Th-229mアイソマー
極低エネルギー準位の測定

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イントロダクション

PERIODIC TABLE

Atomic Properties of the Elements

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Physics Laboratory
physics.nist.gov

Standard Reference Data
www.nist.gov/srd

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum	c	299 792 458 m s^{-1}	(exact)
Planck constant	h	6.6261 x 10^{-34} J s	($\hbar = h/2\pi$)
elementary charge	e	1.6022 x 10^{-19} C	
electron mass	m_e	9.1094 x 10^{-31} kg	
	$m_e c^2$	0.5110 MeV	
proton mass	m_p	1.6726 x 10^{-27} kg	
fine-structure constant	α	1/137.036	
Rydberg constant	R_∞	10 973 732 m^{-1}	
	$R_\infty c$	3.289 842 x 10^{15} Hz	
	$R_\infty hc$	13.6057 eV	
Boltzmann constant	k	1.3807 x 10^{-23} J K^{-1}	

Solids
Liquids
Gases
Artificially Prepared

Group 1 IA | 2 IIA | 3 IIIB | 4 IVB | 5 VB | 6 VIB | 7 VIIB | 8 | 9 VIII | 10 | 11 IB | 12 IIB | 13 IIIA | 14 IVA | 15 VA | 16 VIA | 17 VIIA | 18 VIIIA

Period 1

1 $^2S_{1/2}$ **H** Hydrogen 1.00794 1s 13.5984																	2 $^1S_0$ **He** Helium 4.002602 1s^2 24.5874

Period 2

3 $^2S_{1/2}$ **Li** Lithium 6.941 1s^{2}2s 5.3917	4 $^1S_0$ **Be** Beryllium 9.012182 1s^{2}2s^2 9.3227											5 $^2P^o_{1/2}$ **B** Boron 10.811 1s^{2}2s^{2}2p 8.2980	6 $^3P_0$ **C** Carbon 12.0107 1s^{2}2s^{2}2p^2 11.2603	7 $^4S^o_{3/2}$ **N** Nitrogen 14.0067 1s^{2}2s^{2}2p^3 14.5341	8 $^3P_2$ **O** Oxygen 15.9994 1s^{2}2s^{2}2p^4 13.6181	9 $^2P^o_{3/2}$ **F** Fluorine 18.9984032 1s^{2}2s^{2}2p^5 17.4228	10 $^1S_0$ **Ne** Neon 20.1797 1s^{2}2s^{2}2p^6 21.5645

Period 3

11 $^2S_{1/2}$ **Na** Sodium 22.98976928 [Ne]3s 5.1391	12 $^1S_0$ **Mg** Magnesium 24.3050 [Ne]3s^2 7.6462											13 $^2P^o_{1/2}$ **Al** Aluminum 26.9815386 [Ne]3s^{2}3p 5.9858	14 $^3P_0$ **Si** Silicon 28.0855 [Ne]3s^{2}3p^2 8.1517	15 $^4S^o_{3/2}$ **P** Phosphorus 30.973762 [Ne]3s^{2}3p^3 10.4867	16 $^3P_2$ **S** Sulfur 32.065 [Ne]3s^{2}3p^4 10.3600	17 $^2P^o_{3/2}$ **Cl** Chlorine 35.453 [Ne]3s^{2}3p^5 12.9676	18 $^1S_0$ **Ar** Argon 39.948 [Ne]3s^{2}3p^6 15.7596

Period 4

19 $^2S_{1/2}$ **K** Potassium 39.0983 [Ar]4s 4.3407	20 $^1S_0$ **Ca** Calcium 40.078 [Ar]4s^2 6.1132	21 $^2D_{3/2}$ **Sc** Scandium 44.955912 [Ar]3d4s^2 6.5615	22 $^3F_2$ **Ti** Titanium 47.867 [Ar]3d^{2}4s^2 6.8281	23 $^4F_{3/2}$ **V** Vanadium 50.9415 [Ar]3d^{3}4s^2 6.7462	24 $^7S_3$ **Cr** Chromium 51.9961 [Ar]3d^{5}4s 6.7665	25 $^6S_{5/2}$ **Mn** Manganese 54.938045 [Ar]3d^{5}4s^2 7.4340	26 $^5D_4$ **Fe** Iron 55.845 [Ar]3d^{6}4s^2 7.9024	27 $^4F_{9/2}$ **Co** Cobalt 58.933195 [Ar]3d^{7}4s^2 7.8810	28 $^3F_4$ **Ni** Nickel 58.6934 [Ar]3d^{8}4s^2 7.6399	29 $^2S_{1/2}$ **Cu** Copper 63.546 [Ar]3d^{10}4s 7.7264	30 $^1S_0$ **Zn** Zinc 65.38 [Ar]3d^{10}4s^2 9.3942	31 $^2P^o_{1/2}$ **Ga** Gallium 69.723 [Ar]3d^{10}4s^{2}4p 5.9993	32 $^3P_0$ **Ge** Germanium 72.64 [Ar]3d^{10}4s^{2}4p^2 7.8994	33 $^4S^o_{3/2}$ **As** Arsenic 74.92160 [Ar]3d^{10}4s^{2}4p^3 9.7886	34 $^3P_2$ **Se** Selenium 78.96 [Ar]3d^{10}4s^{2}4p^4 9.7524	35 $^2P^o_{3/2}$ **Br** Bromine 79.904 [Ar]3d^{10}4s^{2}4p^5 11.8138	36 $^1S_0$ **Kr** Krypton 83.798 [Ar]3d^{10}4s^{2}4p^6 13.9996

Period 5

37 $^2S_{1/2}$ **Rb** Rubidium 85.4678 [Kr]5s 4.1771	38 $^1S_0$ **Sr** Strontium 87.62 [Kr]5s^2 5.6949	39 $^2D_{3/2}$ **Y** Yttrium 88.90585 [Kr]4d5s^2 6.2173	40 $^3F_2$ **Zr** Zirconium 91.224 [Kr]4d^{2}5s^2 6.6339	41 $^6D_{1/2}$ **Nb** Niobium 92.90638 [Kr]4d^{4}5s 6.7589	42 $^7S_3$ **Mo** Molybdenum 95.96 [Kr]4d^{5}5s 7.0924	43 $^6S_{5/2}$ **Tc** Technetium (98) [Kr]4d^{5}5s^2 7.28	44 $^5F_5$ **Ru** Ruthenium 101.07 [Kr]4d^{7}5s 7.3605	45 $^4F_{9/2}$ **Rh** Rhodium 102.90550 [Kr]4d^{8}5s 7.4589	46 $^1S_0$ **Pd** Palladium 106.42 [Kr]4d^{10} 8.3369	47 $^2S_{1/2}$ **Ag** Silver 107.8682 [Kr]4d^{10}5s 7.5762	48 $^1S_0$ **Cd** Cadmium 112.411 [Kr]4d^{10}5s^2 8.9938	49 $^2P^o_{1/2}$ **In** Indium 114.818 [Kr]4d^{10}5s^{2}5p 5.7864	50 $^3P_0$ **Sn** Tin 118.710 [Kr]4d^{10}5s^{2}5p^2 7.3439	51 $^4S^o_{3/2}$ **Sb** Antimony 121.760 [Kr]4d^{10}5s^{2}5p^3 8.6084	52 $^3P_2$ **Te** Tellurium 127.60 [Kr]4d^{10}5s^{2}5p^4 9.0096	53 $^2P^o_{3/2}$ **I** Iodine 126.90447 [Kr]4d^{10}5s^{2}5p^5 10.4513	54 $^1S_0$ **Xe** Xenon 131.293 [Kr]4d^{10}5s^{2}5p^6 12.1298

