“Cosmic acceleration” Symposium @ YITP, Kyoto University

Realization of the active pumping of the Thorium-229 isomeric state

(Kobo kenkyu : 18H04353)

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manuscripts

X-ray pumping of the ^{229}Th nuclear clock iso

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February 14, 2019

arXiv:1902.04823v1 [nucl-ex] 13 Feb 2019

Abstract

Thorium-229 is a unique case in nuclear physics: it presents a metastable first excited
electronvolts above the nuclear ground state. This so-called isomer is accessible by VUV lasers
the amazing precision of atomic laser spectroscopy to nuclear physics. Being able to manipulat
at will opens up a multitude of prospects, from studies of the fundamental interactions in p
compact and robust nuclear clock. However, direct optical excitation of the isomer or its ra
ground state has not yet been observed, and a series of key nuclear structure parameters such
half-lives of the low-lying nuclear levels of ^{229}Th are yet unknown. Here we present the first a
^{229m}Th. Our scheme employs narrow-band 29 keV synchrotron radiation to resonantly excite
which then predominantly decays into the isomer. We determine the resonance energy with 0.
half-life of 82.2 ps, an excitation linewidth of 1.70 neV, and extract the branching ratio of the
the ground and isomeric state respectively. These measurements allow us to re-evaluate gamm
have been collected over 40 years.

1 Introduction

The first excited nuclear state of ^{229}Th is known to be
an isomeric state ^{229m}Th (metastable excited state). It

it is the lowest nuclear exci
far. Although the optical exc
to ^{229m}Th is yet to be estab
tions for exploiting it as a ne
vestigations are expanding.

トピックス

放射光で探るレーザー光による超精密原子核制御の可能性：^{229}Th 極低核励起準位

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要 旨 原子核としては異常に低いエネルギー（eV オーダー）の励起準位を持ち，レーザーによる核状態操作が可能で超精密原子核時計等への応用が期待されているアイソトープ ^{229}Th に近年注目が集まっている。我々は，この研究を展開するのに欠かせない低エネルギー準位のエネルギー・寿命の決定のために，高輝度放射光 X 線と高性能検出器・標的システムを組み合わせた核共鳴散乱実験を行っている。高度化した核共鳴測定システムの開発，それを用いた短寿命準位（^{201}Hg の26 keV 準位）の高精度核共鳴実験の結果，および ^{229}Th の核共鳴実験の現状について紹介する。

1. はじめに

原子核は陽子と中性子（総称して核子）が強い力で束縛された系であり，個々の核子はそれぞれがお互いに作る核力ポテンシャルの中で形成される軌道を運動している。また個々の核子の運動だけでなく，原子核全体の回転や振動という集団運動に起因するスペクトルが観測されるという大きな特徴がある。原子物理における軌道電子とは違い，原子核を励起する，つまり核子をより高いエネルギー軌道に上げたり回転・振動モードを励起するには通常 keV から MeV 程度のエネルギーが必要である。このため，量子エレクトロニクス分野で見られるようなレーザー光を利用した高度な量子操作は，原子核に対しては一般的に不可能である。一方で，原子核の量子状態は原子のそれに比べて極めて壊れにくい，外界から隔離された良い量子力学系であるという魅力がある。レーザー光を用いた原子核に対する量子エレクトロニクスの実現は新たな科学分野の開拓につながると期待されている。

このような理由で近年大きく興味を持たれている原子核が ^{229}Th（自然存在比 0%，半減期7880年）である。^{229}Th はその第一励起状態が原子核としては異常に低く，レーザー光でアクセス可能な eV 領域にあることが分かってきた。このことは1970年代から指摘されていたが[1]，このあまりにも低い励起状態を特定することは困難を極め，それがはっきりしてきたのは2000年代に入ってからである。2007年に複数の γ 線測定エネルギーを足し引きすることで，間接的にこの状態の励起エネルギーが7.8±0.5 eV であるという報告[2]がなされ，最近ではその励起エネルギーは確かに6.3～18.3 eV の間に存在することが実験的に確かめられた[3]（Fig. 1）。しかしこのエネルギーを直接的に

“X-ray pumping of the ^{229}Th nuclear clock isomer” arXiv:1902.04823v1

Collaboration

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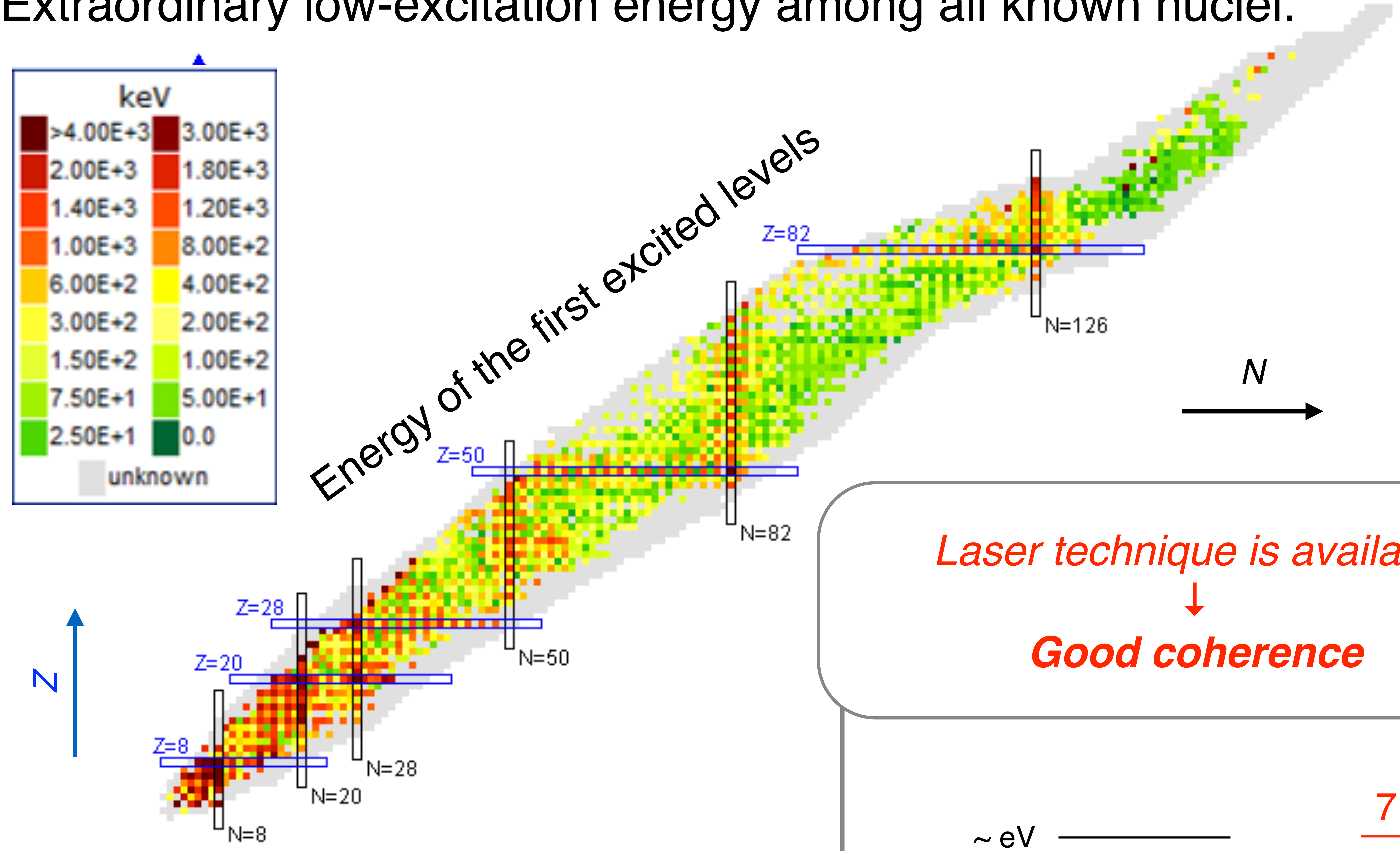
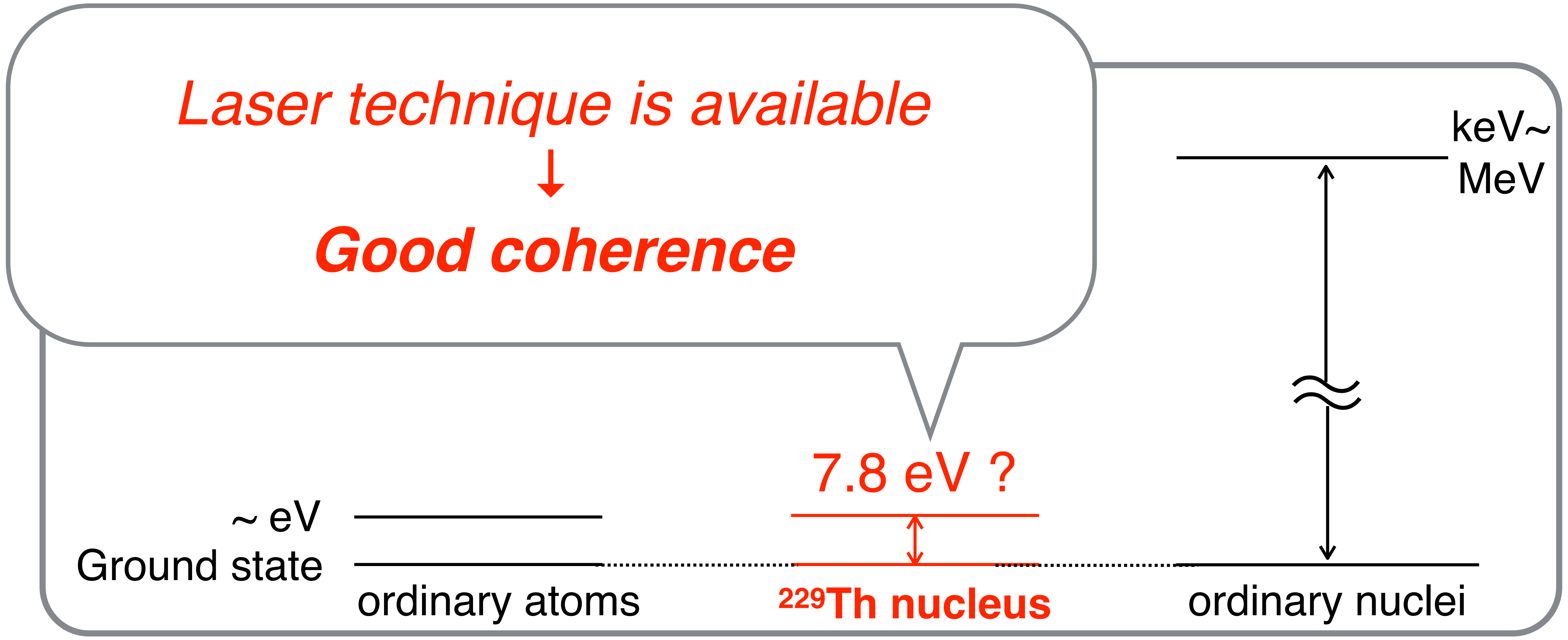
8 institutes, ~ 30 collaborators

