Half-life measurement of isomeric states in $A = 25$ & 26

D. Nishimura[1], K. Aoki[1], T. Nagai[1], Y. Takei[1], A. Takenouchi[1], M. Fukuda[2], J. Chiba[1], K. Chikaato[3], H. Du[2], S. Fukuda[4], A. Ikeda[3], T. Izumikawa[5], S. Kanbayashi[2], N. Kanda[3], Y. Kanke[1], I. Kato[6], A. Kitagawa[4], M. Machida[1], M. Mihara[2], E. Miyata[3], J. Nagumo[1], K. Nishizuka[3], S. Ohmika[6], K. Ohnishi[2], T. Ohtsubo[3], H. Oikawa[1], S. Sato[4], T. Sugihara[2], T. Suzuki[6], N. Tadano[6], H. Takahashi[3], M. Takechi[3], M. Tanaka[2], Y. Tanaka[2], S. Yagi[1], T. Yamaguchi[6], S. Yamaoka[2], and K. Yokoyama[3]

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- Experiment
  - Facility (NIRS-HIMAC, SB2 beam line)
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- Results & Discussion
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  - E_γ, $T_{1/2}$ and Level scheme
  - Transition probabilities and comparison with shell model calc.
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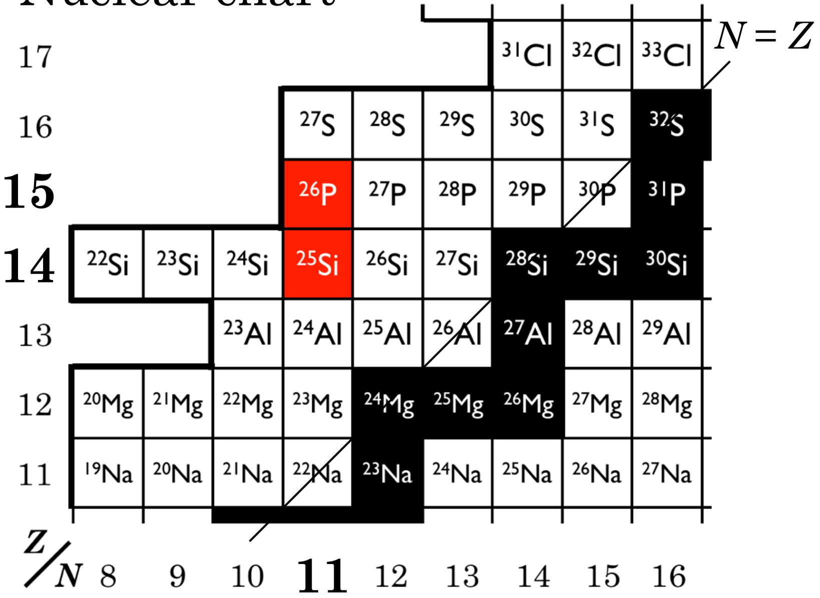
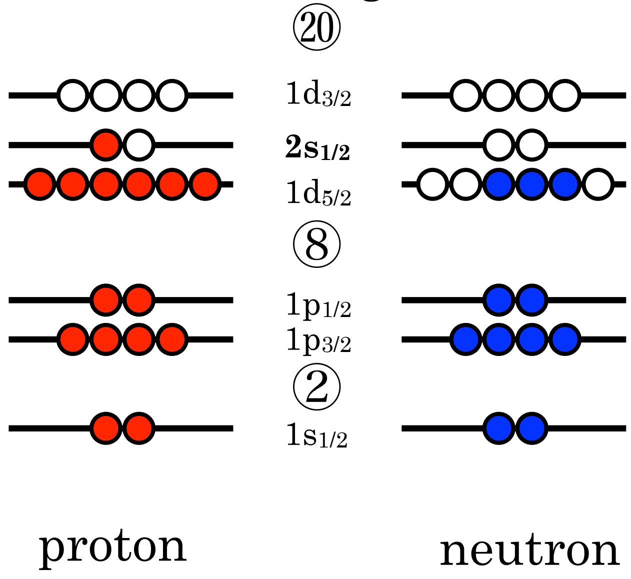
Background & Motivation

^{25}Si & ^{26}P

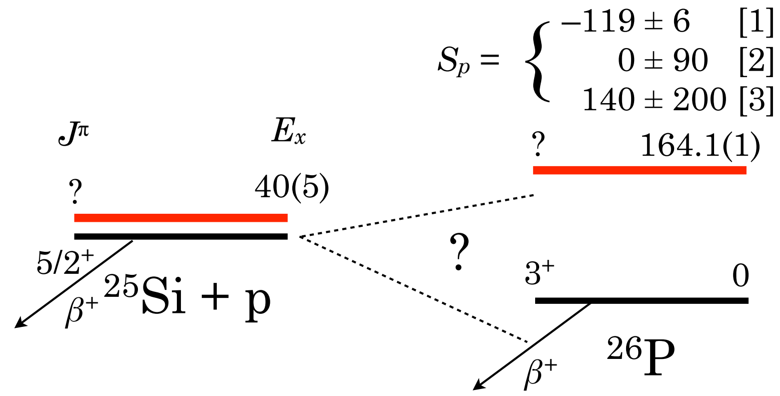
Nuclear chart



Convensional configuration of ^{26}P



Level scheme



Motivation

Possibility of new *rp*-process path

⇩

investigation of ^{25m}Si & ^{26m}P

[1] Improved Kelson-Garvey mass relation: J. Tian et al., Phys, Rev. C 87 014313 (2013)

[2] β decay of ^{25}Si & ^{26}P and IAS-ΔE assumed: J.-C.Thomas et al., Eur. Phys. J. **A** 21, 419 (2004).

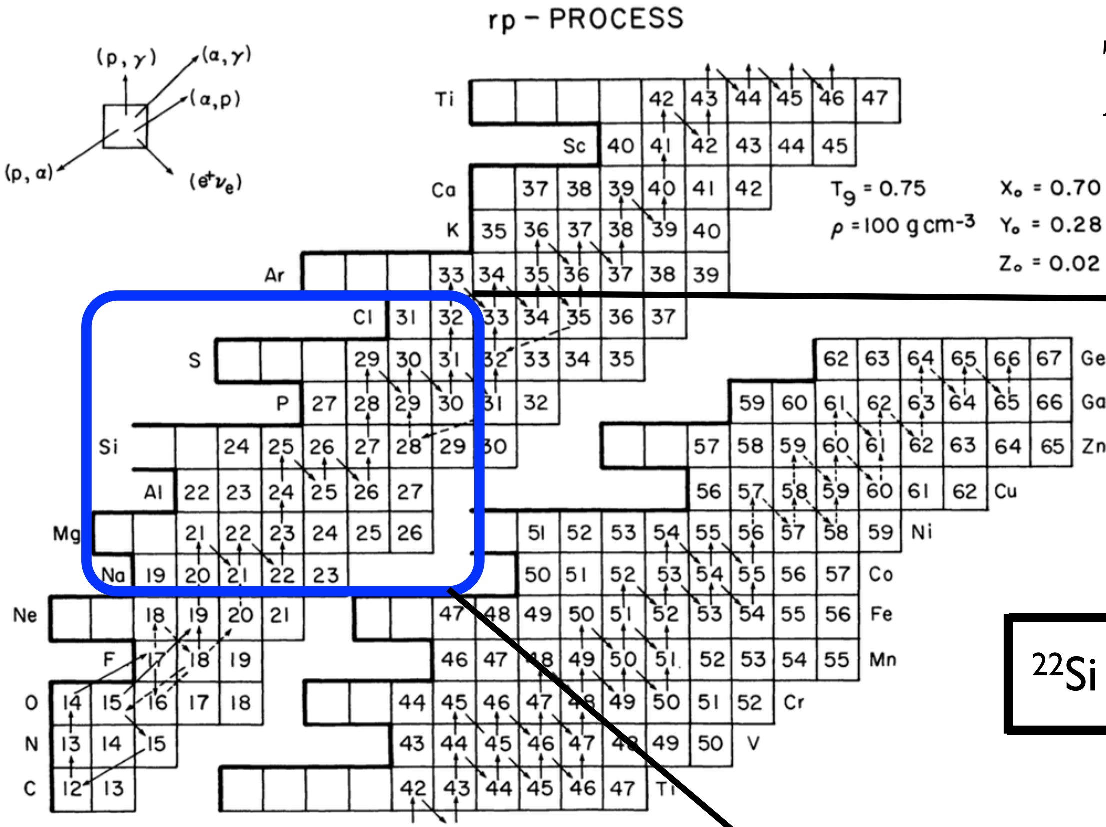
[3] AME2003 mass evaluation: G.Audi, A. H.Wapstra and C.Thibault, Nucl. Phys. **A**729, 337 (2003).

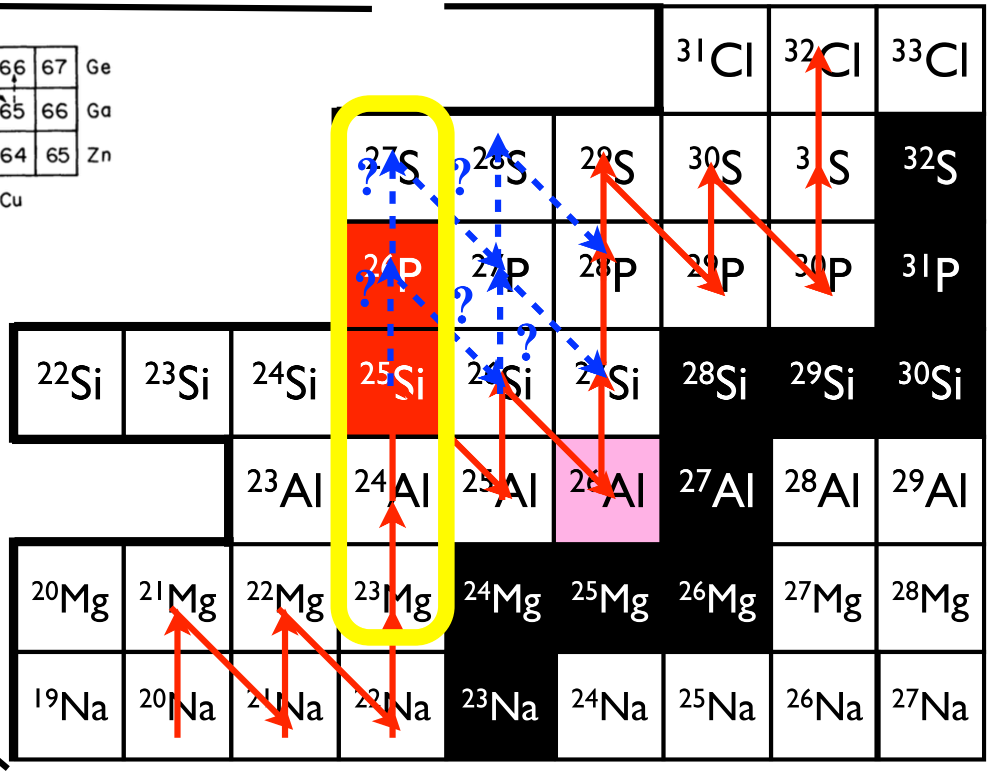
(1) Nuclear Synthesis of *rp*-process

$T \sim 10^{8\text{-}9}$K (= 10-100 keV)

⇩

The low-lying excited states can affect the reaction rate.