Period 6

55 $^2S_{1/2}$ **Cs** Cesium 132.9054519 [Xe]6s 3.8939	56 $^1S_0$ **Ba** Barium 137.327 [Xe]6s^2 5.2117		72 $^3F_2$ **Hf** Hafnium 178.49 [Xe]4f^{14}5d^{2}6s^2 6.8251	73 $^4F_{3/2}$ **Ta** Tantalum 180.94788 [Xe]4f^{14}5d^{3}6s^2 7.5496	74 $^5D_0$ **W** Tungsten 183.84 [Xe]4f^{14}5d^{4}6s^2 7.8640	75 $^6S_{5/2}$ **Re** Rhenium 186.207 [Xe]4f^{14}5d^{5}6s^2 7.8335	76 $^5D_4$ **Os** Osmium 190.23 [Xe]4f^{14}5d^{6}6s^2 8.4382	77 $^4F_{9/2}$ **Ir** Iridium 192.217 [Xe]4f^{14}5d^{7}6s^2 8.9670	78 $^3D_3$ **Pt** Platinum 195.084 [Xe]4f^{14}5d^{9}6s 8.9588	79 $^2S_{1/2}$ **Au** Gold 196.966569 [Xe]4f^{14}5d^{10}6s 9.2255	80 $^1S_0$ **Hg** Mercury 200.59 [Xe]4f^{14}5d^{10}6s^2 10.4375	81 $^2P^o_{1/2}$ **Tl** Thallium 204.3833 [Hg]6p 6.1082	82 $^3P_0$ **Pb** Lead 207.2 [Hg]6p^2 7.4167	83 $^4S^o_{3/2}$ **Bi** Bismuth 208.98040 [Hg]6p^3 7.2855	84 $^3P_2$ **Po** Polonium (209) [Hg]6p^4 8.414	85 $^2P^o_{3/2}$ **At** Astatine (210) [Hg]6p^5 10.4813	86 $^1S_0$ **Rn** Radon (222) [Hg]6p^6 10.7485

Period 7

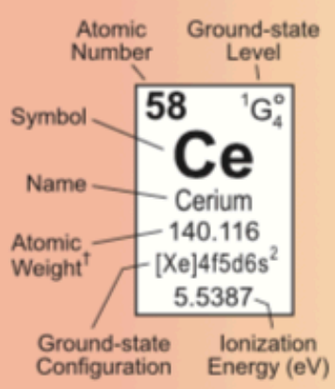
87 $^2S_{1/2}$ **Fr** Francium (223) [Rn]7s 4.0727	88 $^1S_0$ **Ra** Radium (226) [Rn]7s^2 5.2784		104 $^3F_2$? **Rf** Rutherfordium (265) [Rn]5f^{14}6d^{2}7s^2? 6.07	105 **Db** Dubnium (268)	106 **Sg** Seaborgium (271)	107 **Bh** Bohrium (272)	108 **Hs** Hassium (277)	109 **Mt** Meitnerium (276)	110 **Ds** Darmstadtium (281)	111 **Rg** Roentgenium (280)	112 **Cn** Copernicium (285)	113 **Uut** Ununtrium (284)	114 **Uuq** Ununquadium (289)	115 **Uup** Ununpentium (288)	116 **Uuh** Ununhexium (293)	117 **Uus** Ununseptium (294)	118 **Uuo** Ununoctium (294)

Lanthanides

57 $^2D_{3/2}$ **La** Lanthanum 138.90547 [Xe]5d6s^2 5.5769	58 $^1G^o_4$ **Ce** Cerium 140.116 [Xe]4f5d6s^2 5.5387	59 $^4I^o_{9/2}$ **Pr** Praseodymium 140.90765 [Xe]4f^{3}6s^2 5.473	60 $^5I_4$ **Nd** Neodymium 144.242 [Xe]4f^{4}6s^2 5.5250	61 $^6H^o_{5/2}$ **Pm** Promethium (145) [Xe]4f^{5}6s^2 5.582	62 $^7F_0$ **Sm** Samarium 150.36 [Xe]4f^{6}6s^2 5.6437	63 $^8S^o_{7/2}$ **Eu** Europium 151.964 [Xe]4f^{7}6s^2 5.6704	64 $^9D^o_2$ **Gd** Gadolinium 157.25 [Xe]4f^{7}5d6s^2 6.1498	65 $^6H^o_{15/2}$ **Tb** Terbium 158.92535 [Xe]4f^{9}6s^2 5.8638	66 $^5I_8$ **Dy** Dysprosium 162.500 [Xe]4f^{10}6s^2 5.9389	67 $^4I^o_{15/2}$ **Ho** Holmium 164.93032 [Xe]4f^{11}6s^2 6.0215	68 $^3H_6$ **Er** Erbium 167.259 [Xe]4f^{12}6s^2 6.1077	69 $^2F^o_{7/2}$ **Tm** Thulium 168.93421 [Xe]4f^{13}6s^2 6.1843	70 $^1S_0$ **Yb** Ytterbium 173.054 [Xe]4f^{14}6s^2 6.2542	71 $^2D_{3/2}$ **Lu** Lutetium 174.9668 [Xe]4f^{14}5d6s^2 5.4259