$^{229}_{90}$Th

Extraordinary low-excitation energy among all known nuclei.





Examples of applications

Frequency standard "Nuclear Clock"

G.A. Kazakov, et al., *N. J. Phys.* **14**, 083019 (2012).

- Current definition of second (based on Cs atomic clock) : Uncertainty ~10^{-16}
- ^{229}Th nuclear clock can improve the uncertainty to 10^{-19} even in a solid-state.

→ Realize more accurate (& portable) clock

➡ Measurement of the temporal variation of the Fine Structure Constant

- Current limit (based on Yb atomic clock stability) : $\frac{d\alpha/dt}{\alpha} = (-2.0 \pm 2.0) \times 10^{-17}$ / year

N. Hntemann et al., *Phys. Rev. Lett.* **113**, 210802 (2014).

- ^{229}Th nucleus is the most sensitive candidate. **Several orders*!* improvement** is expected.

V.V. Flambaum, *Phys. Rev. Lett.* **97**, 092502 (2006).
J.C. Berengut et al., *Phys. Rev. Lett.* **102**, 210801 (2009).

10^{-22}/year can be possible.
It can constrain parameters in BSMs which relate "cosmic acceleration"

➡ Dark matter search

A. Derevianko and M. Pospelov, Nat. Phys. **10**, 933 (2014).

- Topological defect dark matter

➡ Heavy rare metal search

- Relativistic geodesy

History & situation of the ^{229}Th isomer (^{229m}Th)

year		result
1976	Kroger & Reich *Nucl. Phys. A* **259**(1976) 29. U-233 α-decay γ-spectroscopy	< 100 eV
1994-	Helmer and Reich, Many searches…	3.5 ± 1.0 eV
2007	Beck et al. *Phys. Rev. Lett.* **98**(2007) 142501; LLNL-PROC-415170 (2009). γ-spectroscopy by microcalorimeter (indirect measurement)	7.8 ± 0.5 eV
2015	Jeet et al. *Phys. Rev. Lett.* **114**(2015) 253001. Direct VUV excitation & emission. → Null result	Reject : 7.3-8.8 eV (τ : 1-5600 s)
2016	Wense et al. *Nature* **533**(2016) 47. Observation of IC electron from the isomer state (from ^{233}U α-decay)	6.3-18.3 eV
2017	Seiferle et al. *Phys. Rev. Lett.* **118**(2017) 042501. Lifetime measurement of IC electrons (from ^{233}U α-decay)	τ_{IC} = 7 ± 1 us $\tau_{\gamma} \sim 10^4$ s
2018	Thielking et al. *Nature* **556**(2018) 321. Laser spectroscopy of the isomer state (from ^{233}U α-decay)	HFS, M1, E2 of $^{229m}Th^{2+}$

× Precise energy is not known.

Gamma-ray spectroscopy	**7.8±0.5 eV**
Direct excitation	**7.3 - 8.8 eV excluded**
Electron emission measurement	**6.3 - 18.3 eV**

× Laser excitation & VUV photon emission have never been observed.

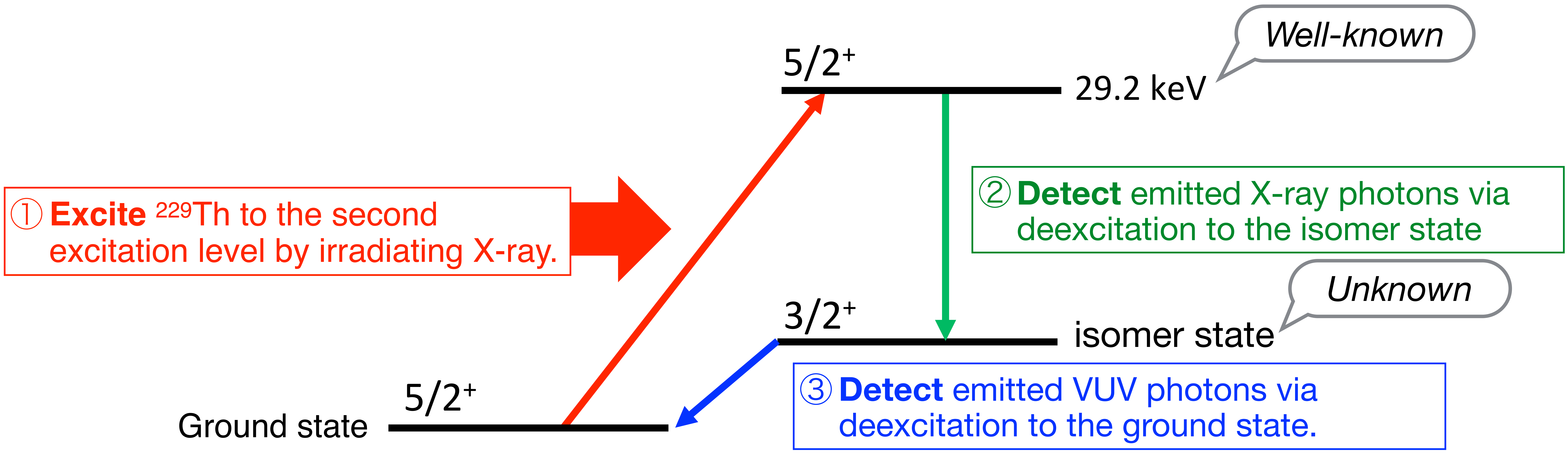
Introduction of our project

All the previous experiments used ^{233}U α-decay as a ^{229}Th isomer source.
But, α-decay is a violent process (huge background, > 80 keV recoil energy, …), and uncontrollable.

More **cleaner and controllable** isomer production method is preferred.