R.K.Wallace and E. Woolsey, Astro. J. 45 389 (1981).

A. Parikh, et al., Phys. Rev. C 79, 045802 (2009).

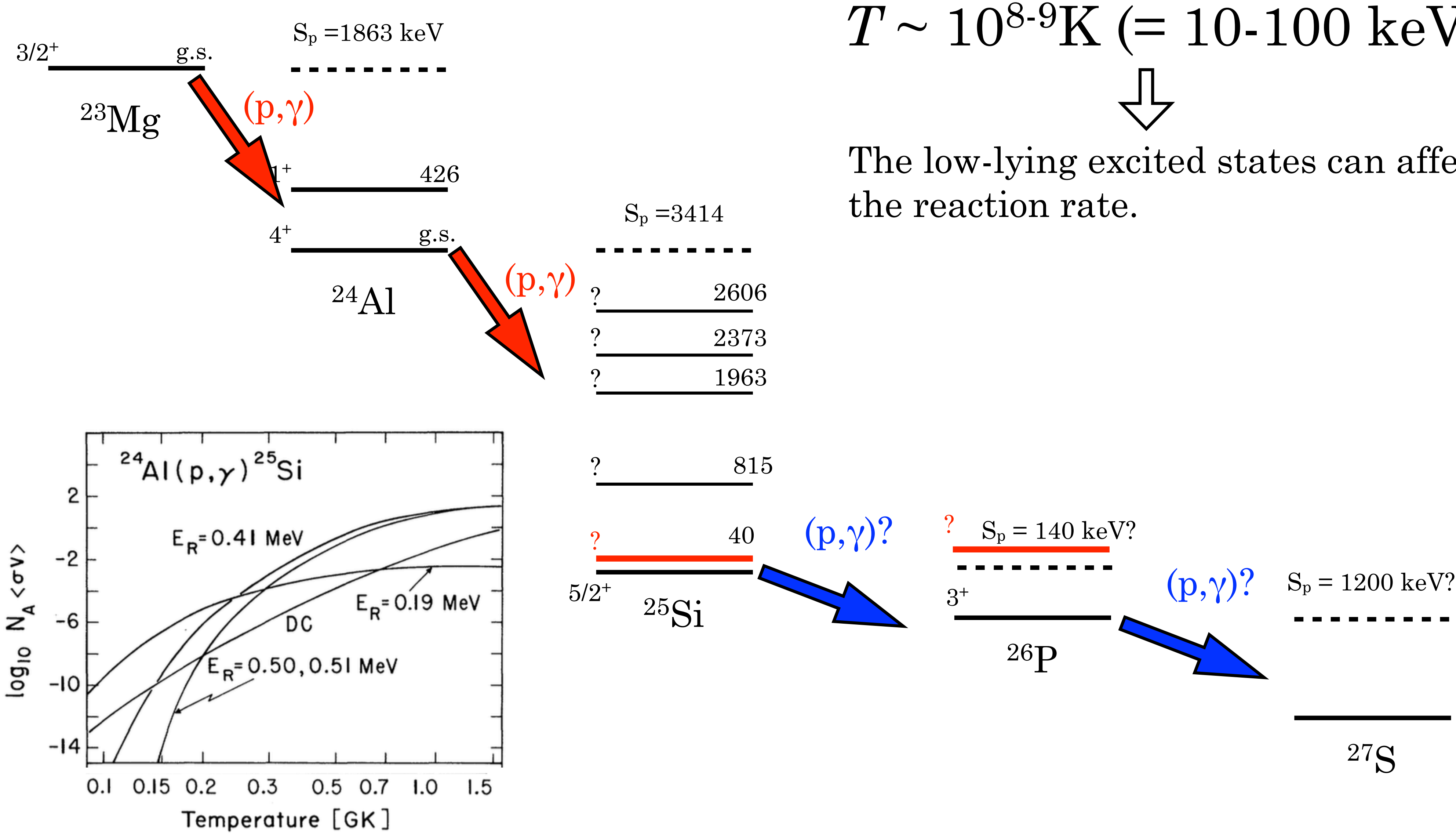
$N = 11$

rp-process in $N = 11$ isotones

$T \sim 10^{8\text{-}9}$K (= 10-100 keV)

⇩

The low-lying excited states can affect the reaction rate.



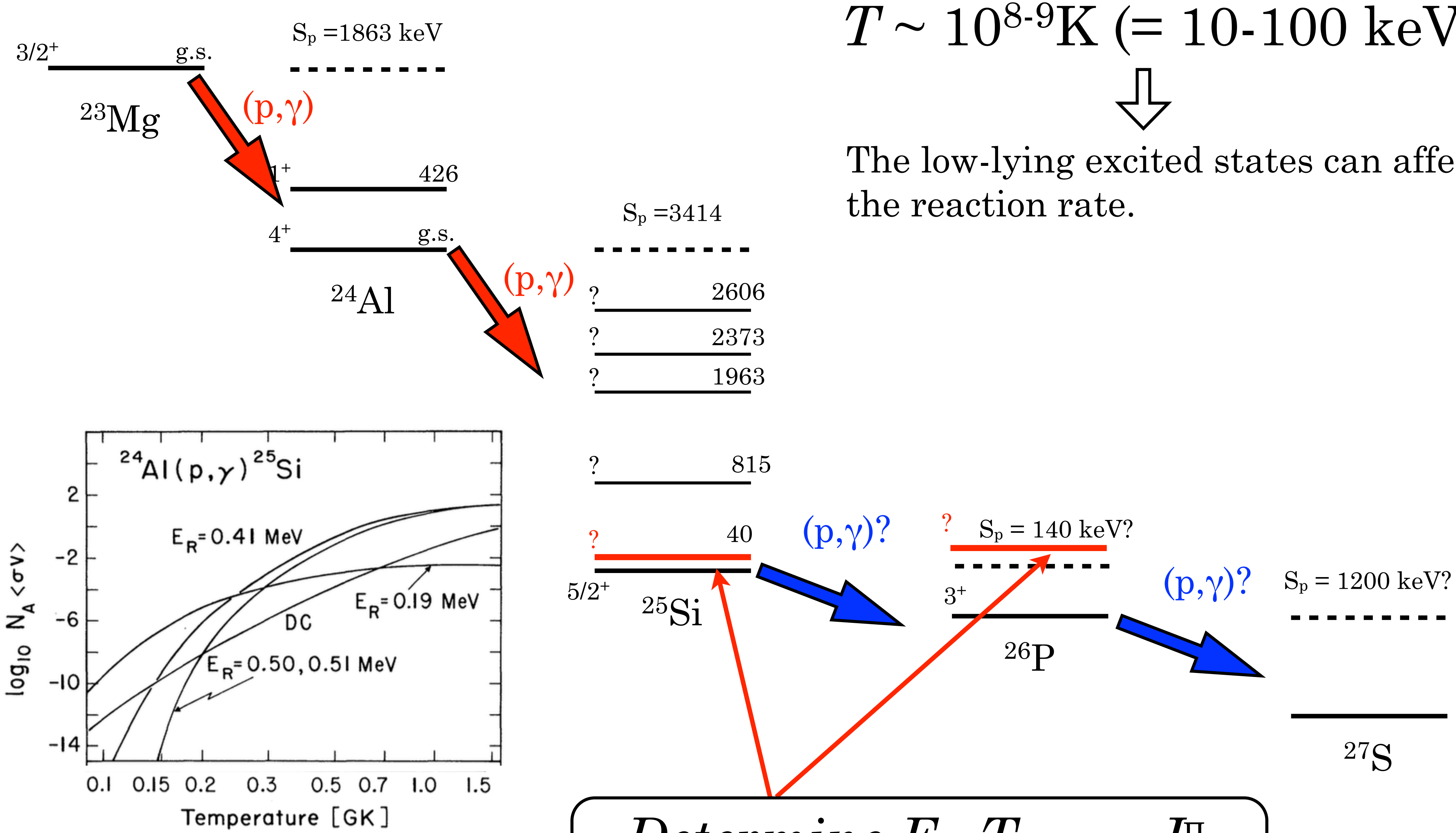
H. Herndl et al., Phys. Rev. C 52, 1078 (1995).

rp-process in $N = 11$ isotones

$T \sim 10^{8\text{-}9}$K (= 10-100 keV)

⇩

The low-lying excited states can affect the reaction rate.



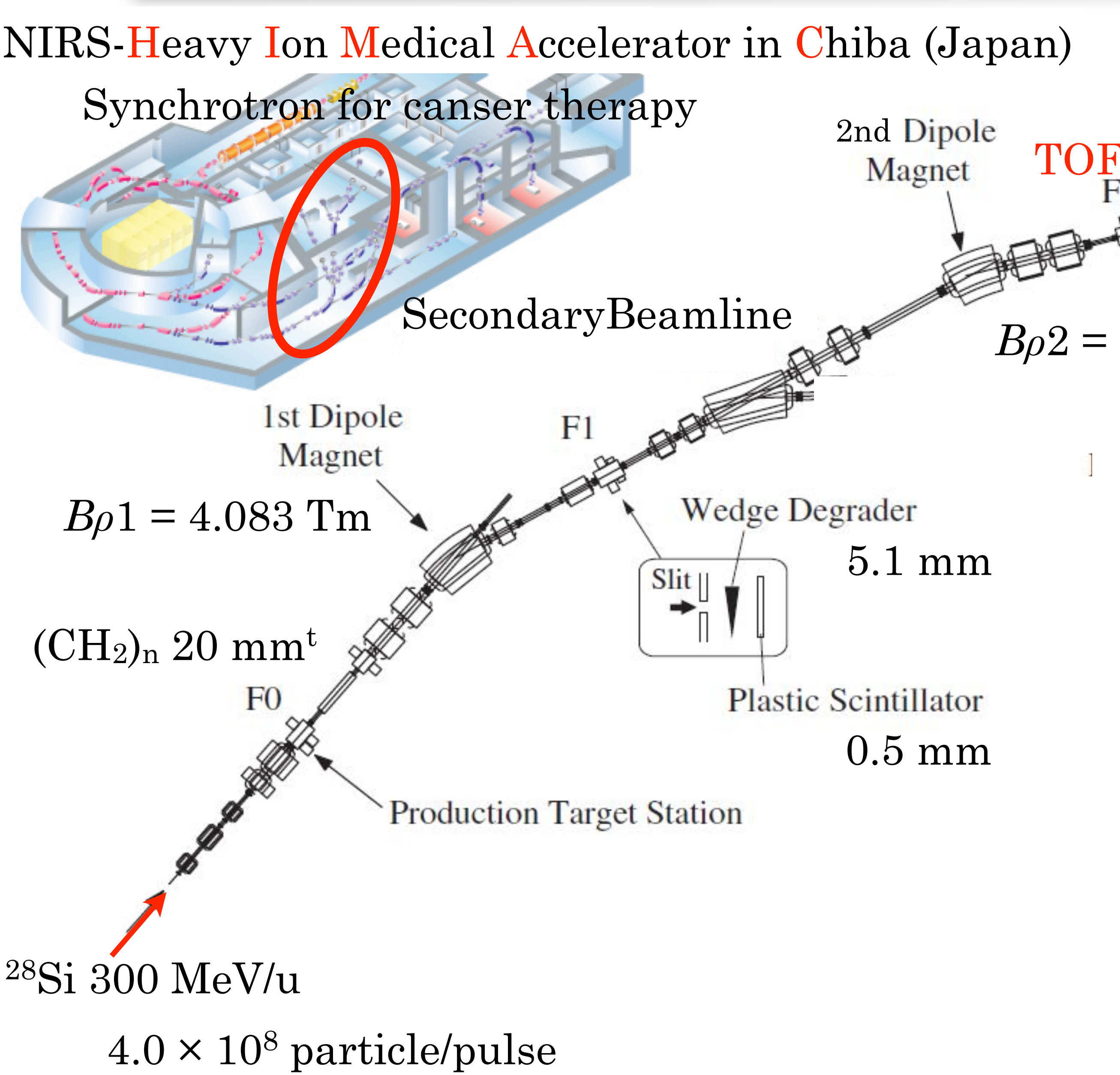
H. Herndl et al., Phys. Rev. C 52, 1078 (1995).