Actinides

89 $^2D_{3/2}$ **Ac** Actinium (227) [Rn]6d7s^2 5.3807	90 $^3F_2$ **Th** Thorium 232.03806 [Rn]6d^{2}7s^2 6.3067	91 $^4K_{11/2}$ **Pa** Protactinium 231.03588 [Rn]5f^{2}6d7s^2 5.89	92 $^5L^o_6$ **U** Uranium 238.02891 [Rn]5f^{3}6d7s^2 6.1939	93 $^6L_{11/2}$ **Np** Neptunium (237) [Rn]5f^{4}6d7s^2 6.2657	94 $^7F_0$ **Pu** Plutonium (244) [Rn]5f^{6}7s^2 6.0260	95 $^8S^o_{7/2}$ **Am** Americium (243) [Rn]5f^{7}7s^2 5.9738	96 $^9D^o_2$ **Cm** Curium (247) [Rn]5f^{7}6d7s^2 5.9914	97 $^6H^o_{15/2}$ **Bk** Berkelium (247) [Rn]5f^{9}7s^2 6.1979	98 $^5I_8$ **Cf** Californium (251) [Rn]5f^{10}7s^2 6.2817	99 $^4I^o_{15/2}$ **Es** Einsteinium (252) [Rn]5f^{11}7s^2 6.3676	100 $^3H_6$ **Fm** Fermium (257) [Rn]5f^{12}7s^2 6.50	101 $^2F^o_{7/2}$ **Md** Mendelevium (258) [Rn]5f^{13}7s^2 6.58	102 $^1S_0$ **No** Nobelium (259) [Rn]5f^{14}7s^2 6.65	103 $^2P^o_{1/2}$? **Lr** Lawrencium (262) [Rn]5f^{14}7s^{2}7p? 4.9 ?

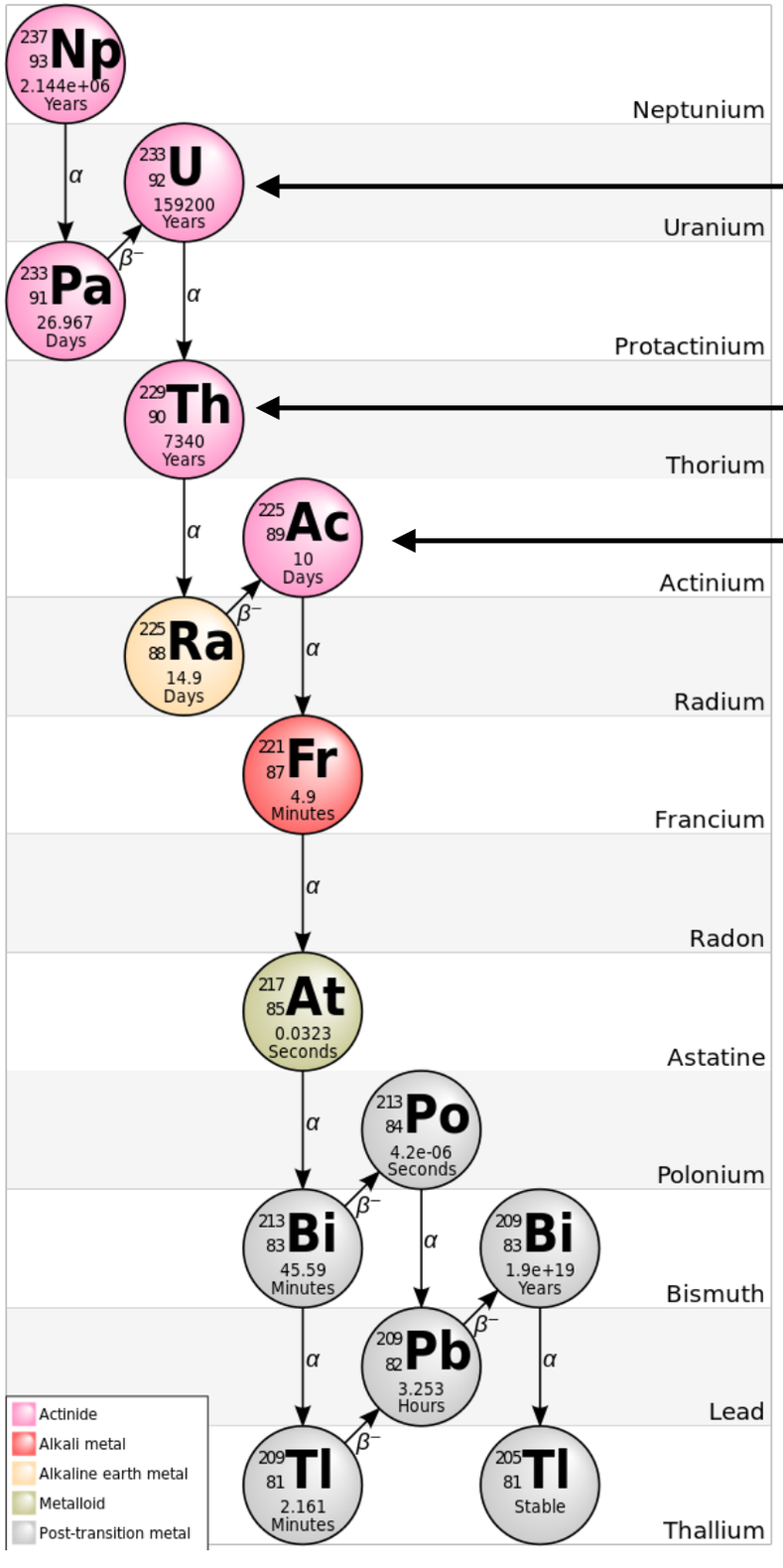


†Based upon ^{12}C. () indicates the mass number of the longest-lived isotope.

For a description of the data, visit physics.nist.gov/data

NIST SP 966 (September 2010)