➡ ***Optical active pumping to the isomer state***

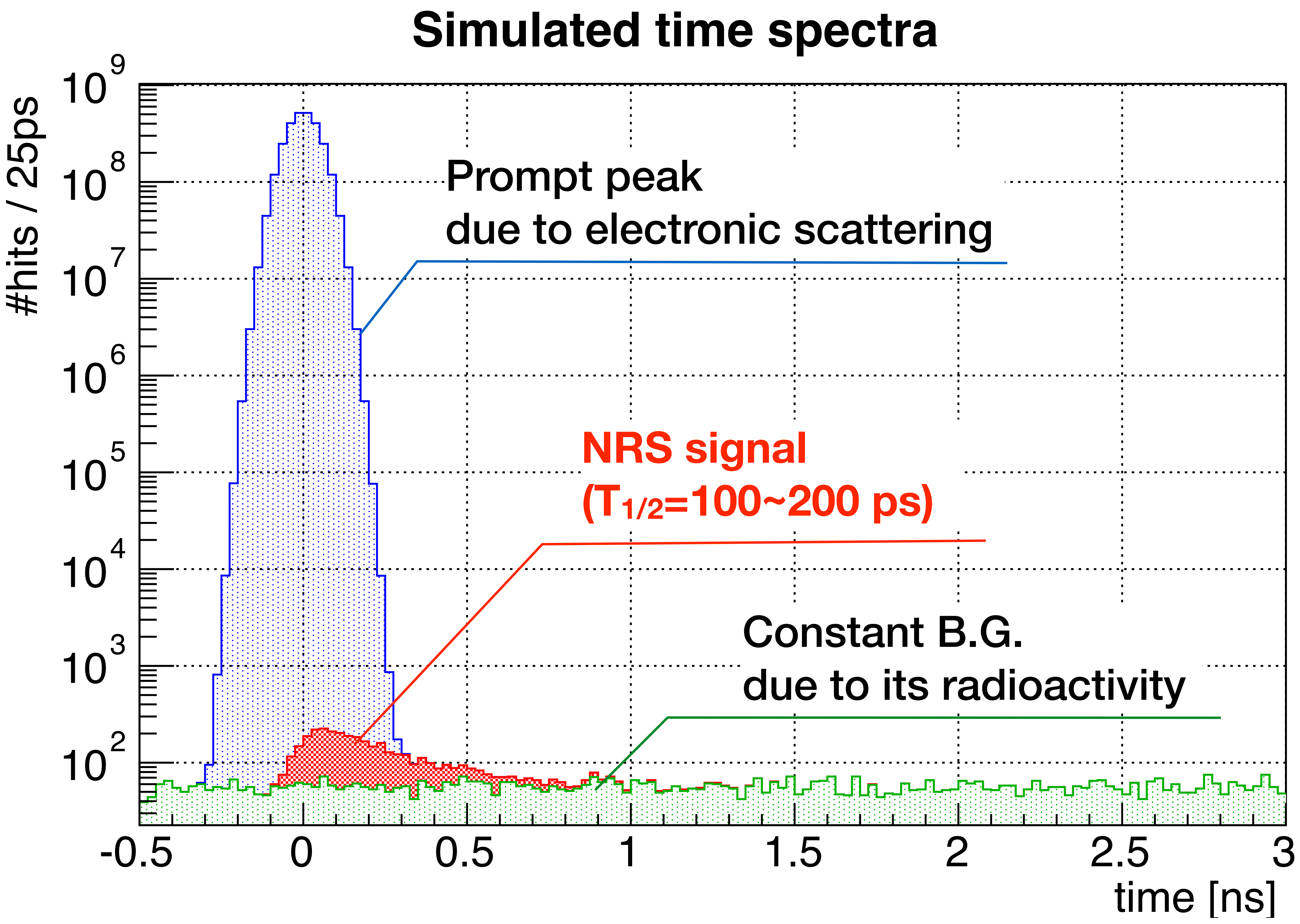
Principle of the pumping



NRS (Nuclear resonant scattering)

By detecting X-ray photon emission in ②, we can confirm the isomer production.
Then, we simply wait for the VUV photon emission in ③ to measure its wavelength.

Key points for Th-229 NRS



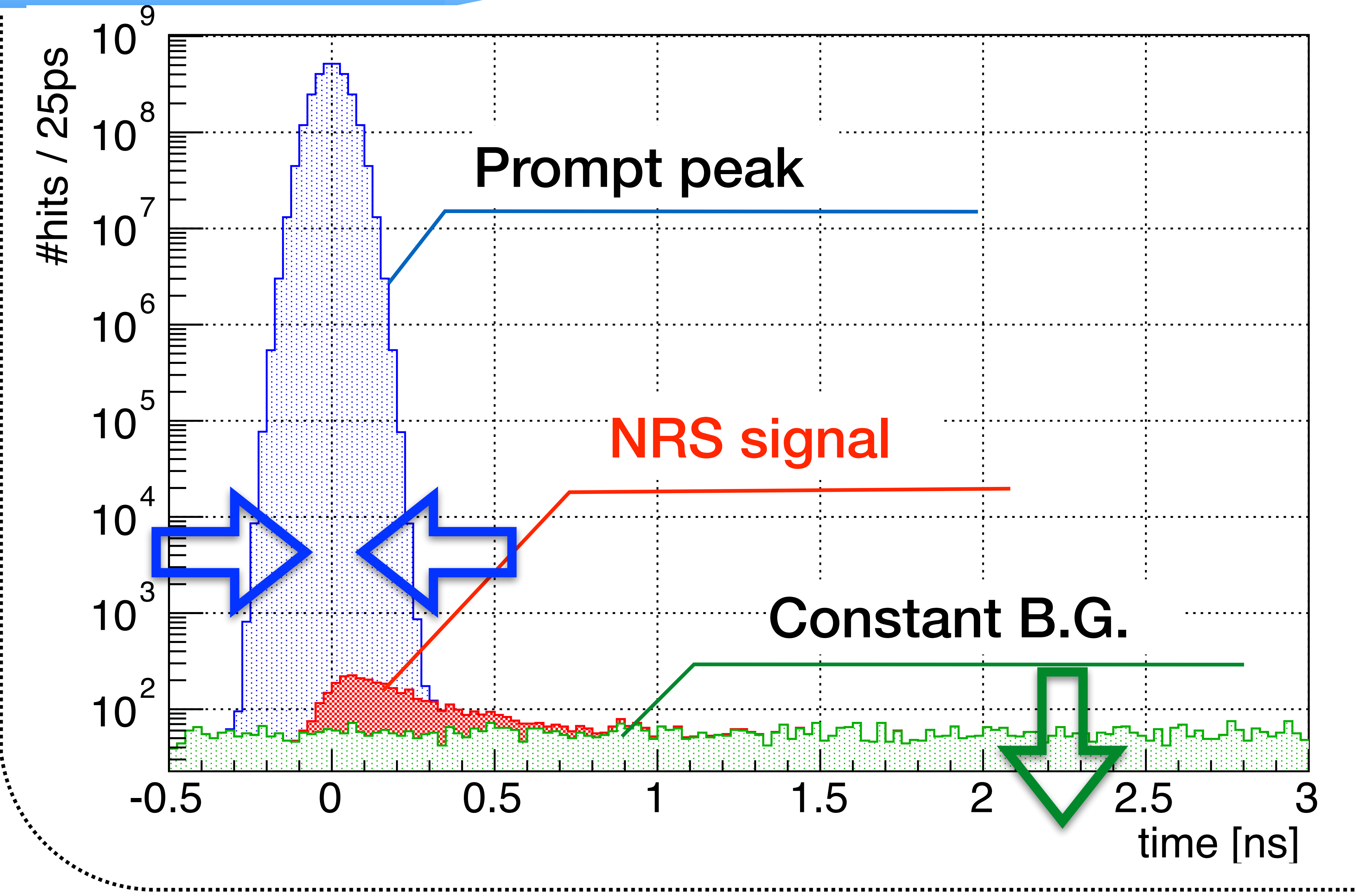
Difficulties ***Poor SNR***

Short lifetime	$T_{1/2}$ = 100 - 200 ps
Low S/N ratio	10^{-6} - 10^{-7}
Low Signal rate	< 1cps
Constant B.G.	Radioactivity

Requirements to apparatus

- Short tail in the time response
- Fast time resolution
- Low dark counts
- High rate tolerance
- Simultaneous energy & timing meas.