Determine E_γ, $T_{1/2}$ and J^π

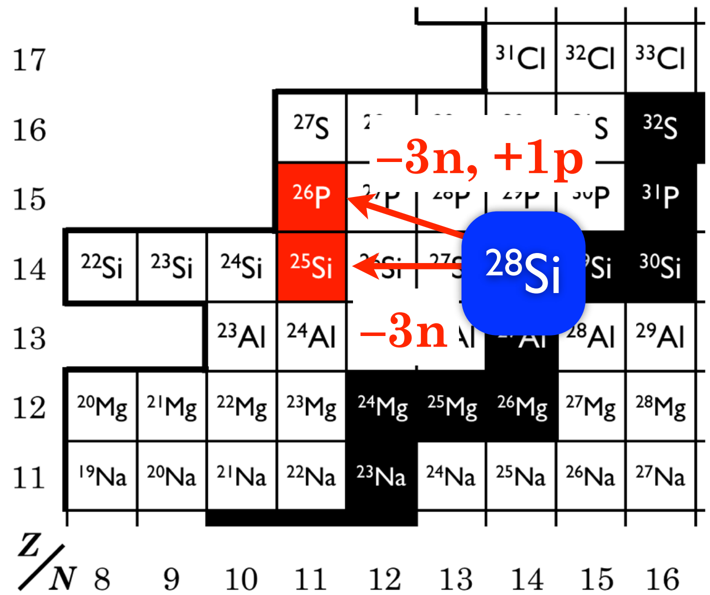
Experiment

SB2 beam line in NIRS-HIMAC

NIRS-Heavy Ion Medical Accelerator in Chiba (Japan)

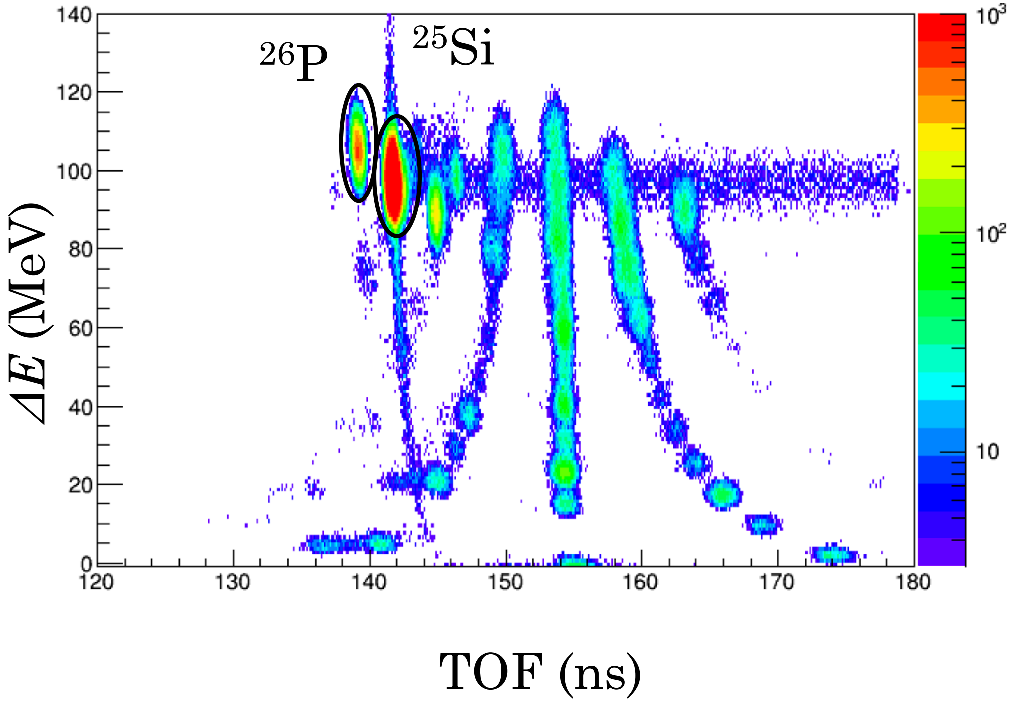


$$^{28}\mathrm{Si} + \mathrm{CH_2} \rightarrow {}^{25}\mathrm{Si} + \mathrm{X}$$
$$\rightarrow {}^{26}\mathrm{P} + \mathrm{X}$$

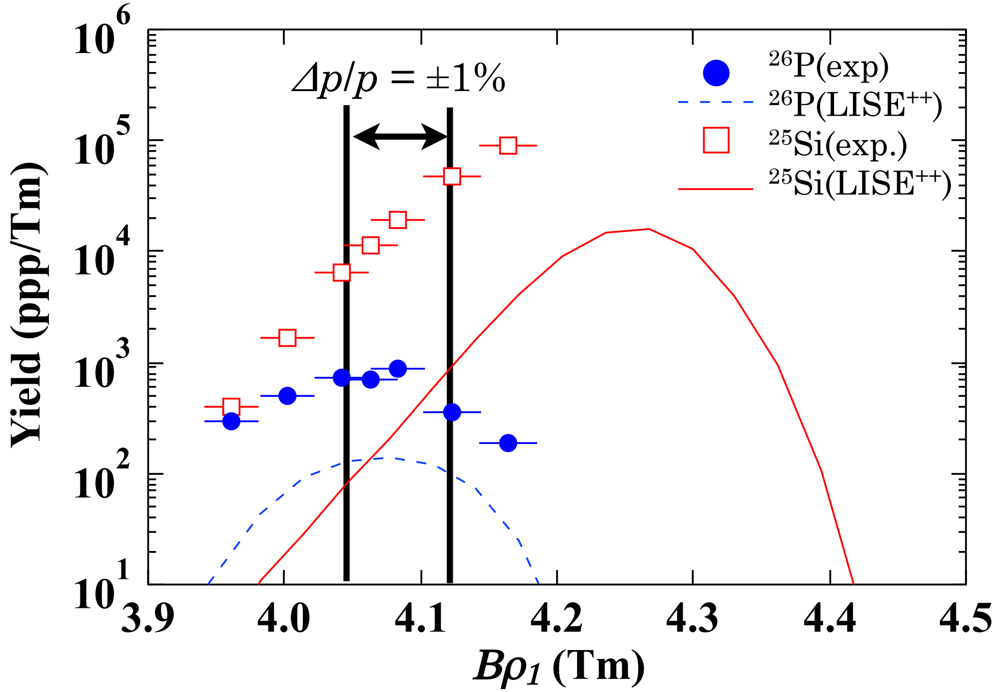


Production of ^{25}Si & ^{26}P

Particle ID prot



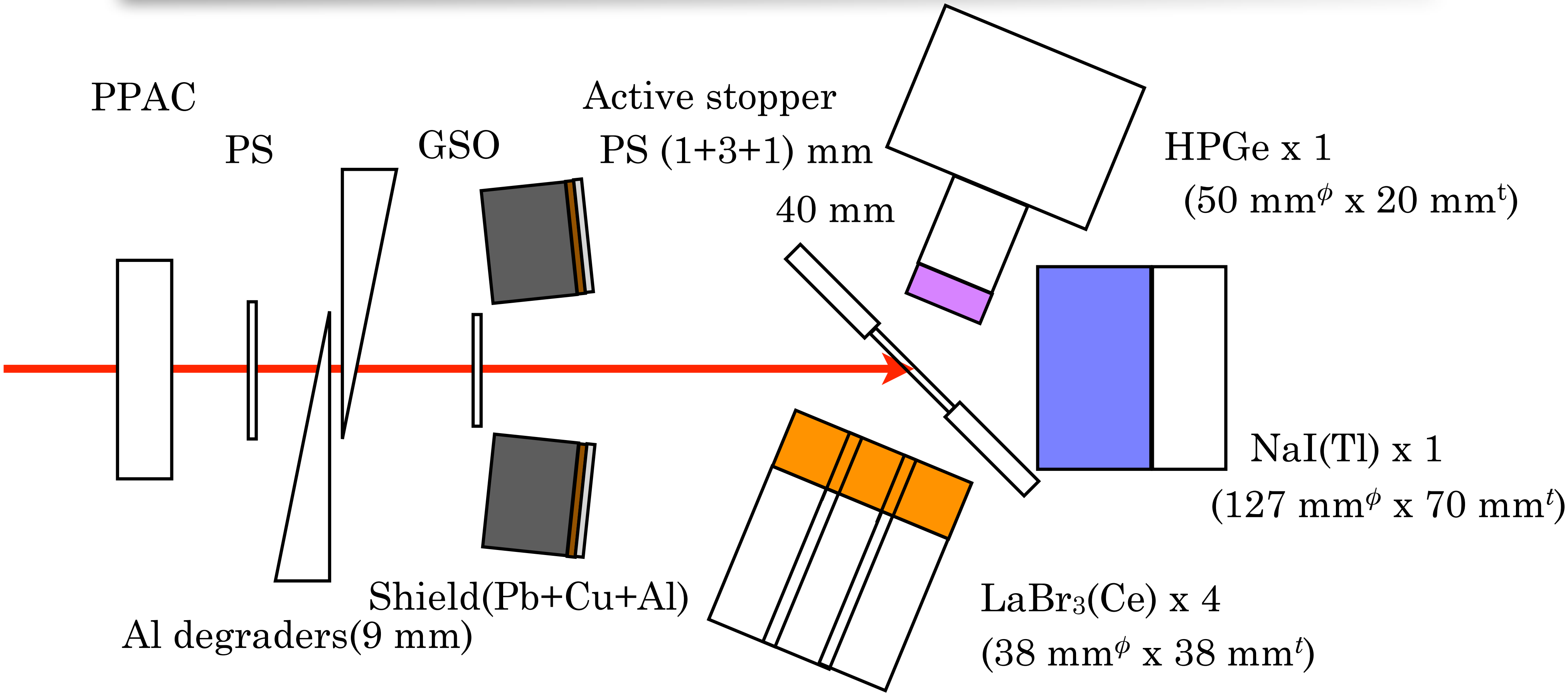
Momentum distribution



		Counting rate (ppp)	Purity (%)	Total (counts)	Ref.
^{28}Si(300MeV/u,0.06pnA) + CH_2 →	^{26}P	**44**	3.6	2.0×10^5	HIMAC
	^{25}Si	850	70	3.9×10^6	
^{36}Ar(150MeV/u,75pnA) + ^{9}Be →	^{26}P	100	74	–	MSU
^{36}Ar(95MeV/u,110pnA) + ^{9}Be →	^{26}P	65	87	–	GANIL