Neptunium Series



Uranium 233 Reactor fuel

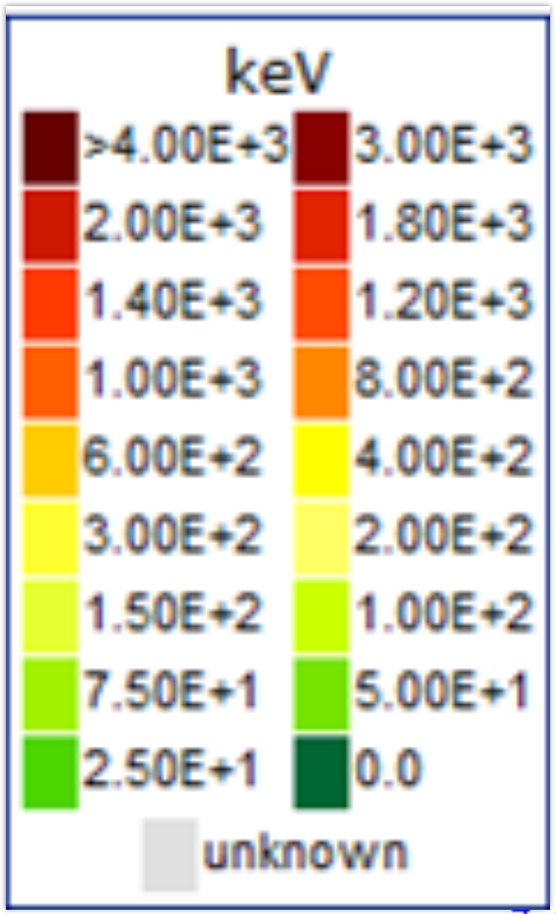
Thorium 229

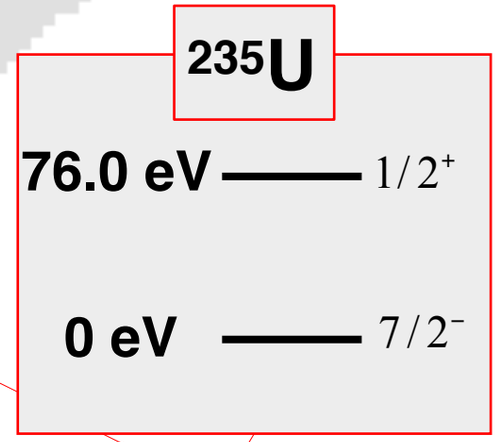
Actinium 225 Unsealed radionuclide therapy