X-ray detector system

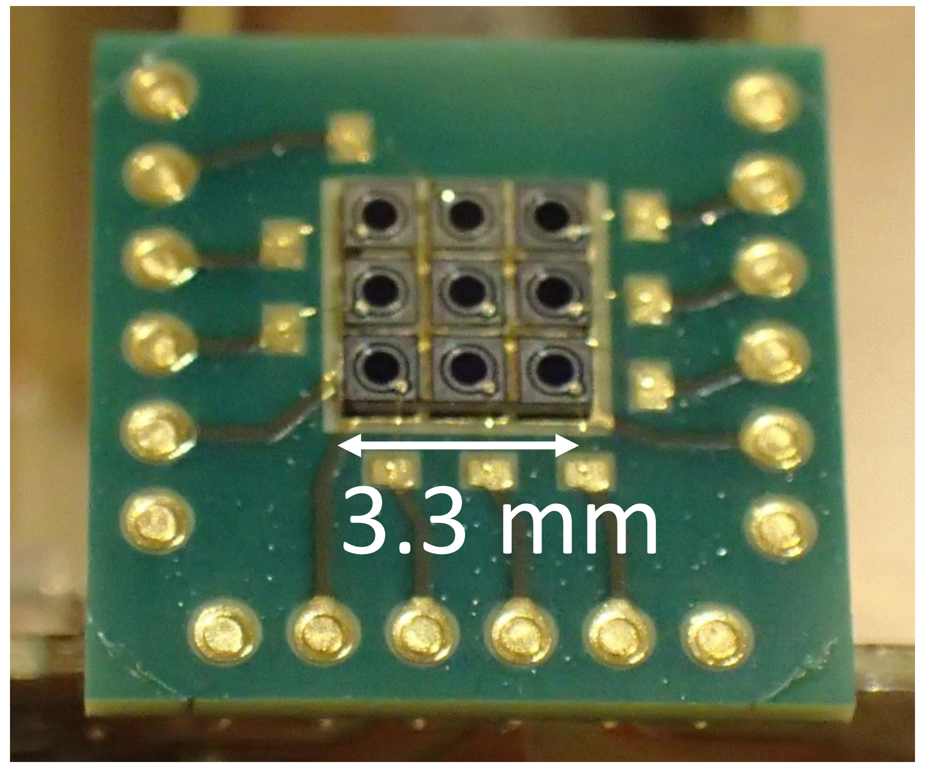


Si-APD: Hamamatsu Photonics S12053-05

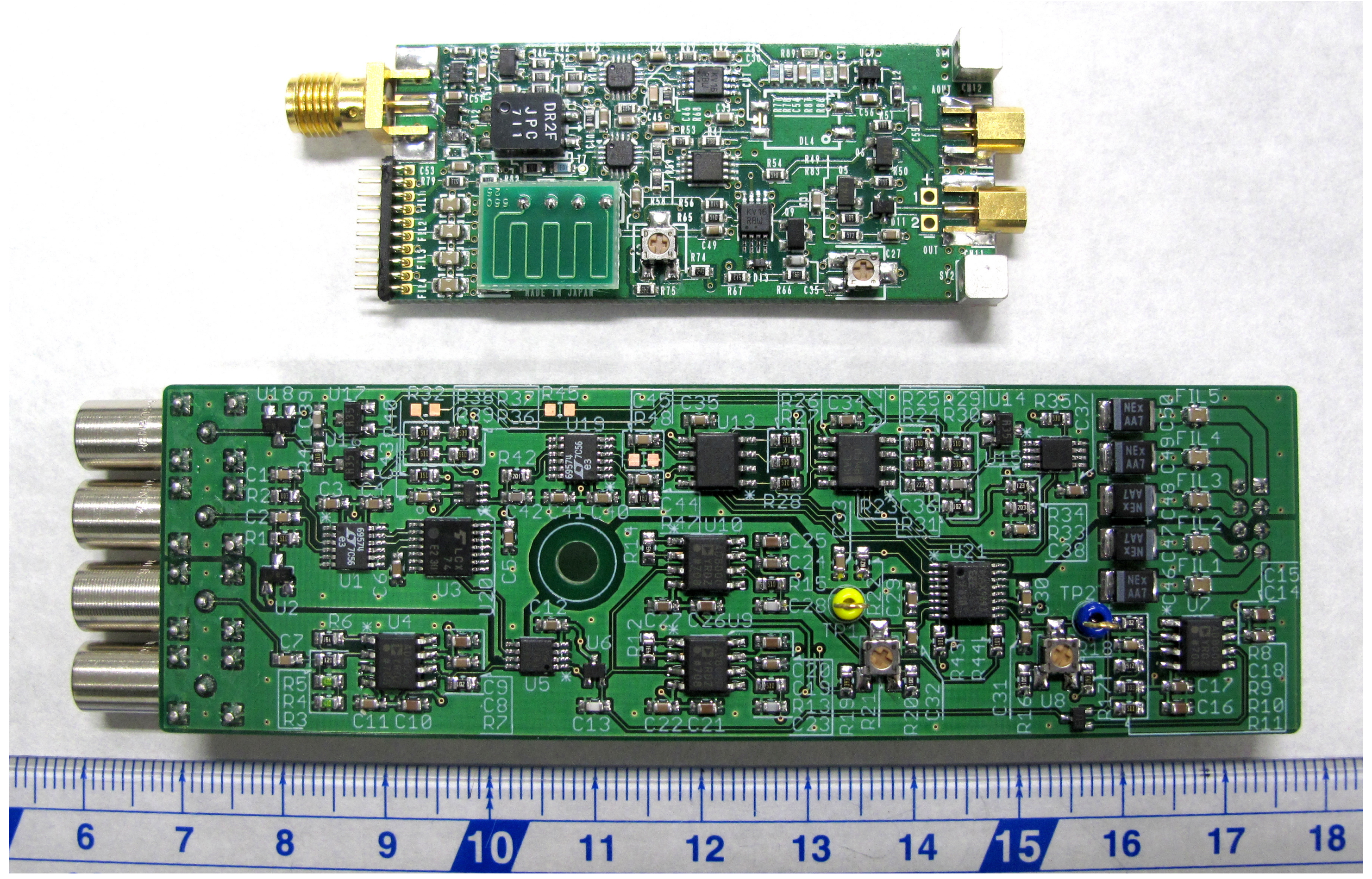
- Small diameter | 0.5mmΦ
- Thin depletion layer | ~10 um

Dedicated fast peripheral circuits

- High rate measurement | 10^6 cps / ch
- Simultaneous energy & timing measurement



customized 9-ch array



Constant fraction discriminator
Amplitude-to-time convertor
Trailing edge discriminator

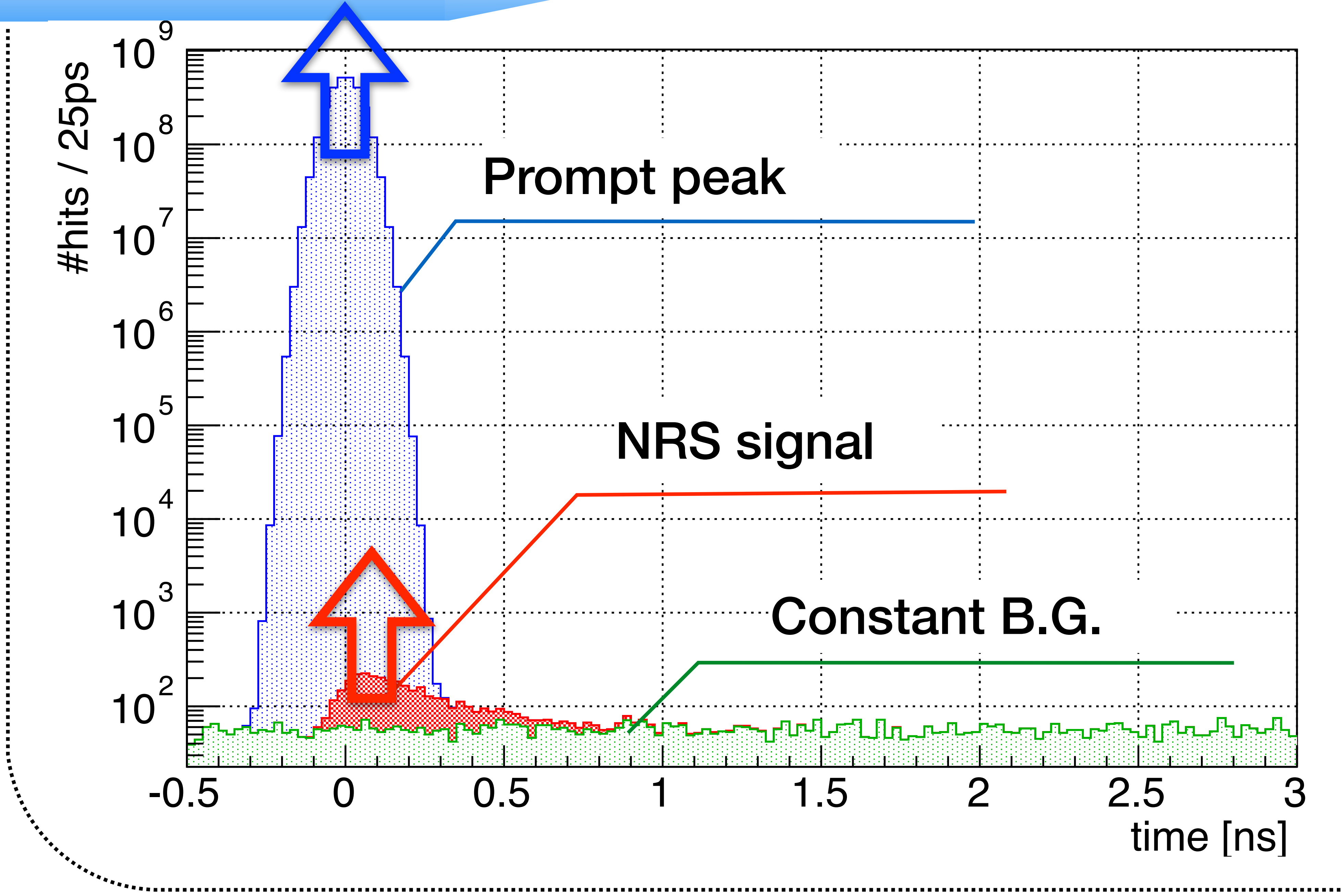
Multihit TDC
MCS6 (FAST ComTec)

T. Masuda et al., *Rev. Sci. Instrum.* **88**, 063105 (2017).
T. Masuda et al., *Nucl. Instrum. Meth. A.* **913**, 72 (2019).
T. Masuda et. al., *Submitted to JPS: Conf. Ser.*