GANIL; J.-C.Thomas et al., Eur. Phys. J. **A** 21, 419 (2004). MSU; M.B. Bennett, *et al.*, PRL 111, 232503 (2013).

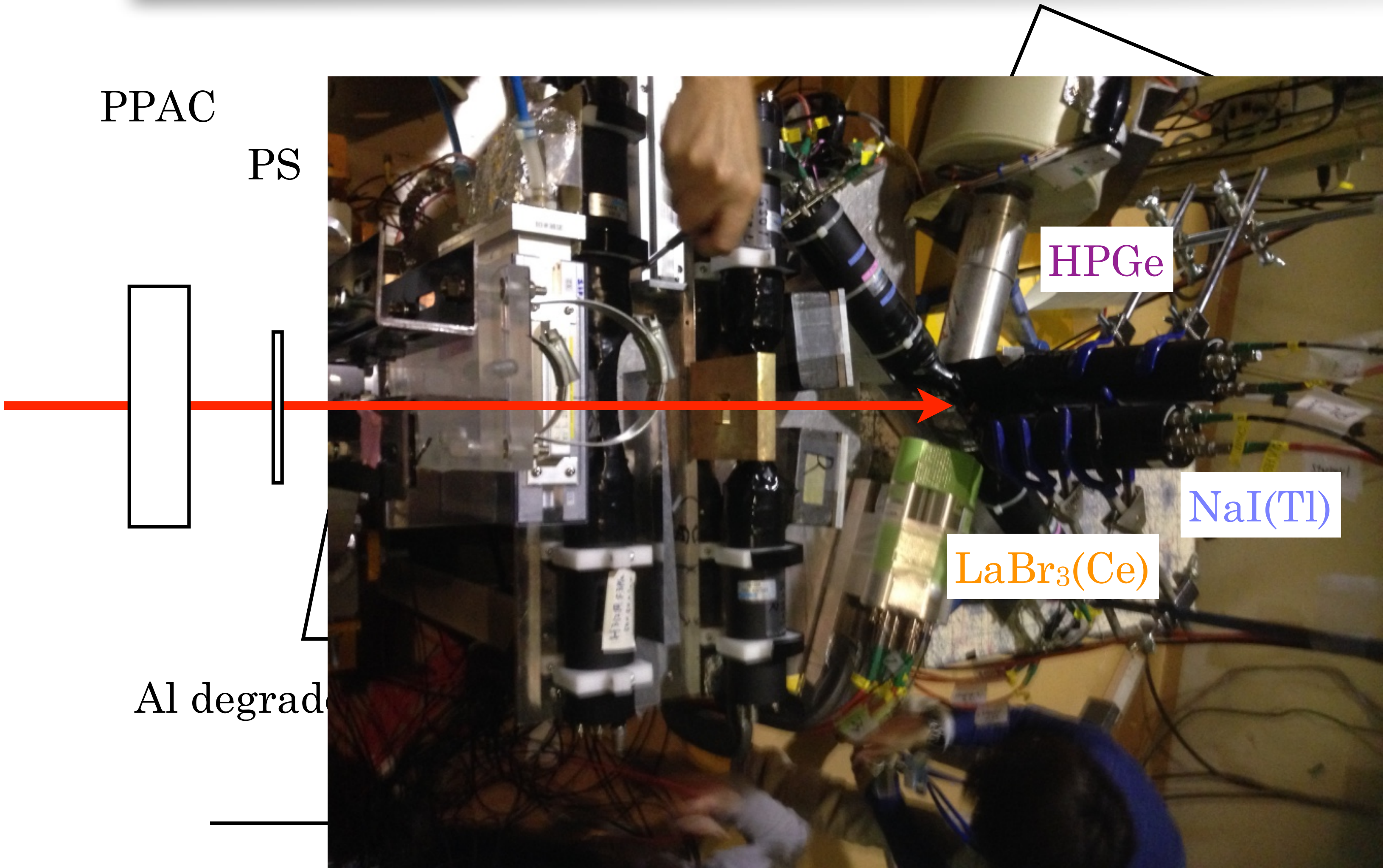
Experimental setup at F3



Properties of γ-ray detectors

	Energy Resolution @662keV	Time Resolution	Distance to stopper	Solid Angle /4π
HPGe	3.6 keV	~80 ns	40 mm	10%
LaBr(Ce)	20 keV	2 ns	53 mm	2.5% × 4 = 10%
NaI(Tl)	45 keV	5 ns	62 mm	20%

Experimental setup at F3



e x 1
mm$^{\phi}$ x 20 mm^{t})

NaI(Tl) x 1
27 mm$^{\phi}$ x 70 mm^{t})

m^{t})

	@662keV	Resolution	stopper	Solid Angle /4π
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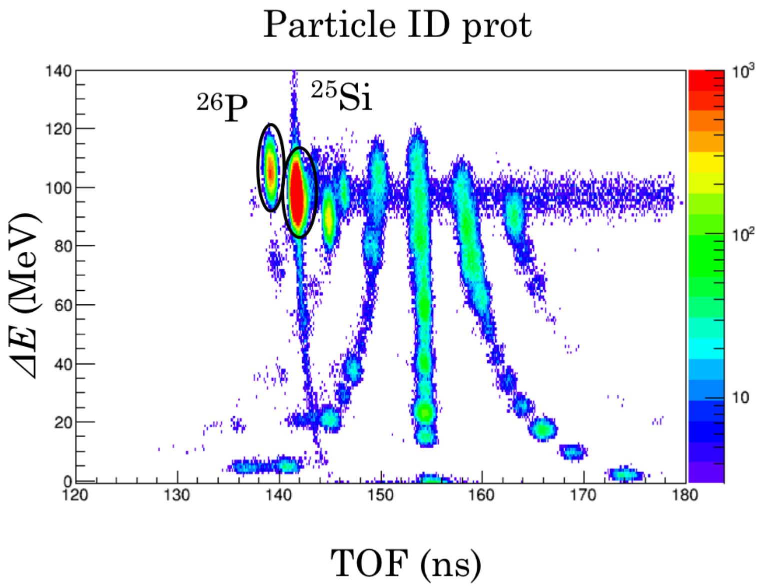
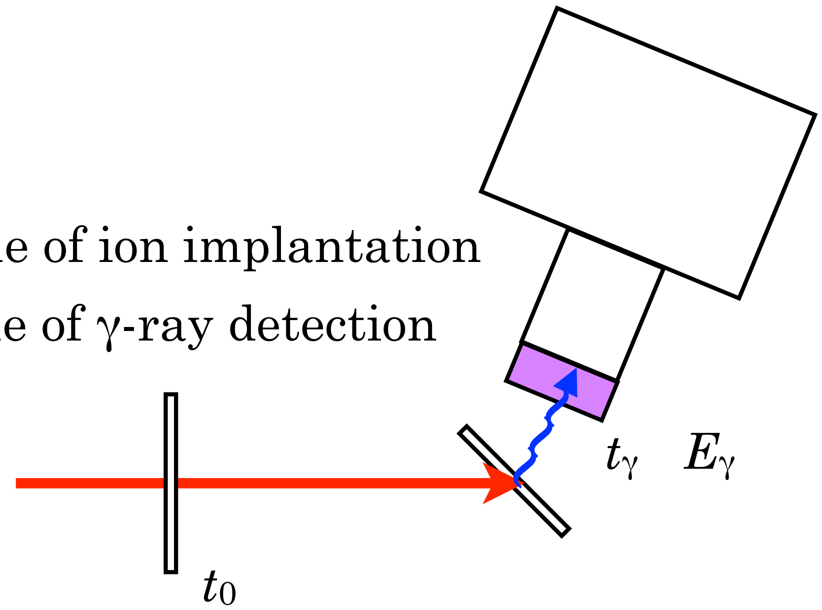
Results & Discussion

