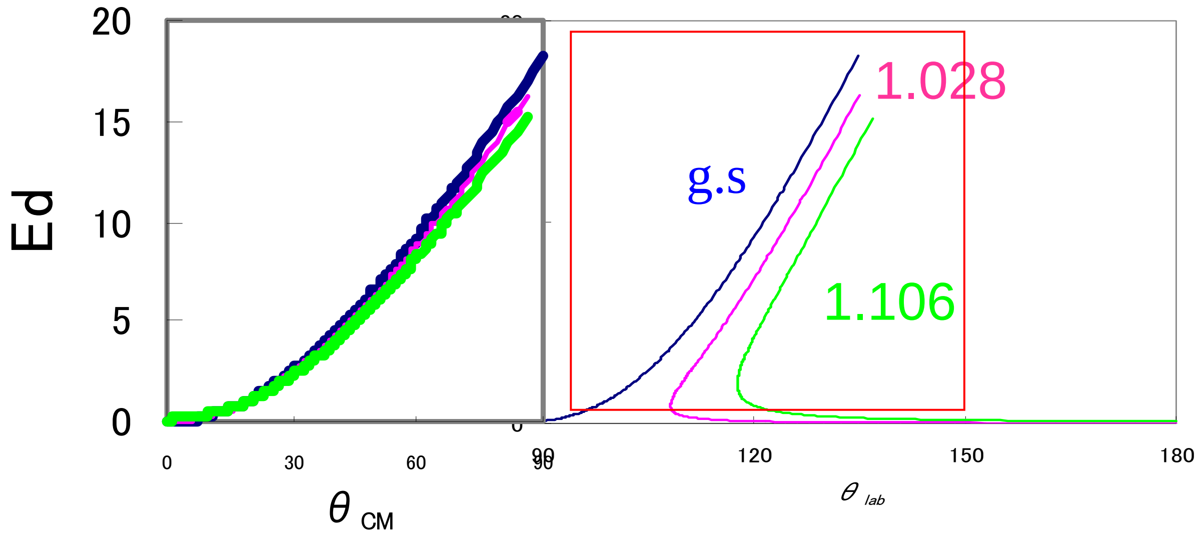
Beam? 10$^4$cps

5mm$^t$ $^3$He gas 1mb

Efficiency 50%

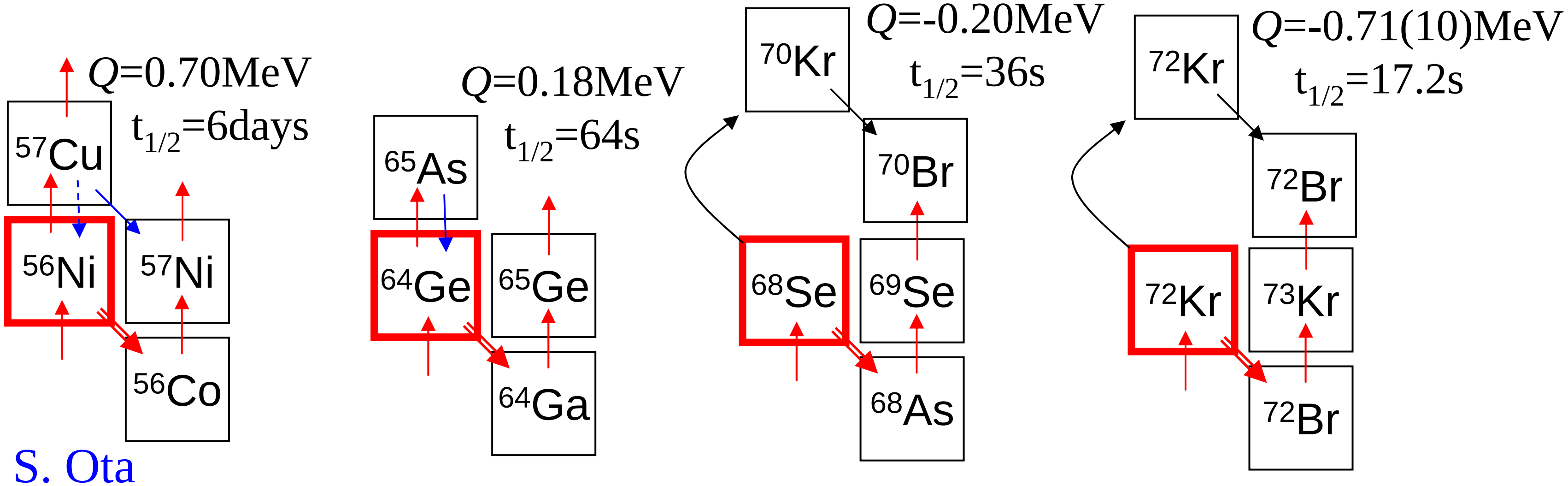
～5 event/day

Higher energy?



# To determine the (n,p) cross section

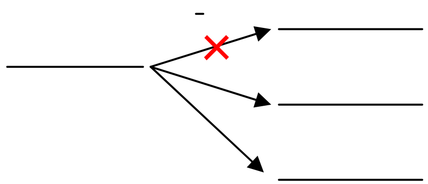
- $^{56}$Ni(n,p), $^{64}$Ge(n,p), $^{68}$Se(n,p), $^{72}$Kr(n,p) reactions