Cf. Natural Thorium-232 100%

$T_{1/2} = 1.4 \times 10^{10}$ y

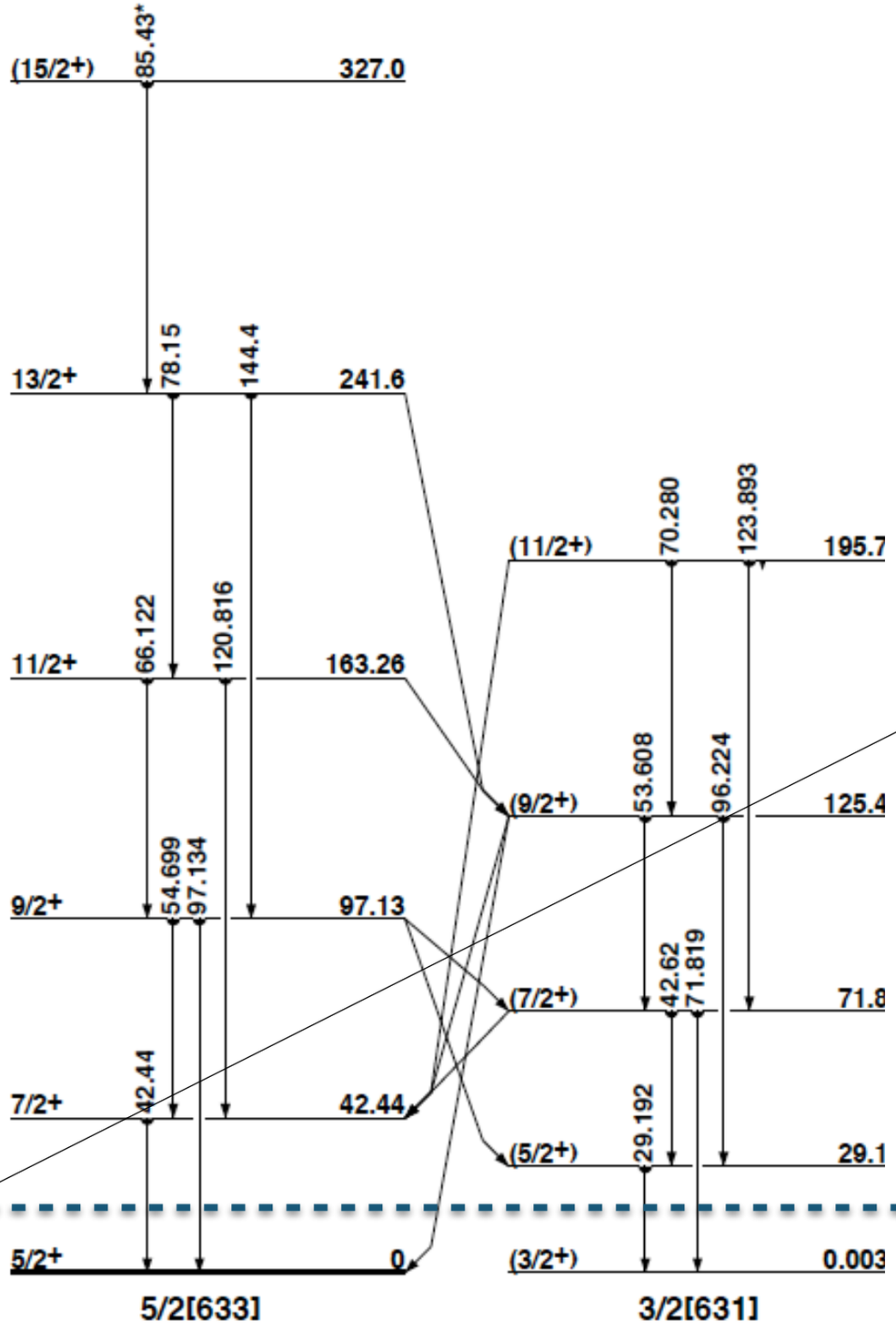
原子核第１励起準位



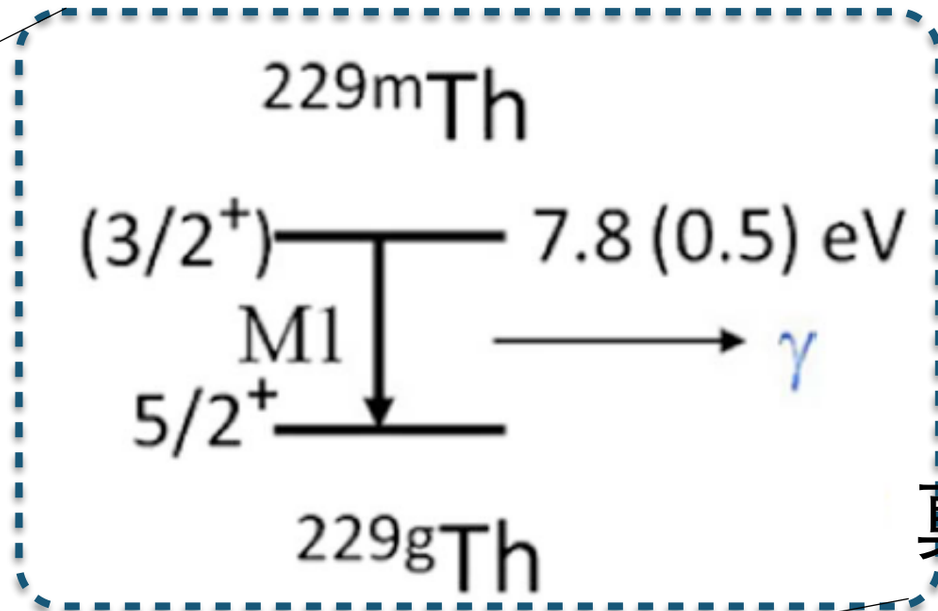


231Np 48.8 M ε: 98.00% α: 2.00%	232Np 14.7 M ε: 100.00% α: 2.0E-4% 50	233Np 36.2 M ε: 100.00% αs 1.0E-3% 34.4	234Np 4.4 D ε: 100.00%	235Np 396.1 D ε: 100.00% α: 2.6E-3% 34.23	236Np 153E+3 Y ε: 86.30% β-: 13.50%	237Np 2.144E+6 Y α: 100.00% SFs 2E-10% 33.19629	238Np 2.117 D β-: 100.00% 26.4266	239Np 2.356 D β-: 100.00% 31.1309
230U 20.8 D α: 100.00% SF < 1E-10% 51.727	231U 4.2 D ε: 100.00% α= 4.0E-3% 40	232U 68.9 Y α: 100.00% SF: 3E-12% 47.573	233U 1.592E+5 Y α: 100.00% 24Ne: 9E-10% 40.350	234U 2.455E+5 Y 0.0054% α: 100.00% SF: 1.6E-9% 43.4981	235U 7.04E+8 Y 0.7204% α: 100.00% SF: 7.0E-9% 0.0760	236U 2.342E7 Y α: 100.00% SF: 9.4E-8% 45.2440	237U 6.75 D β-: 100.00% 11.393	238U 4.468E9 Y 99.2742% α: 100.00% SF: 5.5E-5% 44.916
229Pa 1.50 D ε: 99.52% α: 0.48% 11.4	230Pa 17.4 D ε: 92.20% β-: 7.80% 28	231Pa 3.276E+4 Y α: 100.00% SFs 2E-11% 9.206	232Pa 1.32 D β-: 100.00% ε	233Pa 26.975 D β-: 100.00% 6.671	234Pa 6.70 H β-: 100.00% 73.92	235Pa 24.44 M β-: 100.00% 10	236Pa 9.1 M β-: 100.00% 31.5	237Pa 8.7 M β-: 100.00% 35
228Th 1.9116 Y α: 100.00% 2CO: 1E-11% 57.773	229Th 7932 Y α: 100.00% 0.0076	230Th 7.54E+4 Y α: 100.00% 24Ne: 6E-11% 53.227	231Th 25.52 H β-: 100.00% α= 4E-11% 41.953	232Th 1.40E10 Y 100% α: 100.00% SF: 1.1E-9% 49.369	233Th 21.83 M β-: 100.00%	234Th 24.10 D β-: 100.00% 49.55	235Th 7.2 M β-: 100.00%	236Th 37.3 M β-: 100.00% 48.4
227Ac 21.772 Y β-: 98.62% α: 1.38% 27.37	228Ac 6.15 H β-: 100.00% 6.28	229Ac 62.7 M β-: 100.00% 7.0	230Ac 122 S β-: 100.00% BF: 1.2E-6% 8.99	231Ac 7.5 M β-: 100.00% 5.25	232Ac 119 S β-: 100.00% 7.5	233Ac 145 S β-: 100.00%	234Ac 44 S β-: 100.00%	235Ac 60 S β-: 100.00%

Th-229 エネルギー準位



Excited State
7.8 eV
$T_{1/2}$: 1000s



~160 nm

真空紫外光

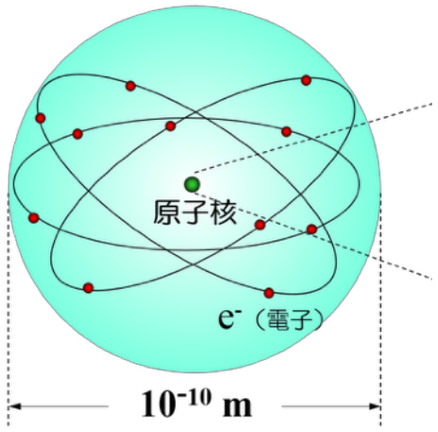
Ground State
$T_{1/2}$: 7340 y

Ground State　　Isomer State

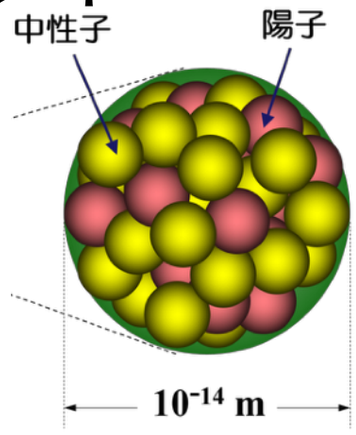
Th-229mの応用

eVオーダーの核励起レベルのインパクト

原子



原子核



eV オーダーの励起準位

MW, レーザーを用いた多彩な実験手法

分光，冷却，BEC，トラップ

keV, MeV オーダーの励起準位

加速器を用いた実験手法

原子時計(光格子時計，イオン時計)

10^{-18}

レーザーで励起できれば..

原子核時計の実現?