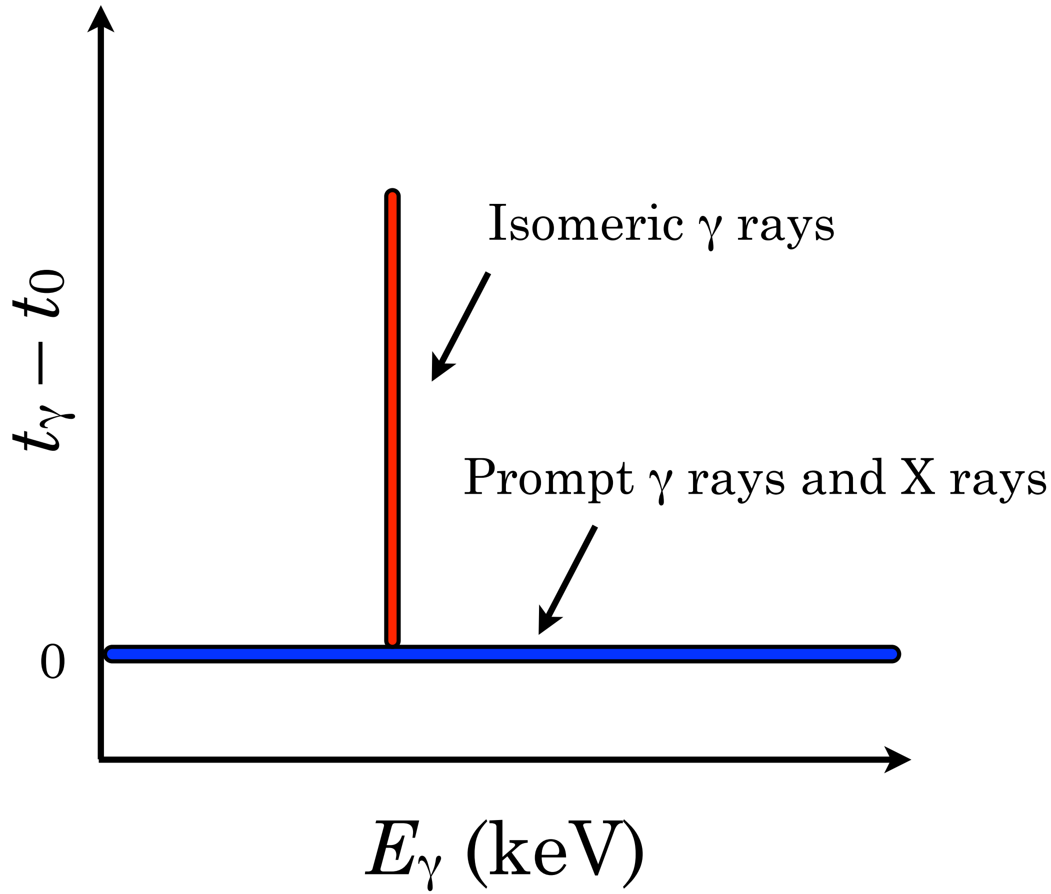
How to Search Isomeric States



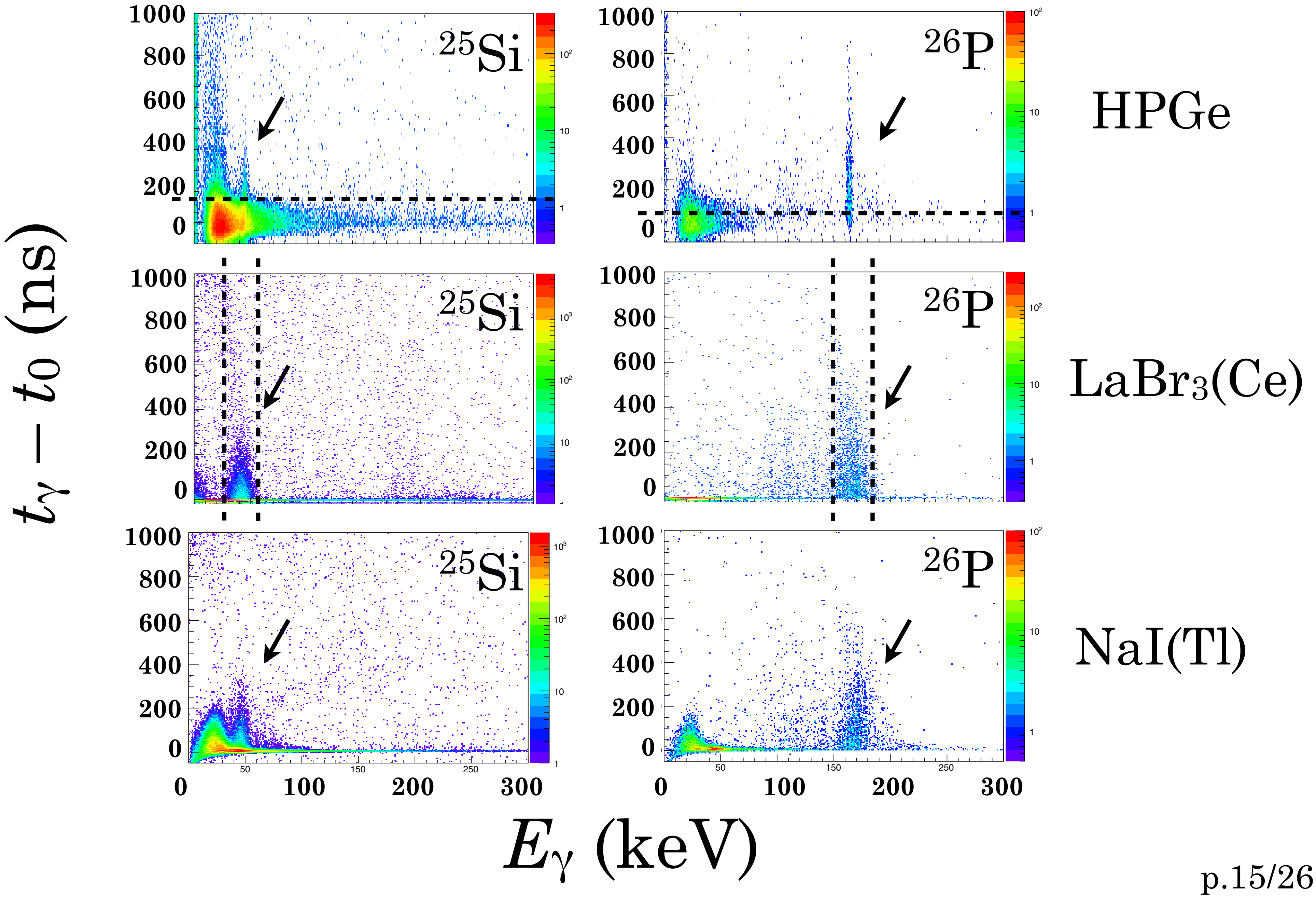
t_0: time of ion implantation

t_γ: time of γ-ray detection



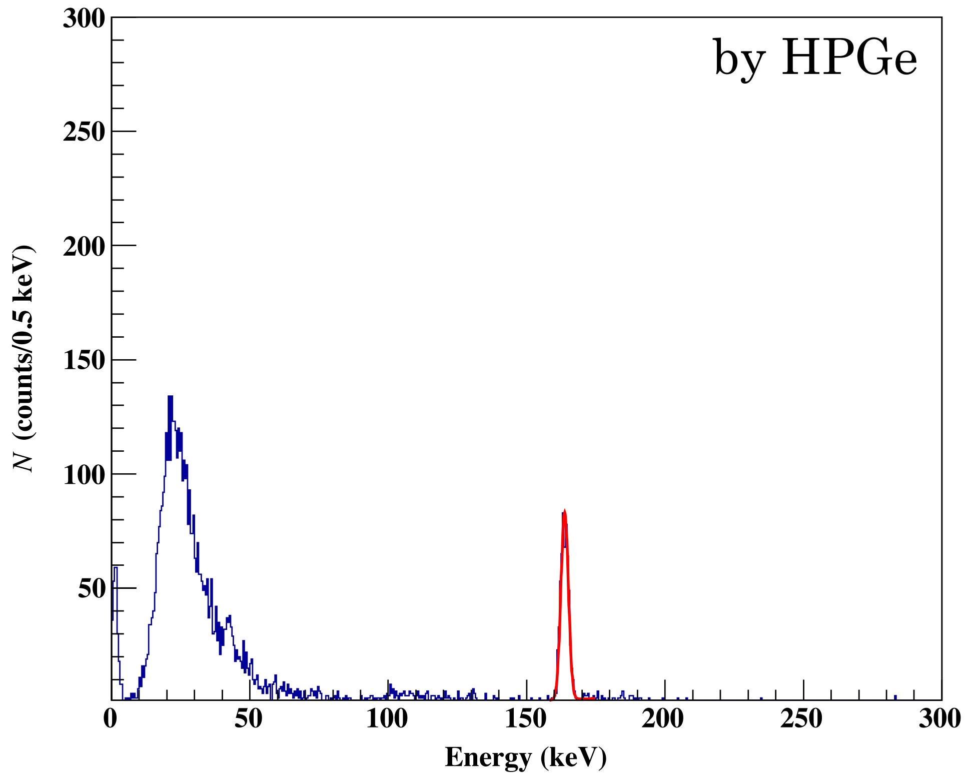


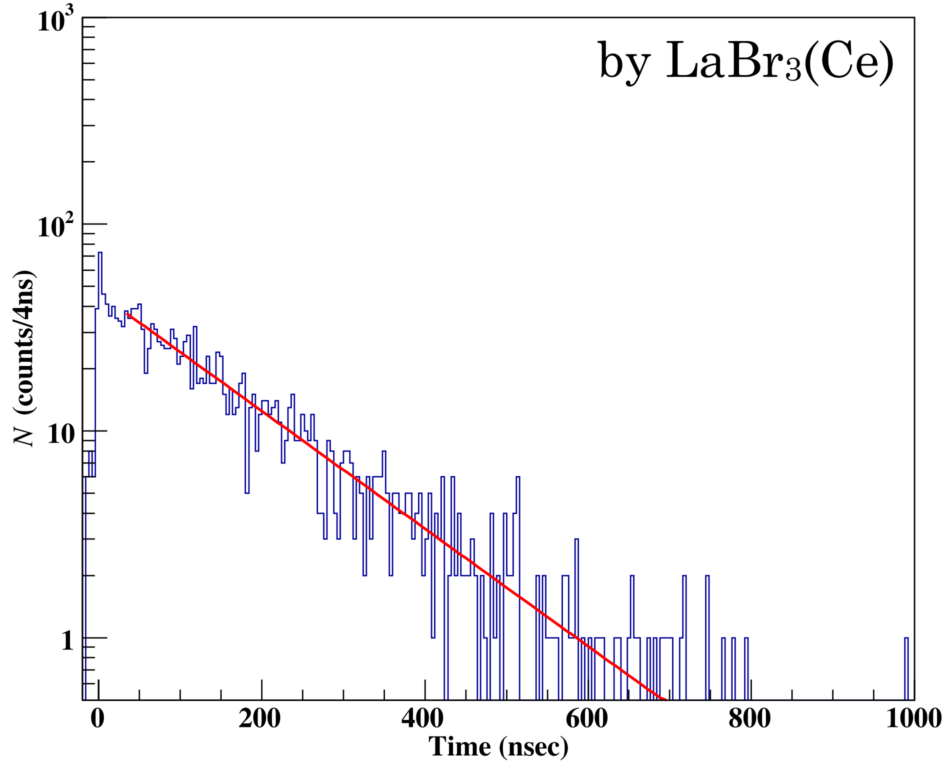
Energy-Timing correlations of γ rays



γ-ray Energy & Timing Spectra

^{26}P





$E_\gamma = 163.7(2)$ keV

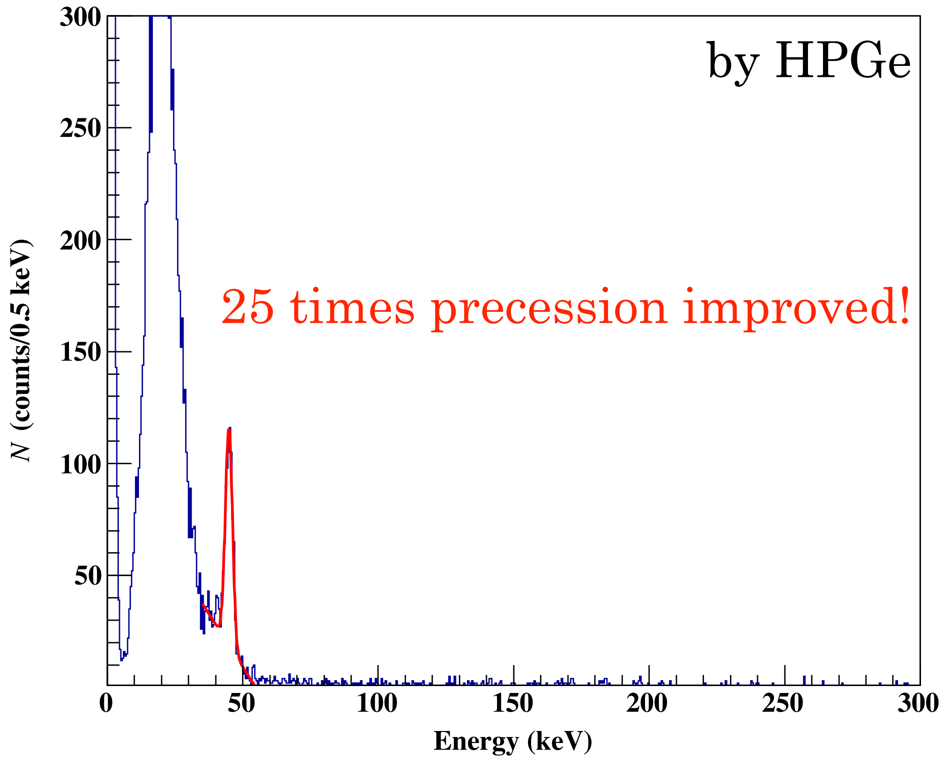
c.f. 164.1(1) keV of our previous exp.

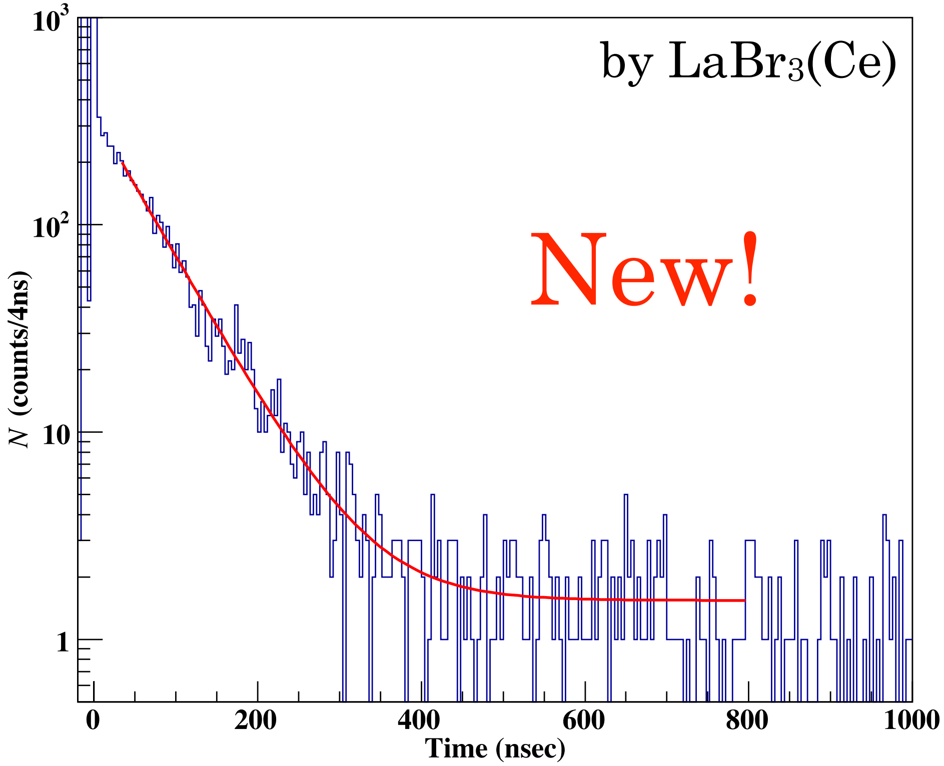
$T_{1/2} = 106(4)$ ns

c.f. 120(9) ns of our previous exp.

γ-ray Energy & Decay Time Spectra

^{25}Si





$$E_\gamma = 44.9(2)\ \text{keV}$$

c.f. 40.0(50) keV

$$T_{1/2} = 43.2(8)\ \text{ns}$$

Weiskoppf estimation

	^{26}P		^{25}Si	
	α	W.u.	α	W.u.
E1	0.00221	1.68×10^{-6}	0.115	1.82×10^{-4}
M1	0.00142	4.81×10^{-5}	0.0302	5.49×10^{-3}
E2	0.0191	9.89×10^{0}	2.99	4.16×10^{3}
M2	0.00993	2.85×10^{2}	0.662	2.78×10^{5}
E3	0.139	8.07×10^{7}	65.2	3.12×10^{10}
M3	0.0687	2.46×10^{9}	14.4	3.74×10^{12}