Dense target & beam

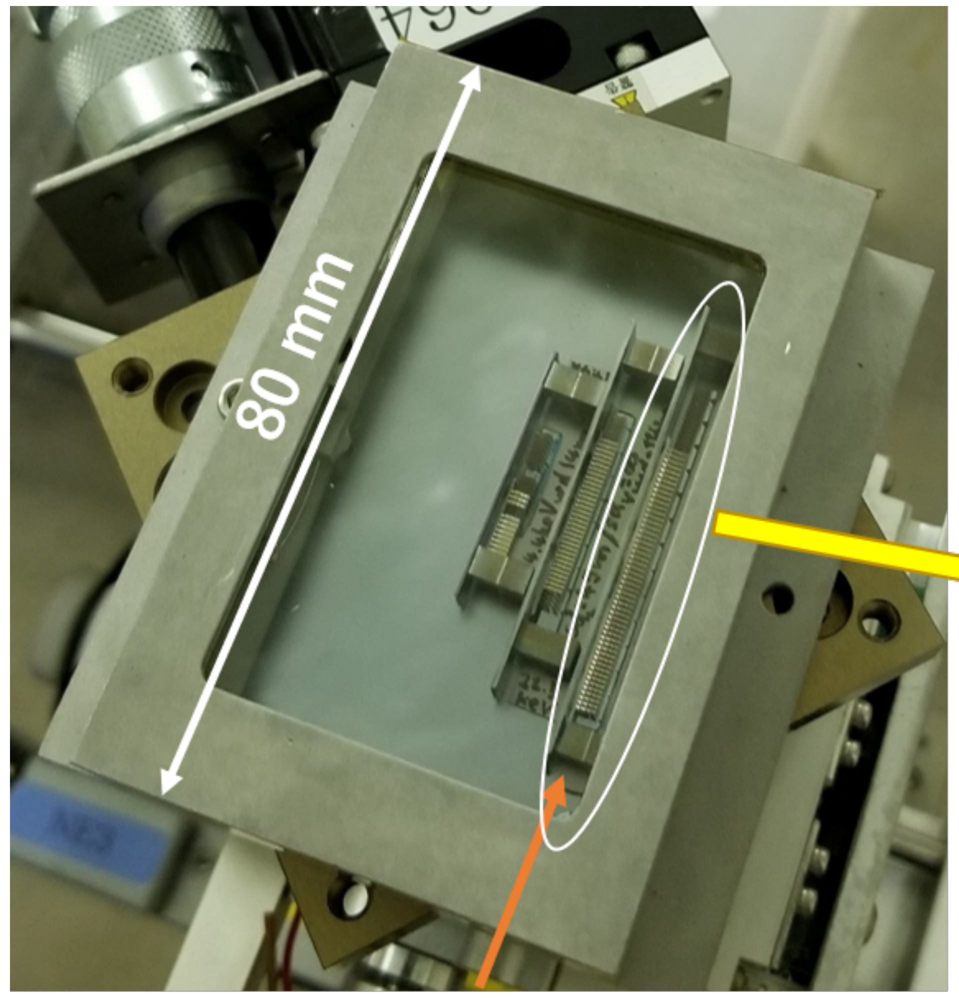
“Dense” Th target

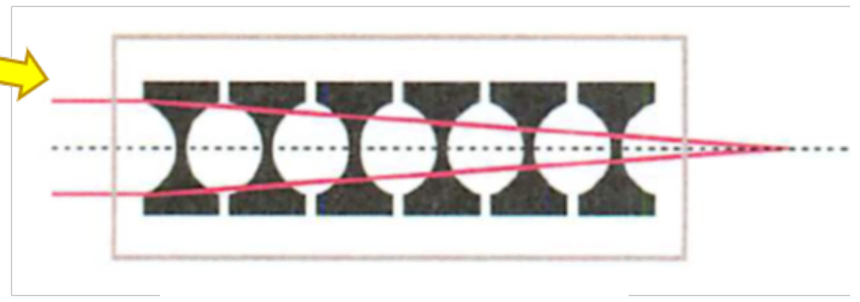
- dry-up method
- 0.24 μg, 0.4mmΦ

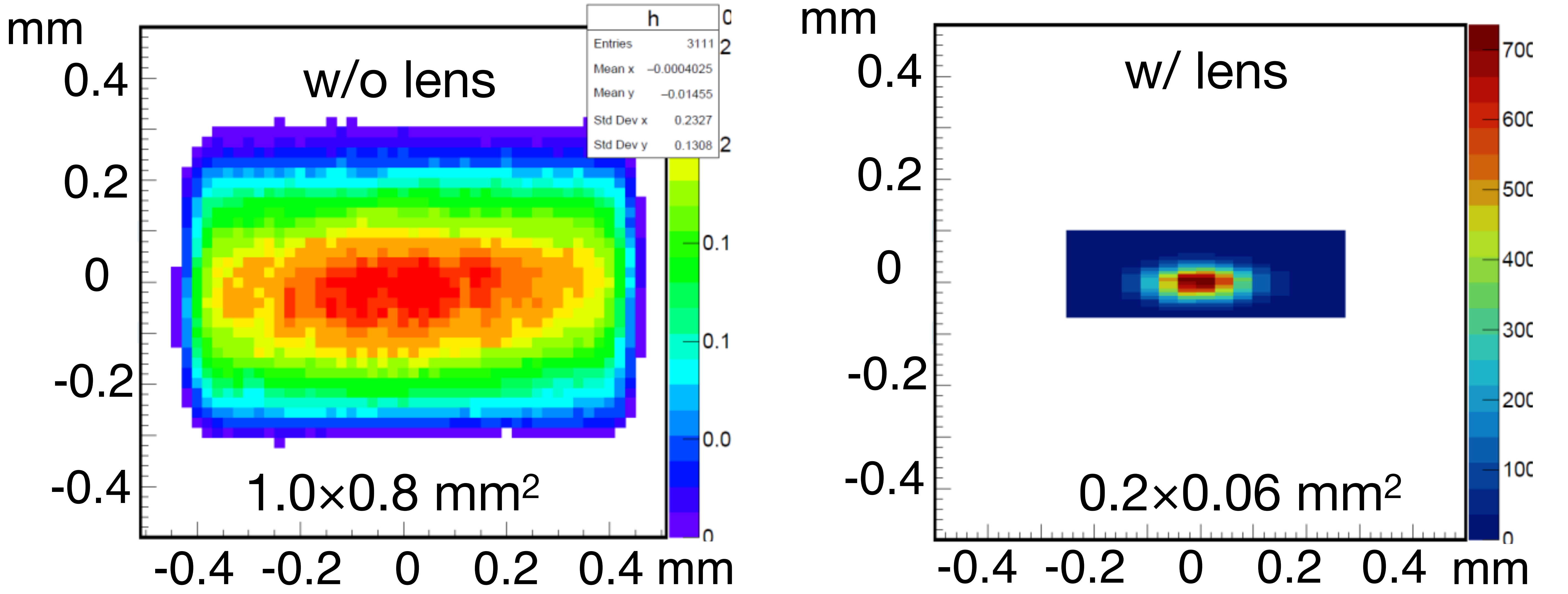


“Focused” X-ray beam

- Focused with a refractive lens array
- $1.0\times0.8\ mm^2 \rightarrow 0.2\times0.06\ mm^2$ (FWHM)