are of crucial importance to determine reaction rate of the νp process




S. Ota

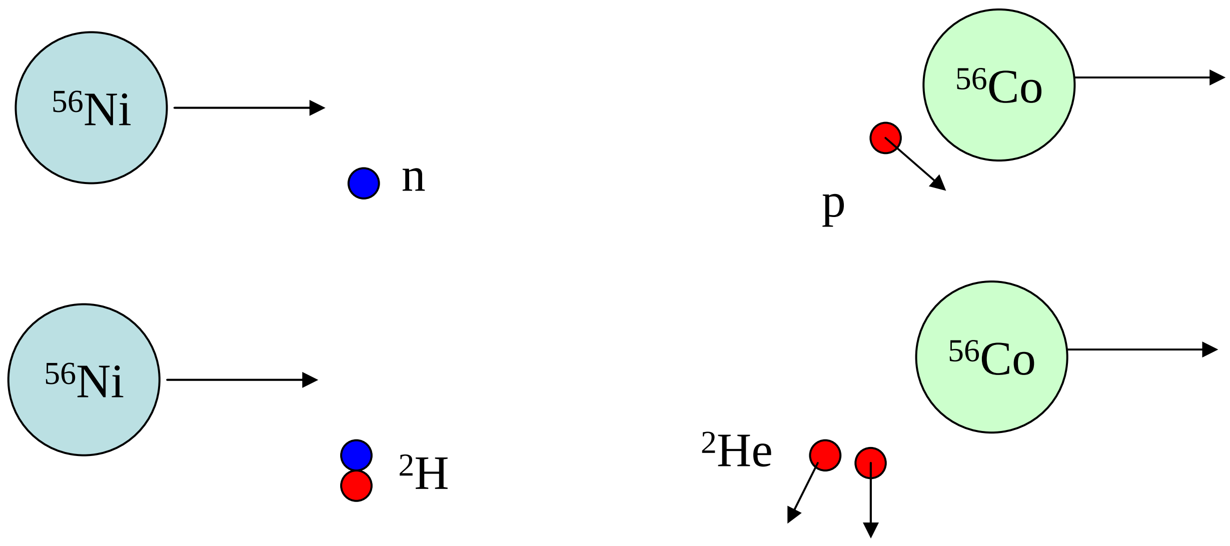
- Determination with the direct method is impossible because both $^{56}$Ni, $^{64}$Ge and neutron are not stable (radioactive).
- Beta decay:

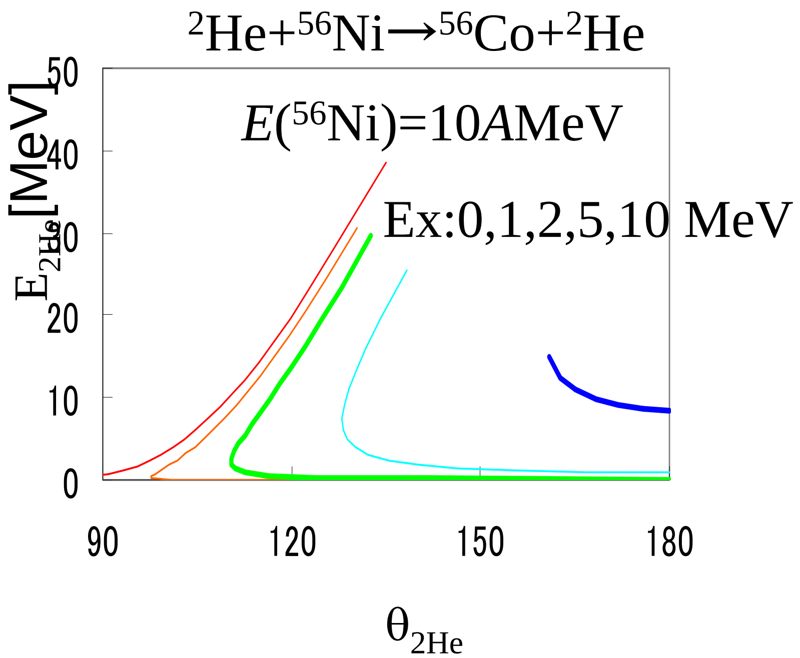
$$\sigma_{(n,p)}(0) \propto B(\mathrm{GT}), B(\mathrm{F})$$

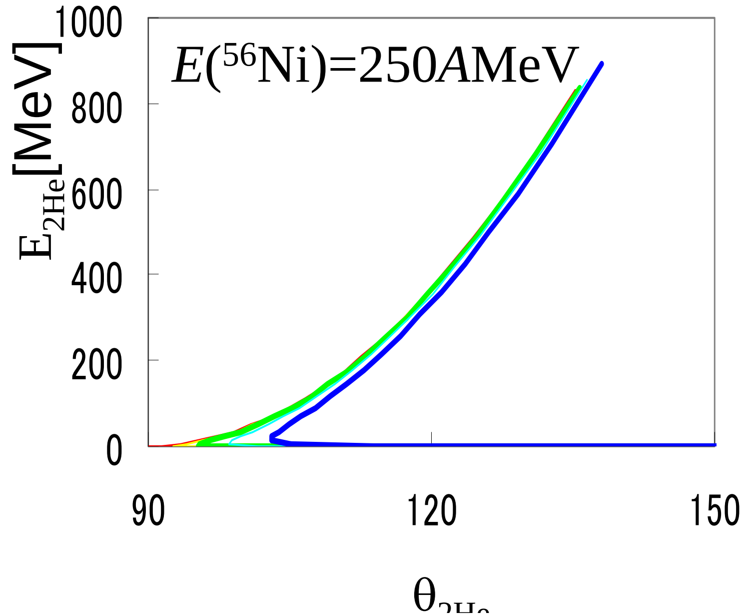


•Alternative method is desired to determine the (n,p) cross section.
→ To study $B$(GT), (d,2p) reactions in reversed kinematics.