α : internal conversion coefficients

BRICC code: T. Kibedi, *et al.*, NIM A 589. 202(2008).

Weiskoppf estimation

	^{26}P		^{25}Si	
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M3	0.0687	~~2.46×10^{9}~~	14.4	~~3.74×10^{12}~~

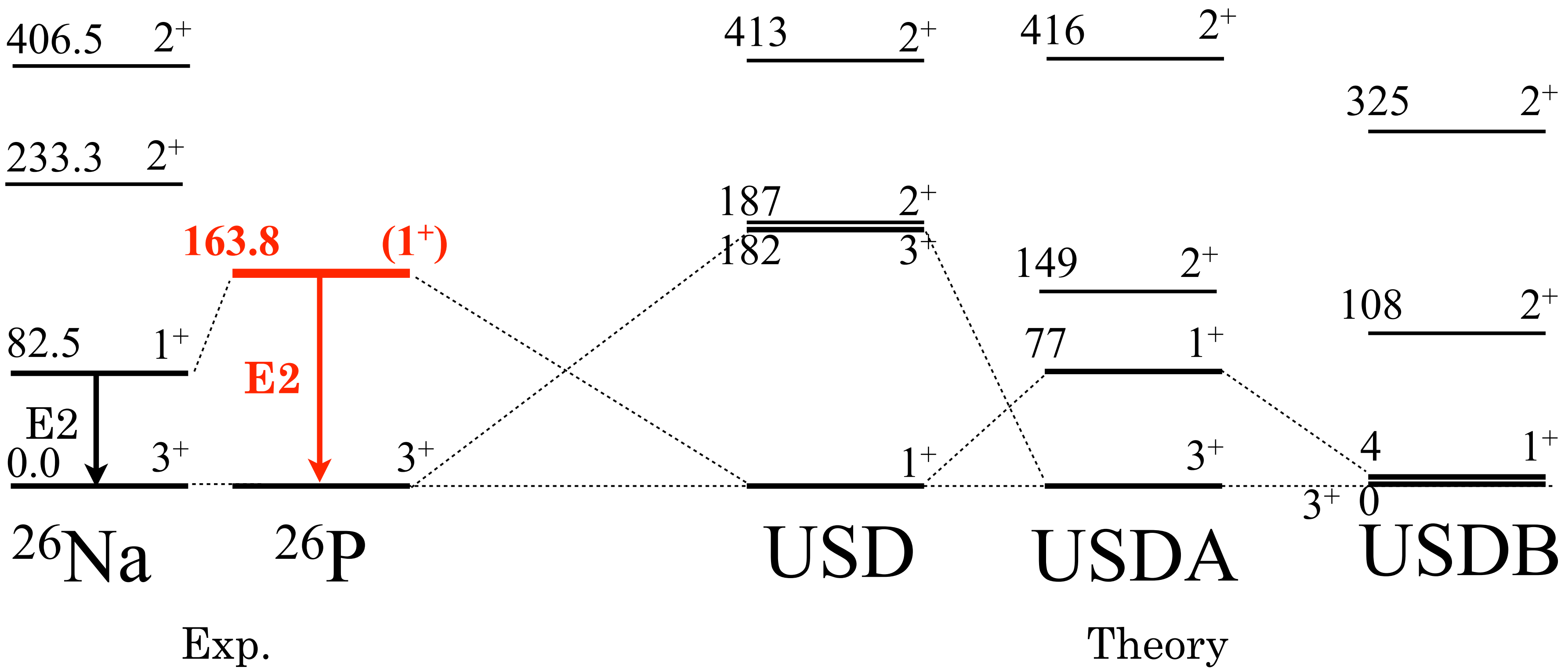
Since B(M1) of $8.61\times10^{-5}\ \mu_N^2$ for ^{26}P is extremely hindered,
M1 transition can be probably rejected.

Since there are no negative parity states, E1 transition can be rejected.

α : internal conversion coefficients

BRICC code: T. Kibedi, *et al.*, NIM A 589. 202(2008).

Comparison with Shell Model (^{26}P)



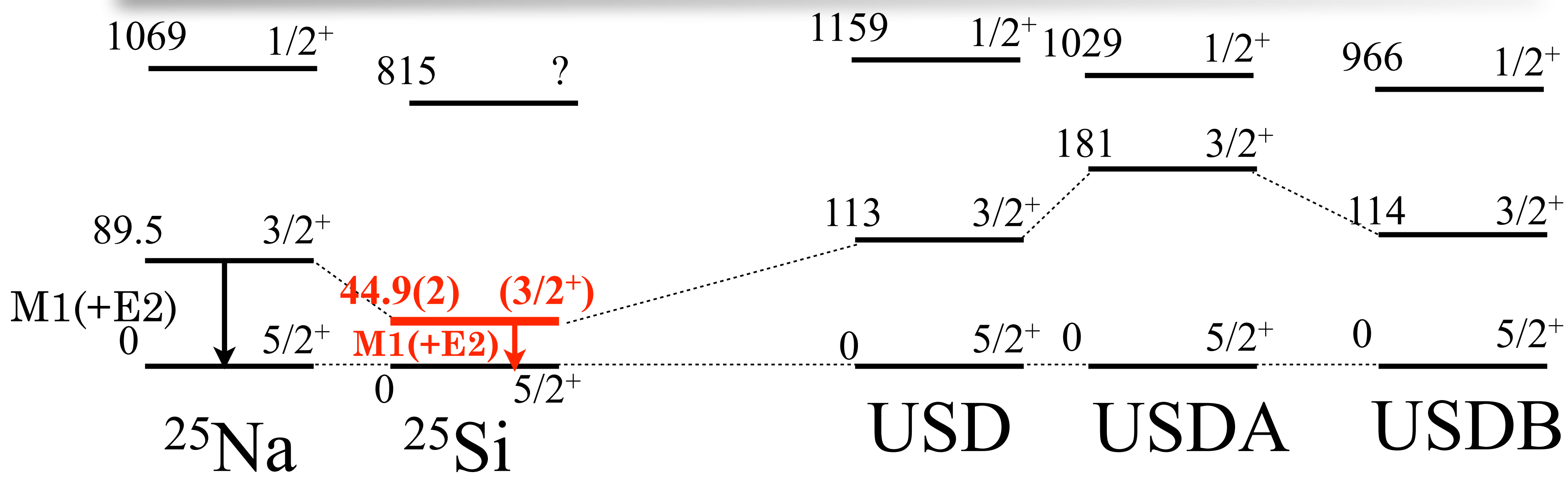
B(E2)↓ values (in units of e^2 fm^4).

	exp.	USD	USDA	USDB
^{26}P	45.3	31.2	32.3	24.0
^{26}Na	31.3*	39.3	38.1	31.3

* $T_{1/2}$ =4.16(25)μs, α = 0.137 is used.
e_p = 1.36 & e_n = 0.45 are used

W.A. Richter *et al.*, Phys. Rev. C 78, 064302 (2008).
D. Nishimura *et al.*, EPJ Web of Conf. 66, 02072 (2014).
B. Siebeck *et al.*, Phys. Rev. C 91, 014311 (2015).