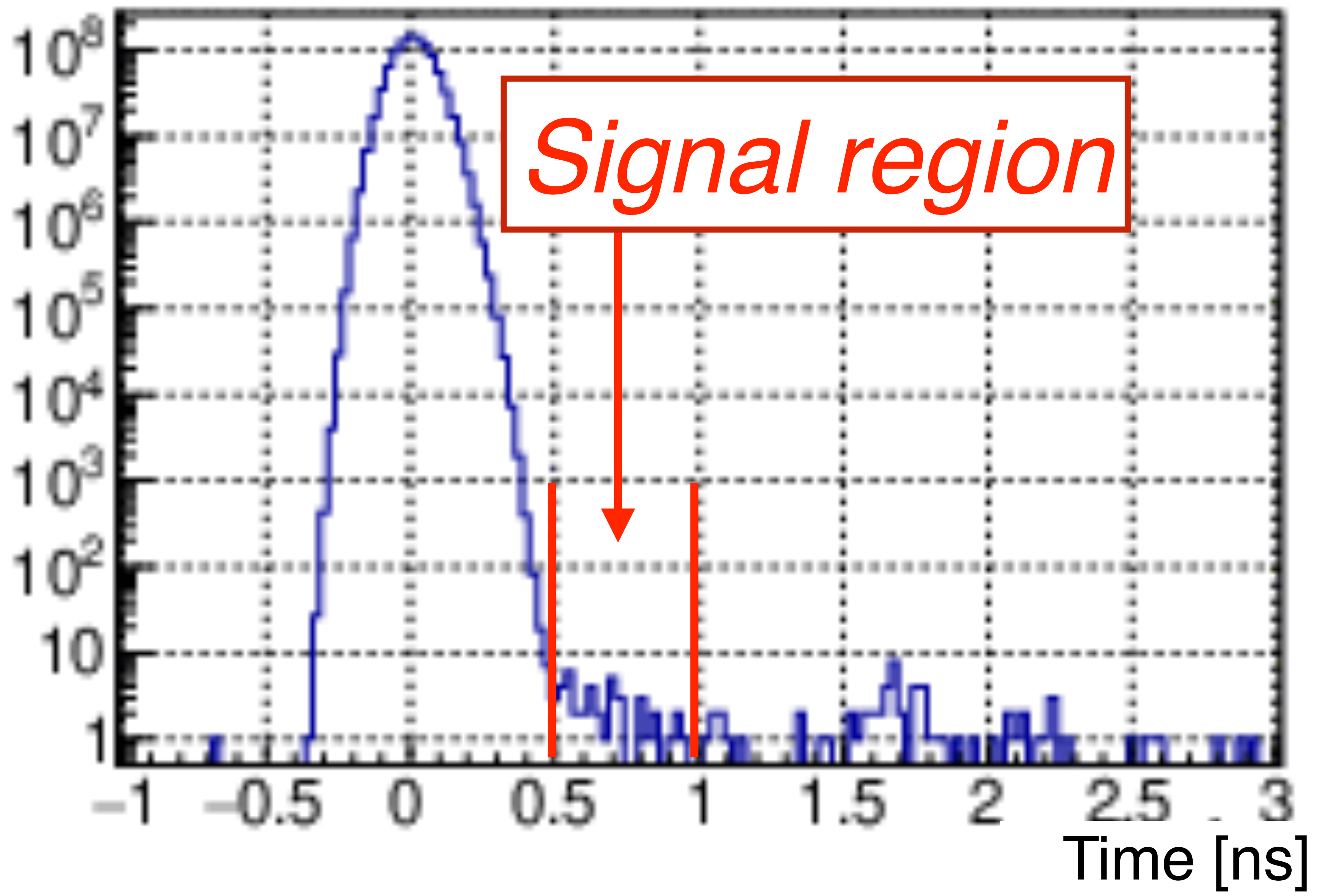


SPring-8

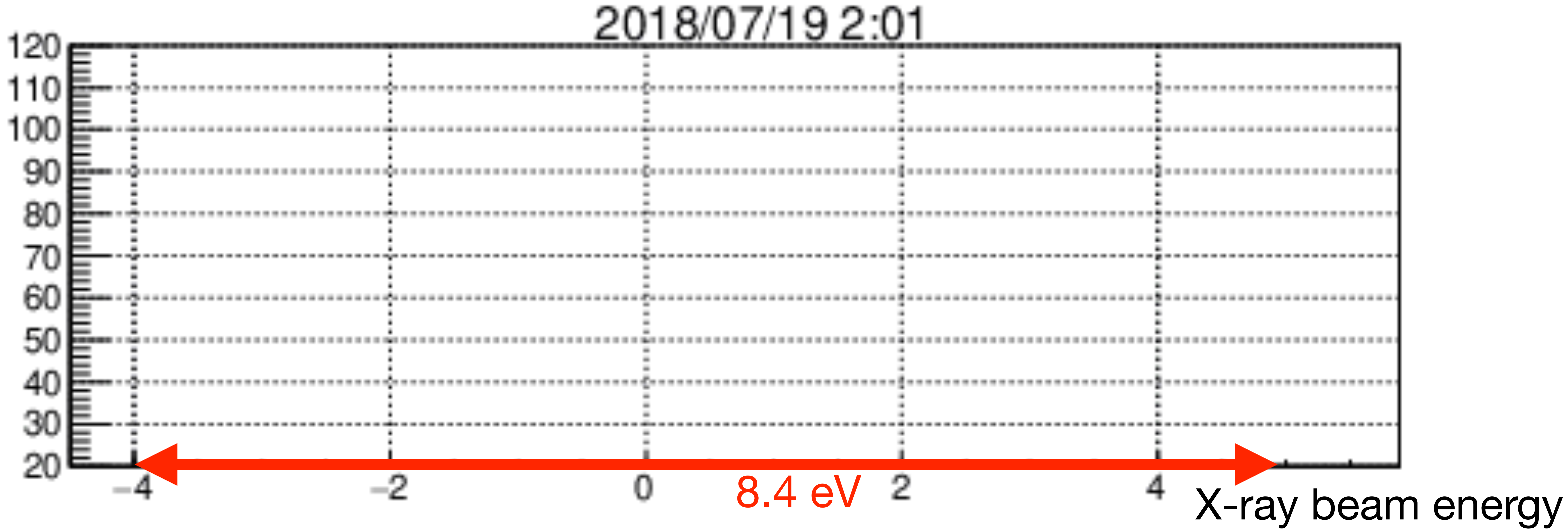
The most intense X-ray synchrotron radiation facility in Japan.

NRS search

Beam time	2018/7/15 9:00- 7/23 9:00
Monochro.	Si440
Scan range	8.4 eV (0.1 eV step)
Scan points	113 points (1800s/point)
Scan time	67 hours (7/19 2:00 - 21 21:00)

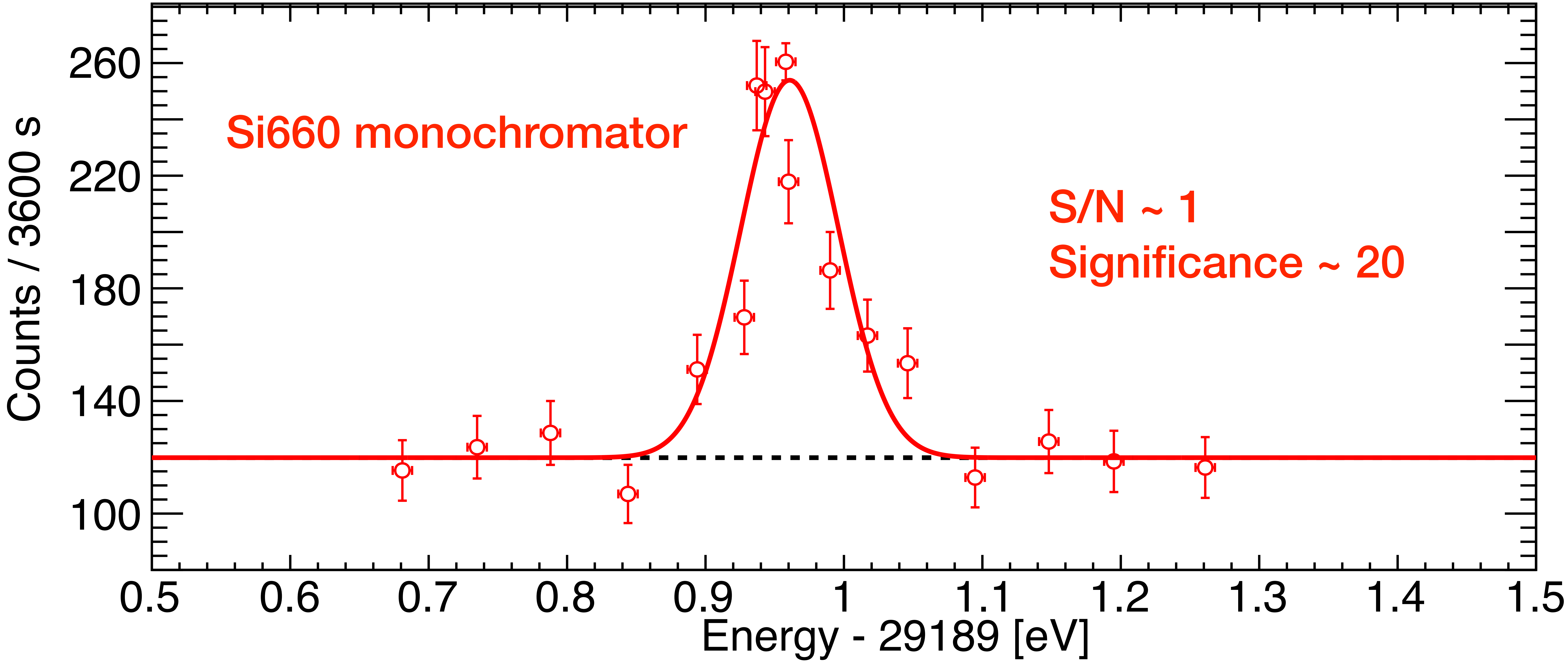


Number of events in the signal region



Results

The NRS peak has been observed.