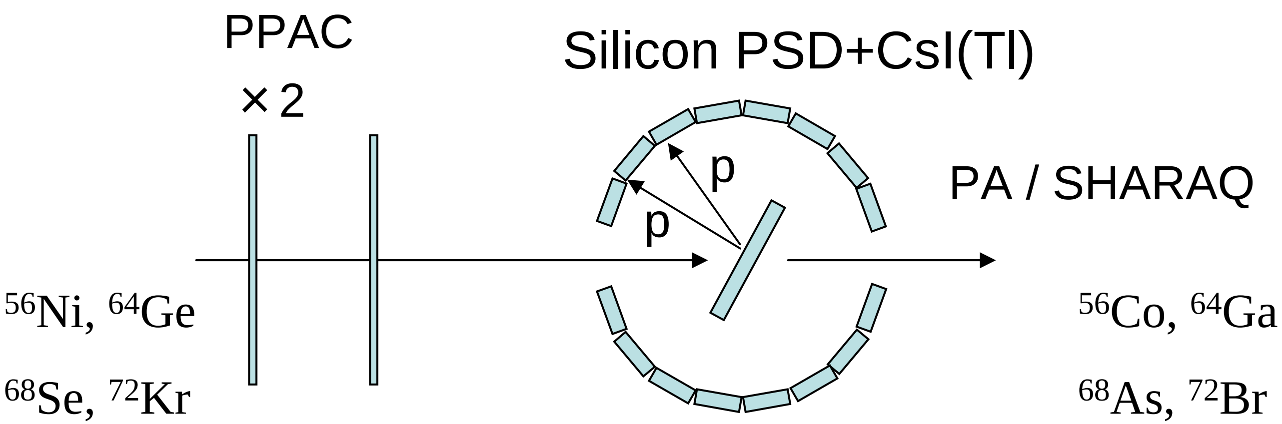
# (d,2p) reaction in reverse kinematics



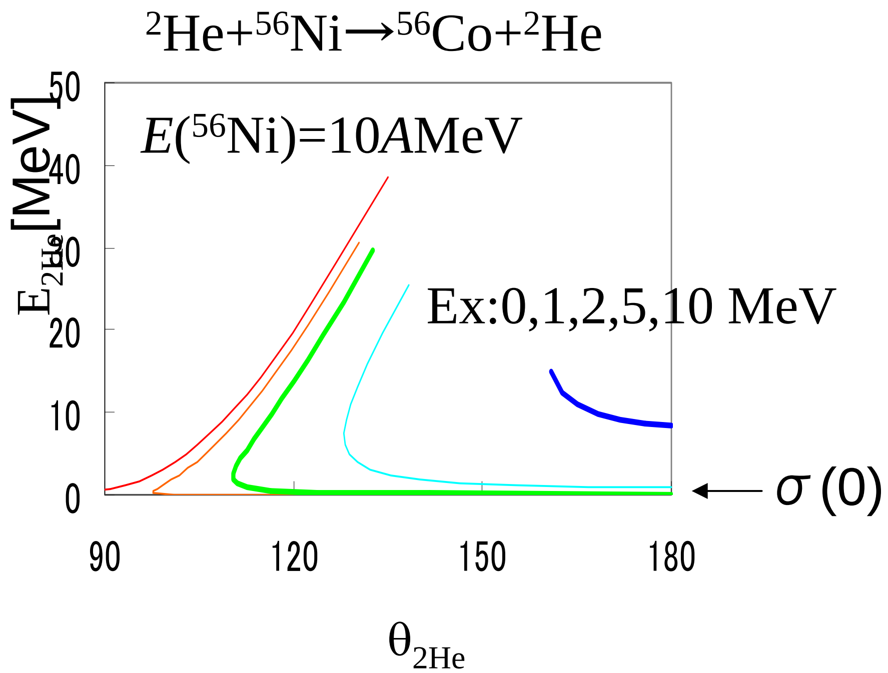
# A example of experimental setup




collaboration with S. Ota's group
detectors for 2 proton will be discussed

$^{56}$Ni
$^{64}$Ge
$^{68}$Se
$^{72}$Kr

Problem: charge states of Co, Ga, As, Br



# まとめ

- $^{56}$Ni(p,γ)$^{57}$Cu、$^{57}$Cu(p,γ)$^{58}$Zn 反応率の実験的導出

  クーロン励起(分解)反応:強力な道具 ($\Gamma_p >> \Gamma_\gamma$, $\Gamma_p \sim \Gamma_\gamma$ :SN)

  reaction rate, branching ratio

  $\Gamma_p << \Gamma_\gamma$ (nova): 逆運動学の($^3$He,d)反応

  6*A*MeV,$10^4$cps以上の$^{56}$Niビーム→実験可能

- $^{56}$Ni(n,p)$^{56}$Co, $^{64}$Ge(n,p)$^{64}$Ga, $^{68}$Se(n,p)$^{68}$As

  逆運動学の(d,$^2$He)?　　(t,$^3$He)?

  charge state 問題

  $^2$Heが標的中に停止→薄い標的

  (t,$^3$He): 放射性同位体標的、(t,pd)(t,n2p)と分離可能か?