$<10^{-19}$

電子による遮蔽

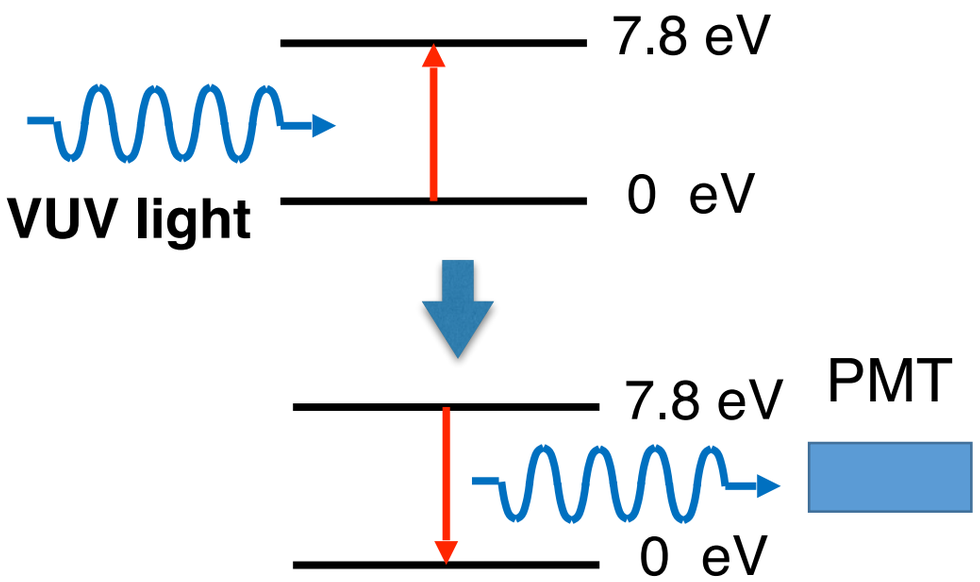
外場の影響を受けにくい

固体原子時計

物理定数の経時変化

直接励起の試み

VUV light source



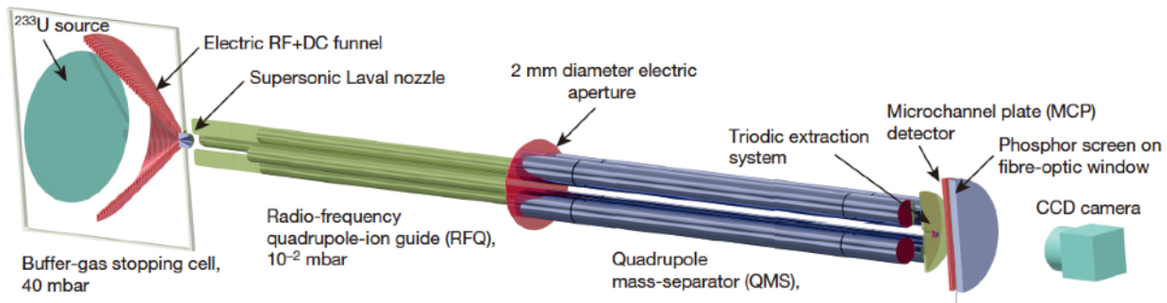
J. Jeet et al., PRL 114, 253001 (2015)

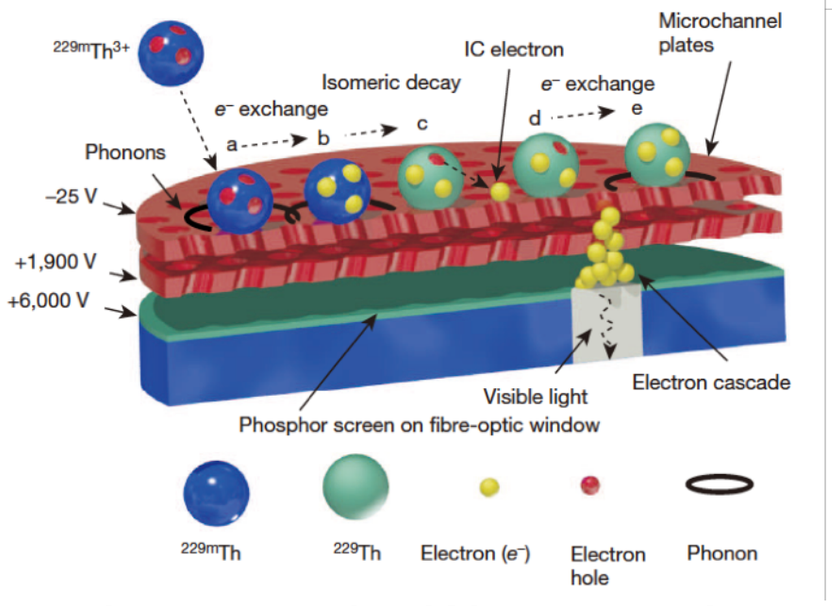
E=7.29 - 8.86 eV at ALS
No clear signal

A. Yamaguchi et al.,
New J. Phys. 17 (2015) 053053

E=3.54 - 9.54 eV at MLS
No clear signal

Th Ion beam





Lars von der Wense et al.,
Nature 533 (2016)