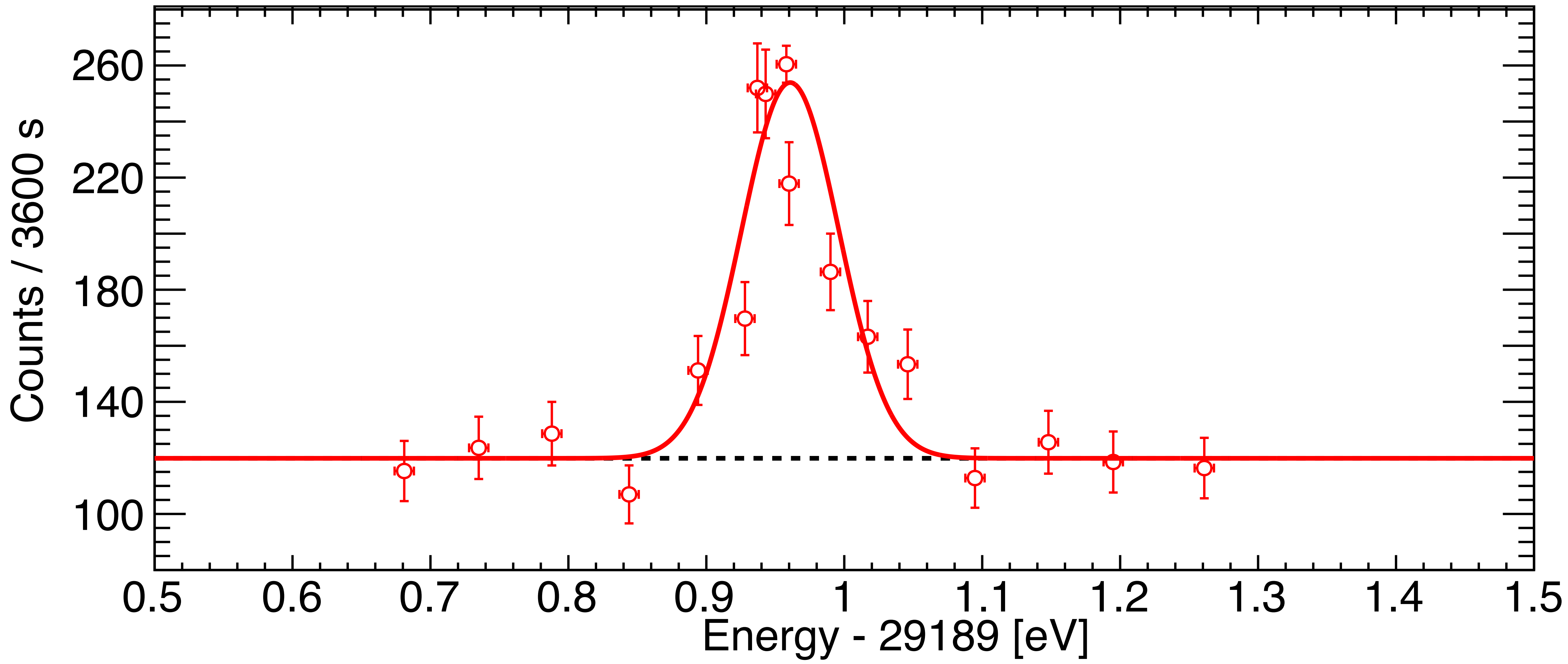


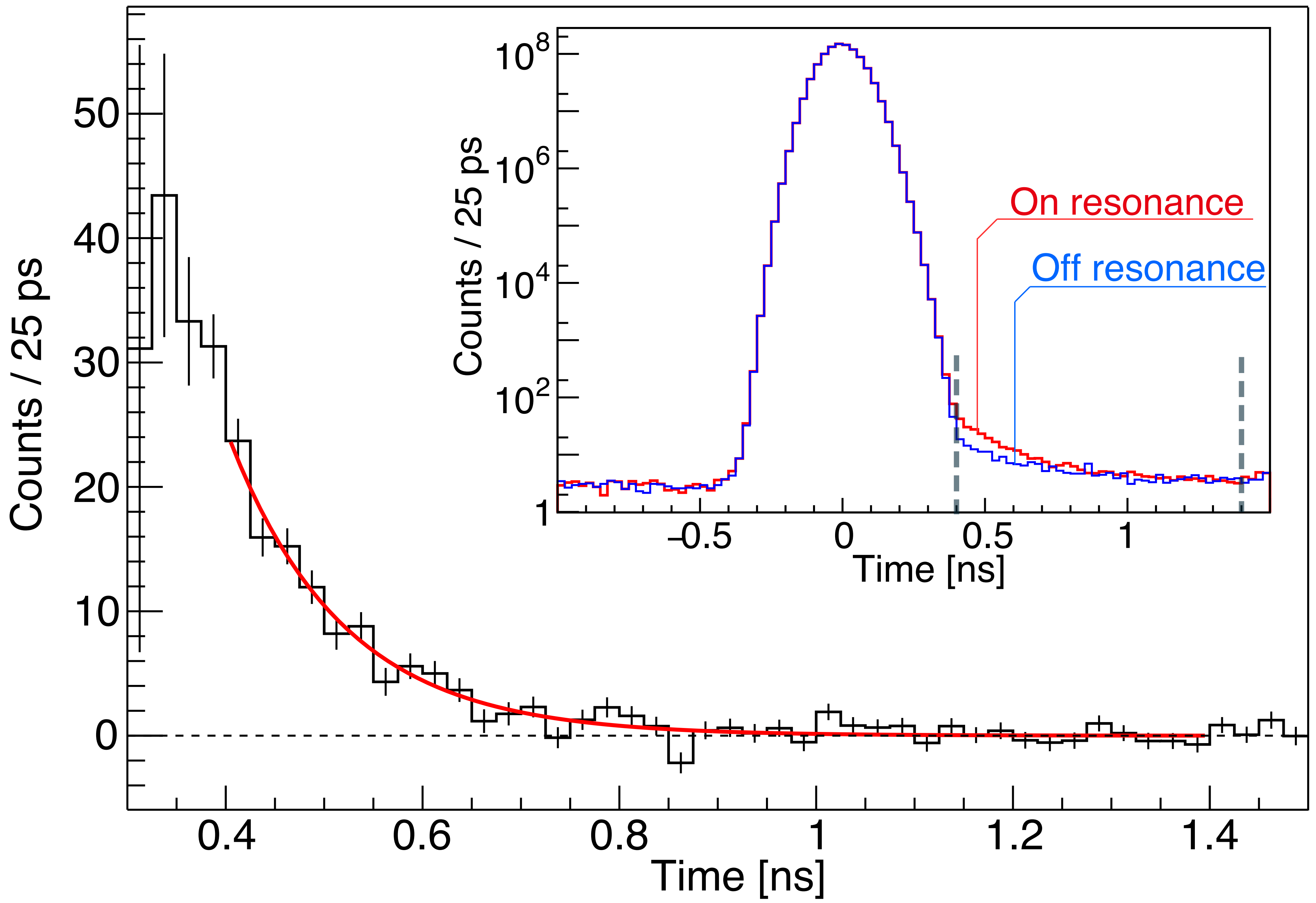
The world's first demonstration on

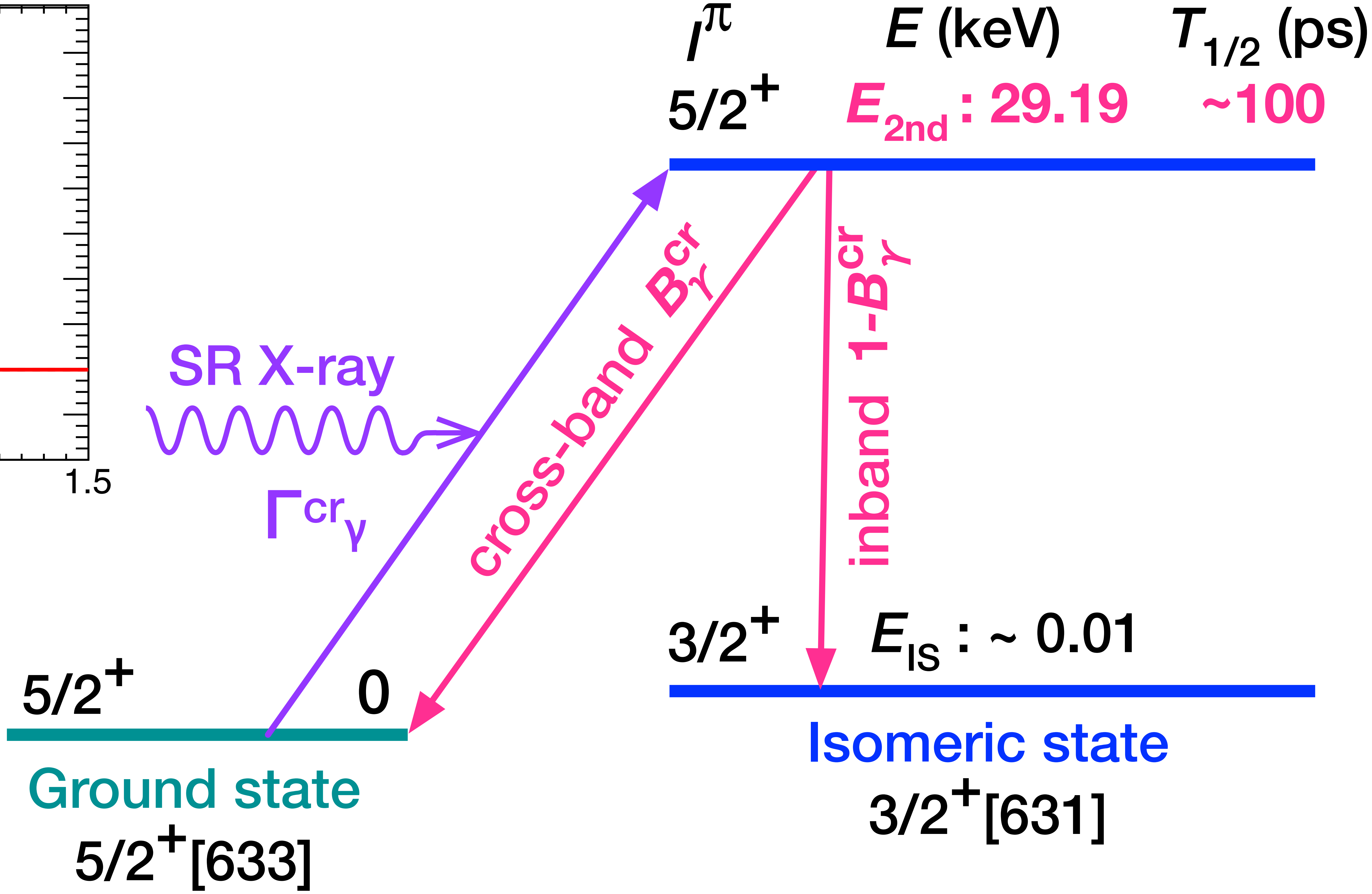
the active pumping to the isomer state


Significance
クレーン停止場所

Obtained nuclear parameters

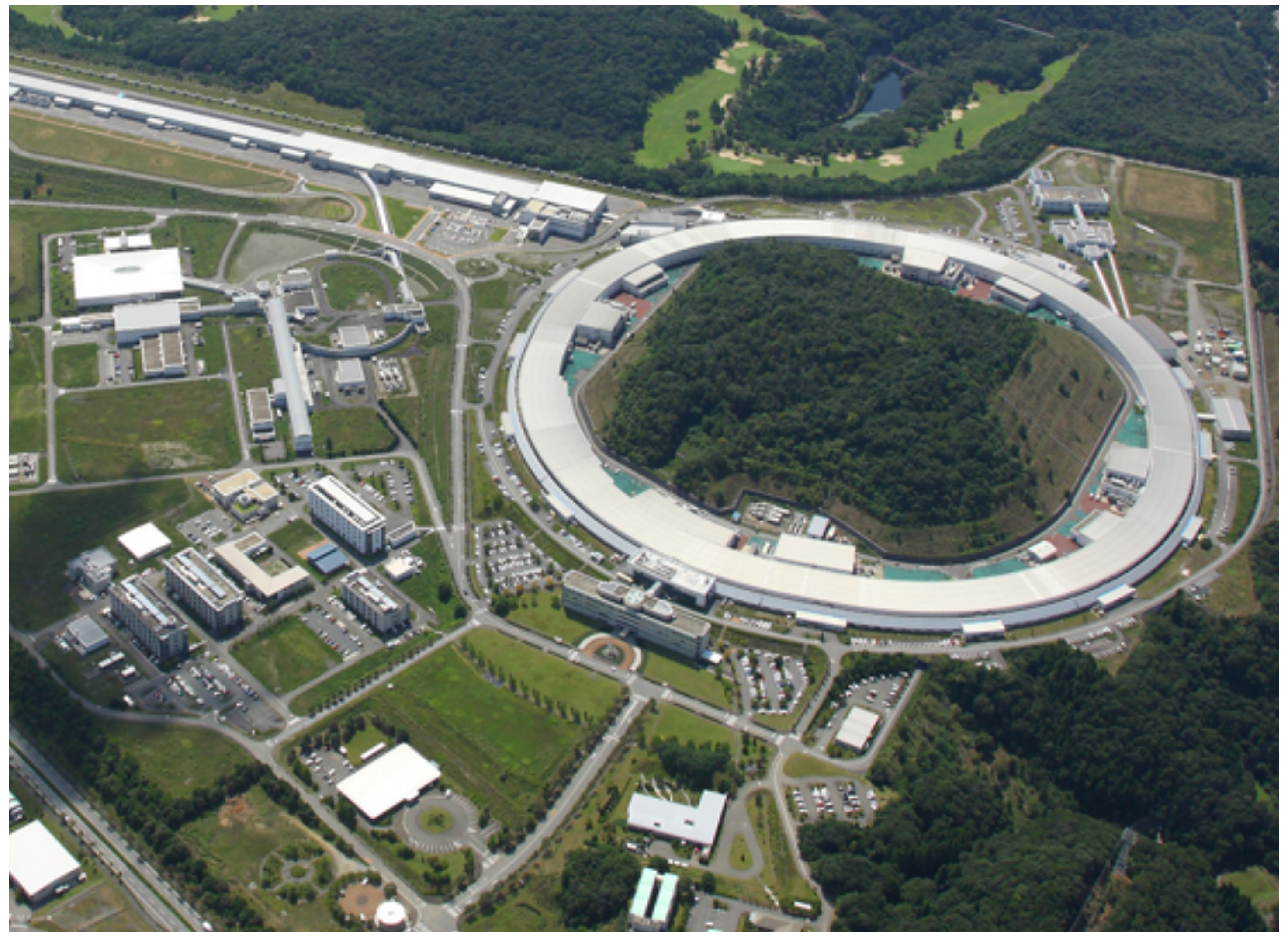


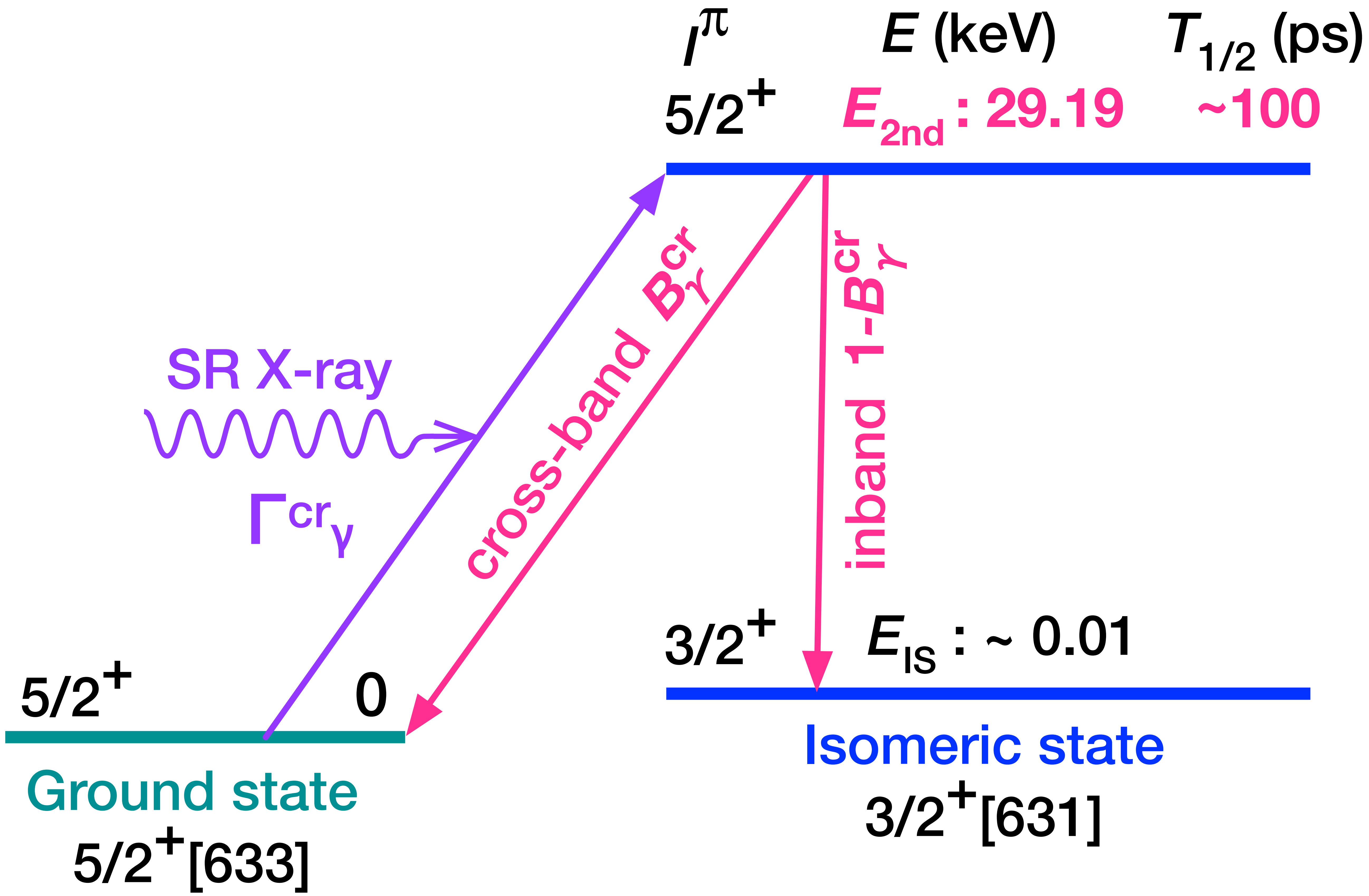




E_{2nd} = 29189.93 ± 0.07 eV (2 ppm)
$T_{1/2}$ = 82.2 ± 4.0 ps (Fastest NRS meas.)
$\Gamma^{cr}{}_\gamma$ = 1.70 ± 0.40 neV
$B^{cr}{}_\gamma$ = 1/(9.4±2.4) ~ 0.11

Isomer factory





***Isomer production rate* ~ 2.5×10^4 cps**

Summary & Prospects

- Isomer state of Th-229 : the extremely-low energy ~ 8 eV
  will building a new bridge between atomic & nuclear physics

- The world's first artificial pumping to the isomer state has been realized.

- The next step : VUV emission detection & spectroscopy