Comparison with Shell Model (^{25}Si)

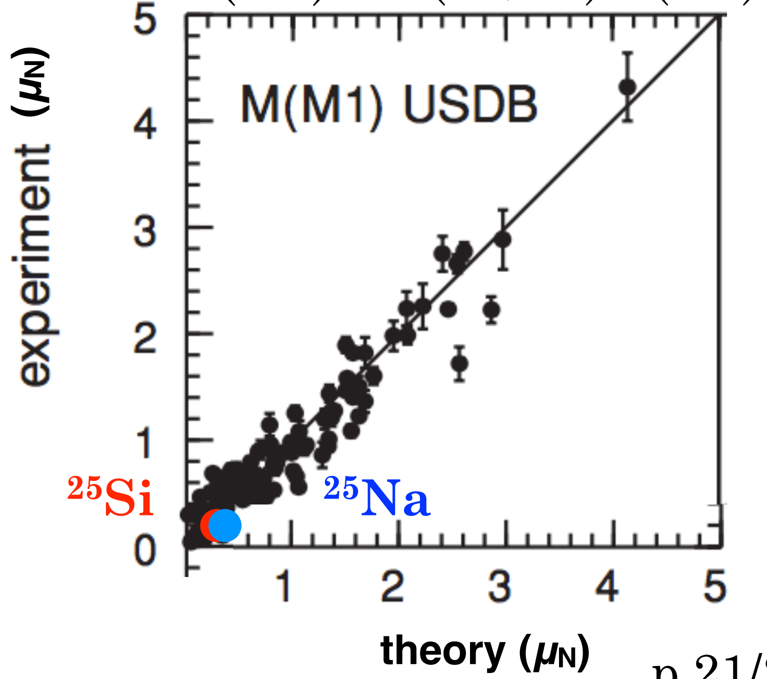


B(M1)↓ values in units of μ_N^2

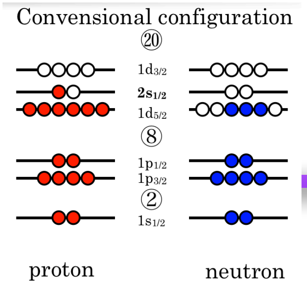
	exp.	USD	USDA	USDB
^{25}Si	0.0098(3)	0.0490	0.0292	0.0302
^{25}Na	0.0108(6)	0.0703	0.0444	0.0439

assuming mixing ratio δ =0.

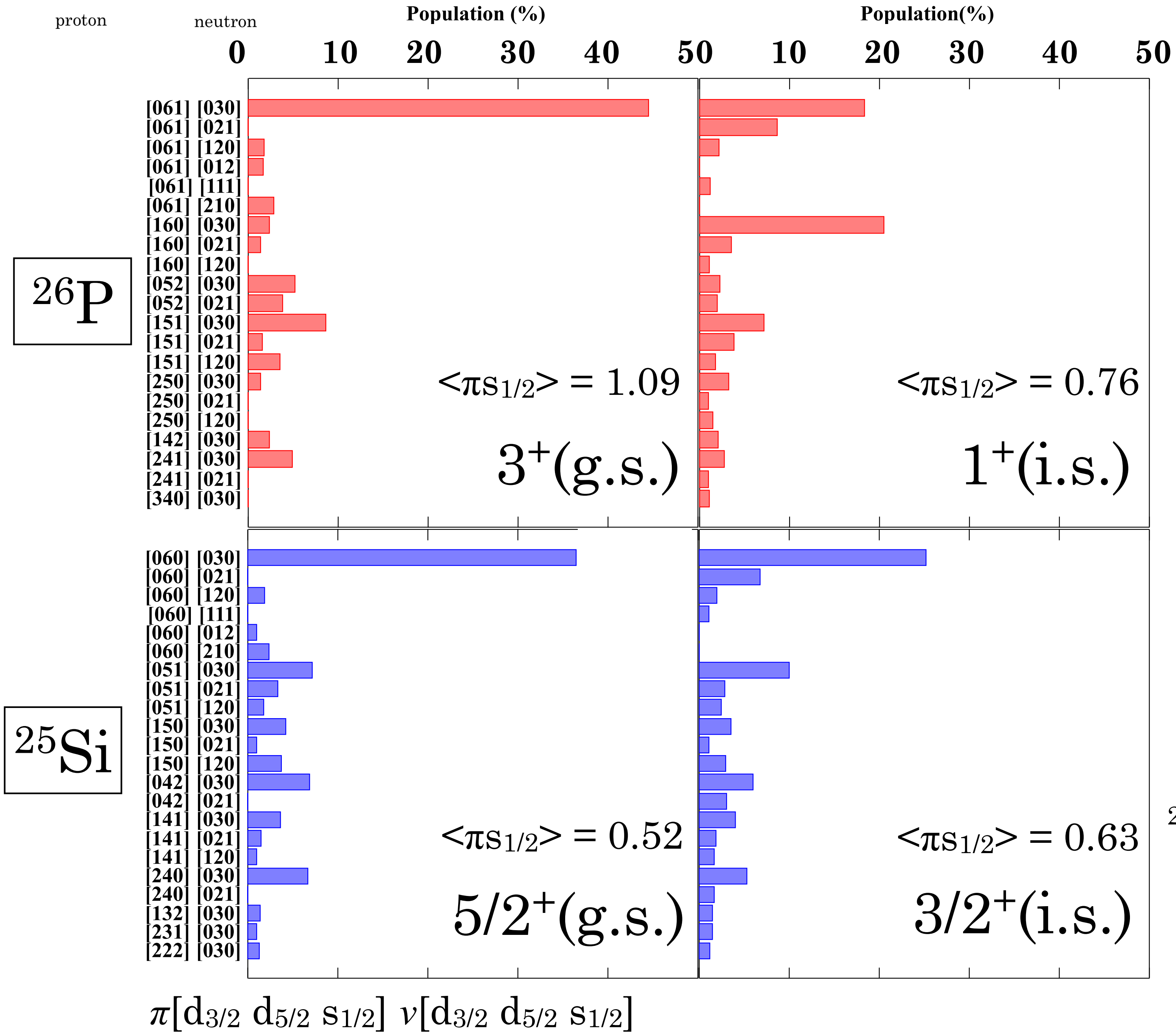
$M(\mathrm{M1}) = \sqrt{(2J_i + 1)\, B(\mathrm{M1})}$

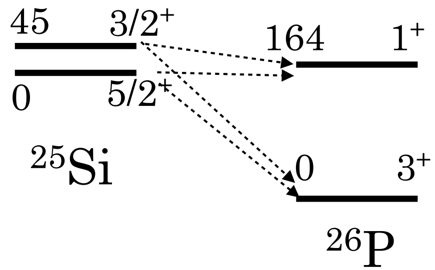


W.A. Richter *et al.*, Phys. Rev. C 78, 064302 (2008).



Configuration Mixing by using USDA

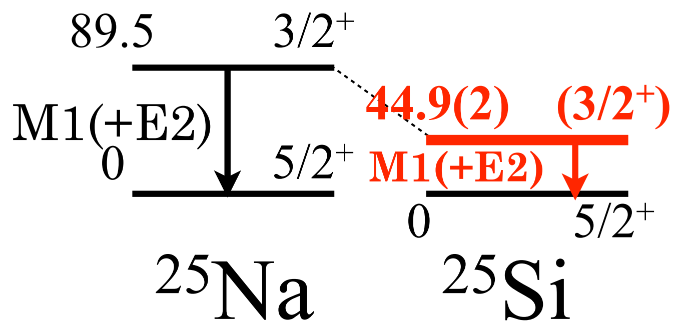




Spectroscopic factors
C^2S

^{25}Si \ ^{26}P	3^+(g.s.)	1^+(i.s.)
$5/2^+$(g.s.)	0.614	0.291
$3/2^+$(i.s.)	0.003	0.248

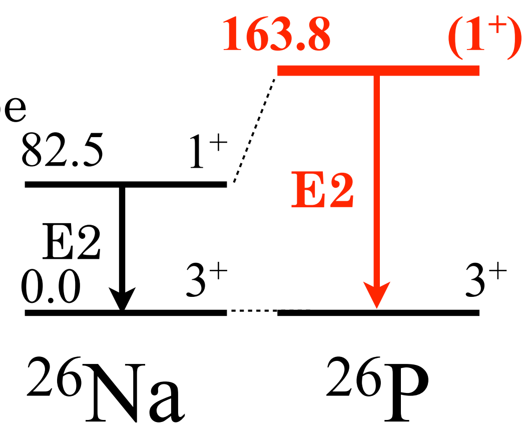
Summary



- Proton-rich nuclei ^{25}Si and ^{26}P have attracted much interest since they are related to nuclear synthesis of *rp*-process.
- The low-lying isomeric states in ^{25}Si and ^{26}P have been investigated by using γ-ray spectroscopy at NIRS-HIMAC.
- The γ-ray energy and half-life for ^{25}Si and ^{26}P are determined to be

$$E_\gamma = 44.9(2)\ \text{keV},\quad E_\gamma = 163.8(2)\ \text{keV}$$

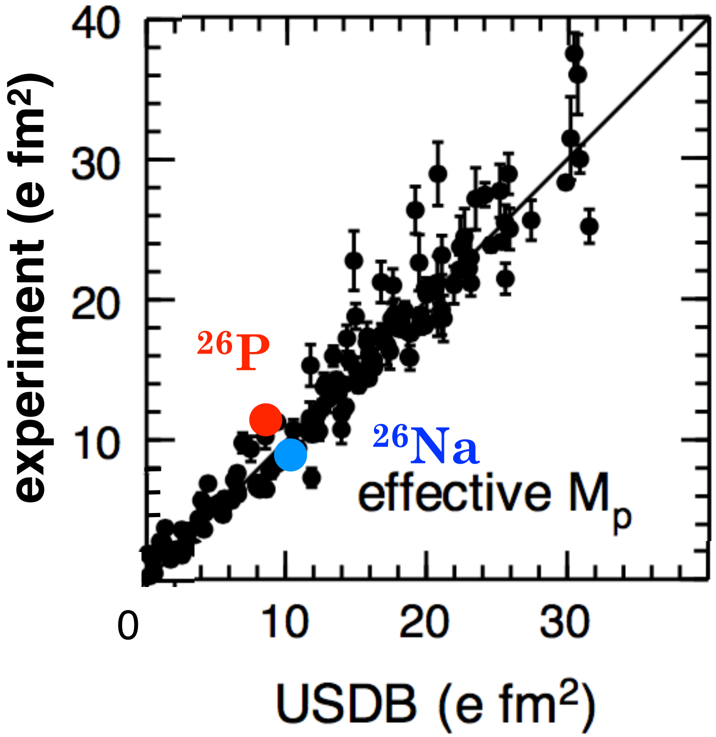
$$T_{1/2} = 43.0(6)\ \text{ns},\quad T_{1/2} = 104(3)\ \text{ns}$$