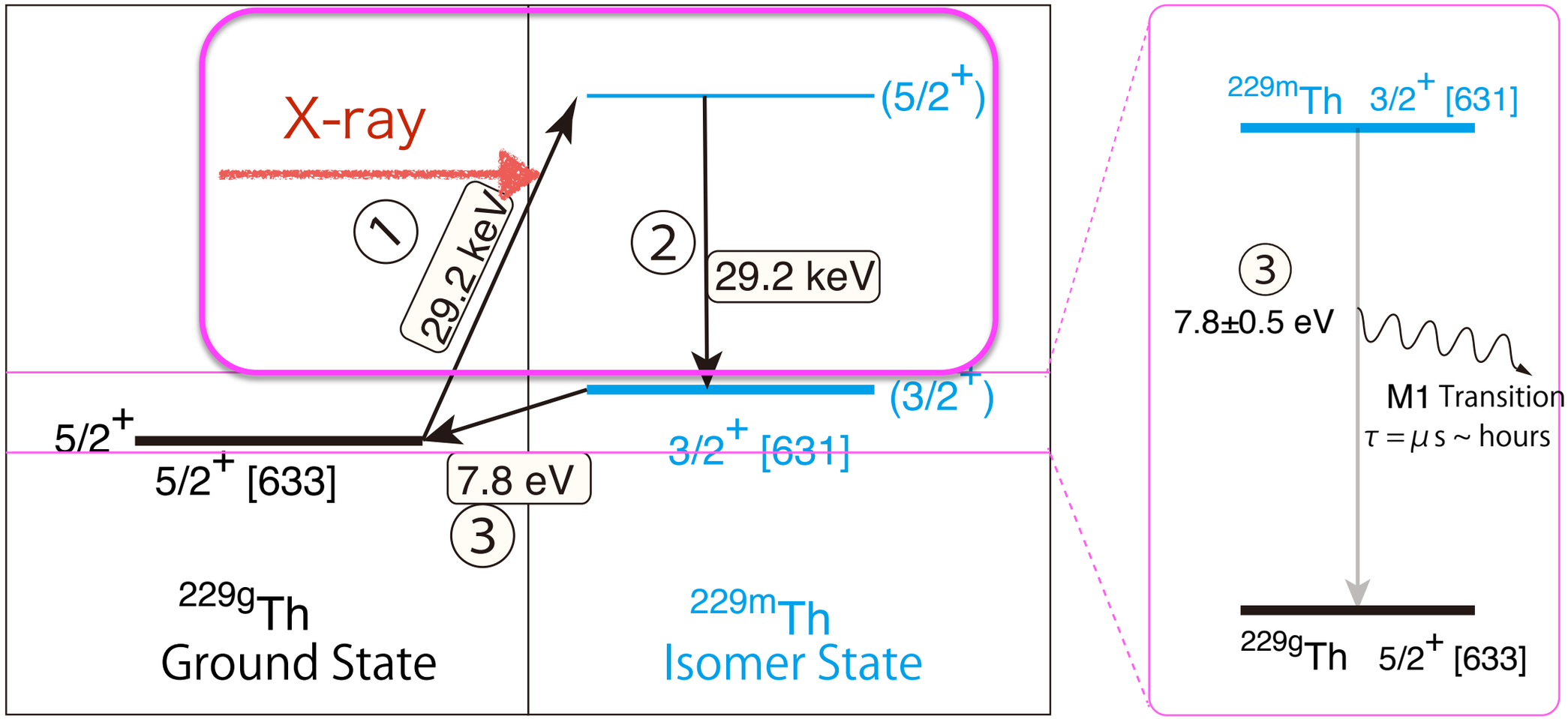
E=6.3~18.3 eV

Physics World 2016 Breakthrough of the Year
3rd Place

脱励起真空紫外光はまだ観測されていない

高輝度X線を用いた新しい手法

核共鳴散乱



① 励起　　**確実な励起**

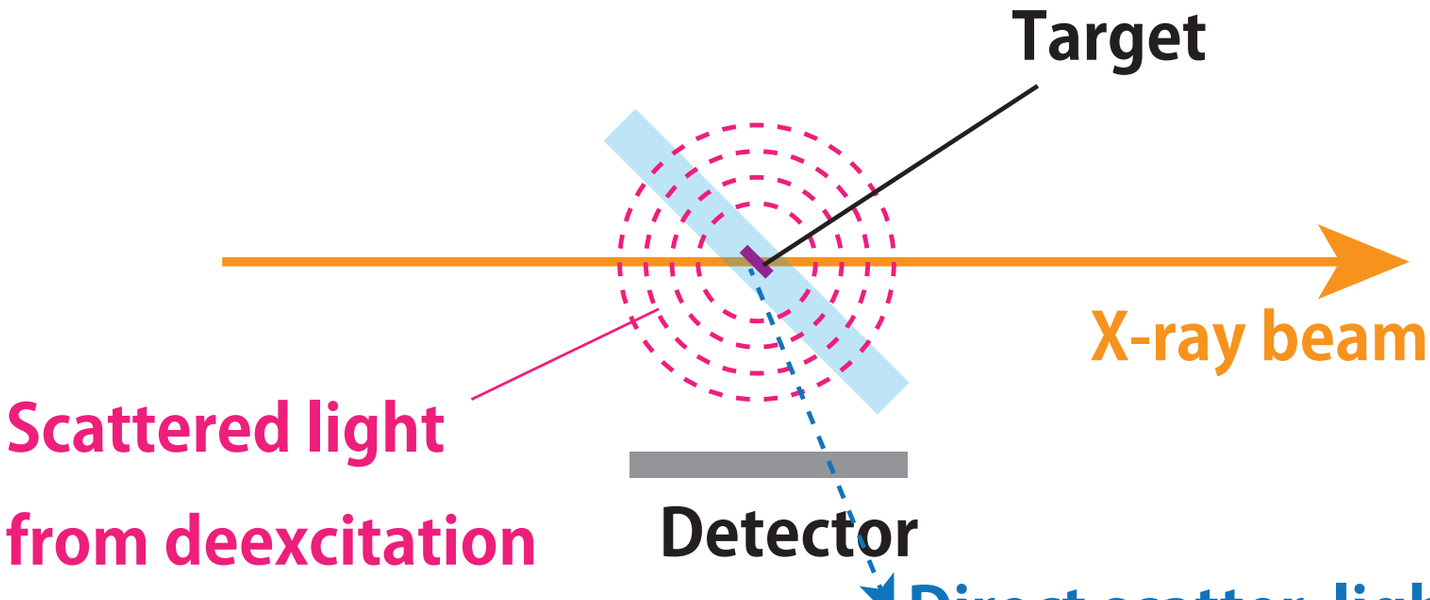
② 観測　　**アイソマー状態を確認**

③ 測定　　**脱励起真空紫外光の観測**

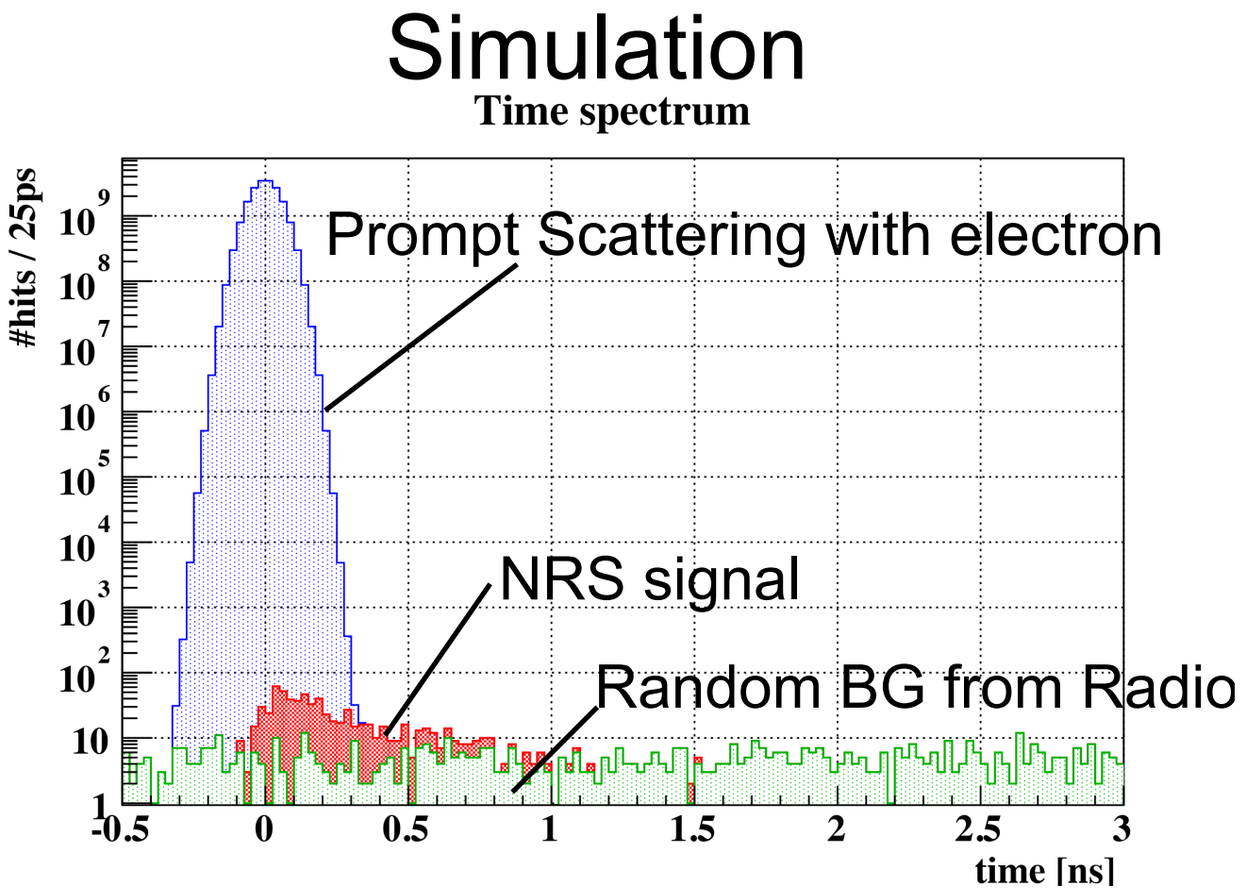
Originally proposed in Tkalya et al., PRC 61, 064308, 2000