- M1 for ^{25}Si and E2 for ^{26}P transitions are suggested by calculating the transition probabilities with the above E_γ and $T_{1/2}$. Therefore, $J^\pi = 3/2^+$ and $J^\pi = 1^+$ are expected for their isomeric states.
- In order to calculate $N_A\langle\sigma v\rangle$, theoretical support and precise mass measurement are desiable.

Backups

E2 matrix element in sd shell



$$\begin{cases} e_p = 1.36 \\ e_n = 0.45 \end{cases}$$

Matrix element

$$M_p = \sqrt{(2J_i + 1)\, B(E2)}$$

$$M_p = e_p A_p + e_n A_n$$

Assuming that shell model results of

$$A_p = 4.74 \text{ and } A_n = 5.95$$

$$A_n(T_Z = -2) = A_p(T_Z = +2)$$

We can solve e_p and e_n

$$\begin{cases} e_p = 0.19 \\ e_n = 1.81 \end{cases} \quad \leftarrow \text{very strange !!}$$

Shell model does not perfectly reproduce the isospin symmetry of B(E2) in ^{26}P & ^{26}Na pair.

W.A. Richter *et al.*, Phys. Rev. C 78, 064302 (2008).

Results of E_γ & $T_{1/2}$

^{26}P

	E_γ(keV)	$T_{1/2}$(ns)
HPGe	163.7(02)	103(8)
$LaBr_3$(Ce)	164.1(10)	106(4)
NaI(Tl)	163.8(10)	102(4)
Ave.	**163.8(2)**	**104(3)**

^{25}Si

	E_γ(keV)	$T_{1/2}$(ns)
HPGe	44.9(02)	42.3(30)
$LaBr_3$(Ce)	42.0(20)	43.2(08)
NaI(Tl)	44.8(20)	42.8(08)
Ave.	**44.9(2)**	**43.0(6)**

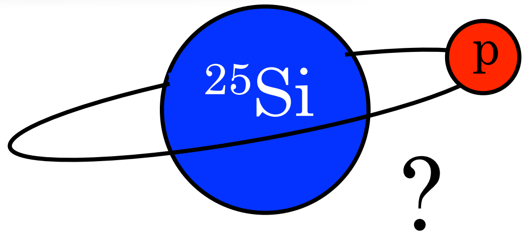
c.f. 40.0(50) keV

(2) Candidate for proton halo

$^{26}P = {}^{25}Si + p\ (2s_{1/2})$ $S_p = \begin{cases} -119 \pm 6 & \text{keV [1]} \\ 0 \pm 90 & \text{keV [2]} \\ 140 \pm 200 & \text{keV [3]} \end{cases}$

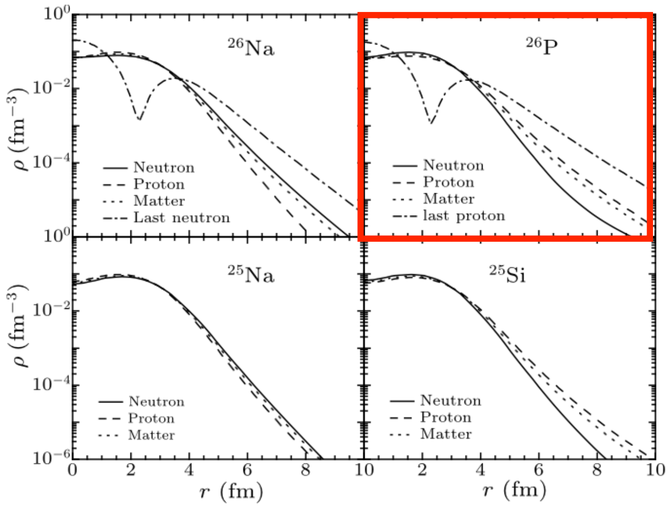
c.f. $^{8}B = {}^{7}Be + p\ (1p_{3/2})$ $S_{1p} = 137$ keV

$^{17}Ne = {}^{15}O + 2p\ (2s_{1/2})$ $S_{2p} = 943$ keV

$^{26}P =$ 

Theory

$\rho(r)$ deduced by RMF calc.



large tail

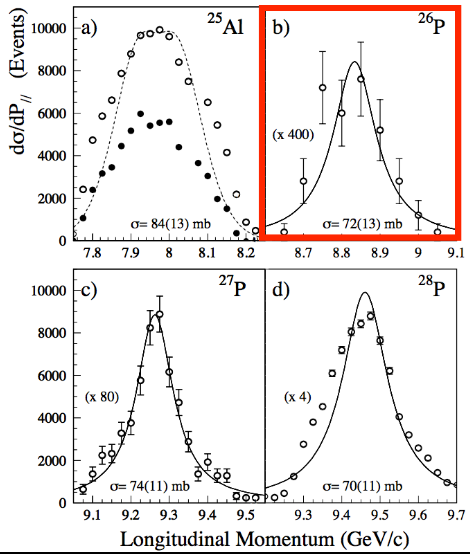
Fig. 2. Density distributions of nucleons in ^{26}Na-^{26}P and their core nuclei.

Y.-J Liang *et al.*, Chin. Phys. Lett. 26, 032102 (2009).

c.f. Shell model: B.A. Brown & P.G. Hansen Phys. Lett. B 381 391 (1996).

Experiment

$P_{//}$ distribution

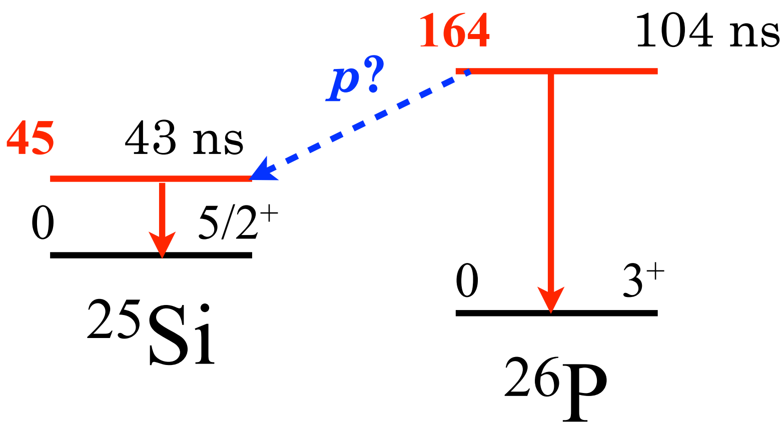


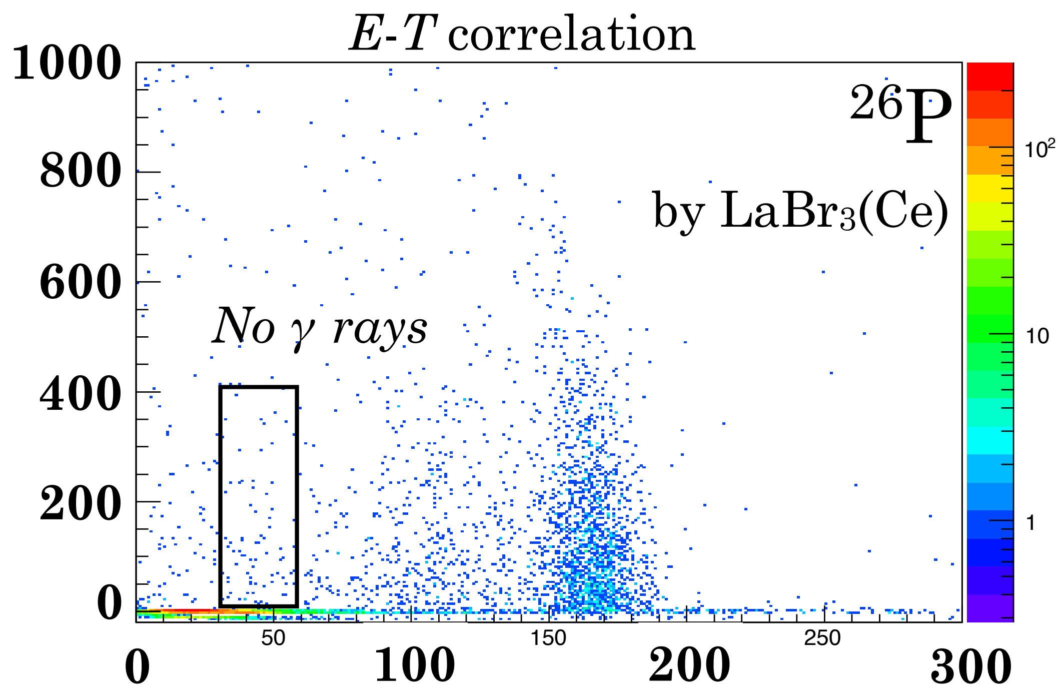
	Γ (MeV/c)	σ_{-1p} (mb)
^{9}Be(^{26}P, ^{25}Si)X	137(33)	72(13)
^{9}Be(^{27}P, ^{26}Si)X	116(8)	74(11)
^{9}Be(^{28}P, ^{27}Si)X	143(14)	70(11)

narrow large

A. Navin et al., Phys. Rev. Lett. 81 5089 (1998).

Check of Direct Proton Emission





We did not observe 44-keV & 104-ns γ rays in ^{26}P. $I_\gamma(44)/I_\gamma(164) < 5\%$.