核共鳴散乱

観測される信号は



Simulation



問題点

極短寿命 ($T_{1/2}$ 100~200ps)

低頻度

高バックグランド

Baruch De Spinoza

Last part of “Ethica”

Sed omnia praeclara tam difficilia, quam rara sunt.

But all things excellent are as difficult as they are rare.

しかし，すべて高貴なものは稀であるとともに困難である

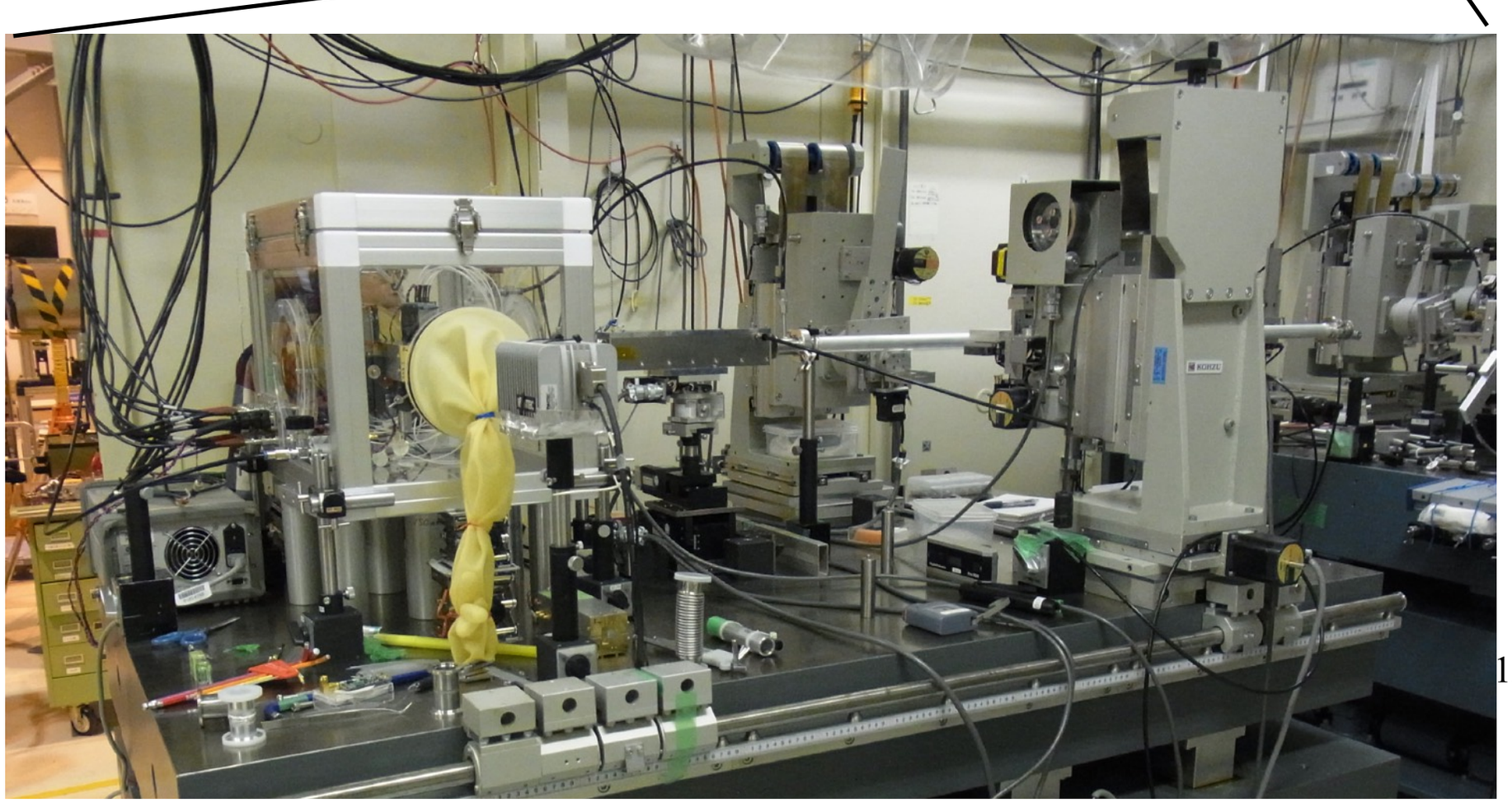
Inspired by T. Komatsubara (Rare K-decay)

核共鳴散乱発見への道のり

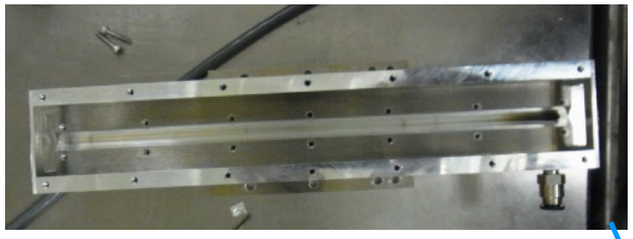
SPring-8 実験

Bunch mode	203 bunches
Bunch interval	23.6 nsec
Photon flux	4 x 10^{13} photon/s
Line width	4 eV
Pulse width	~35 PS

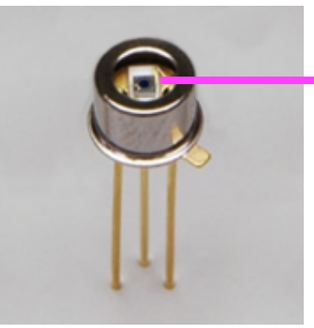
Monochro Meter → Experimental Hutch

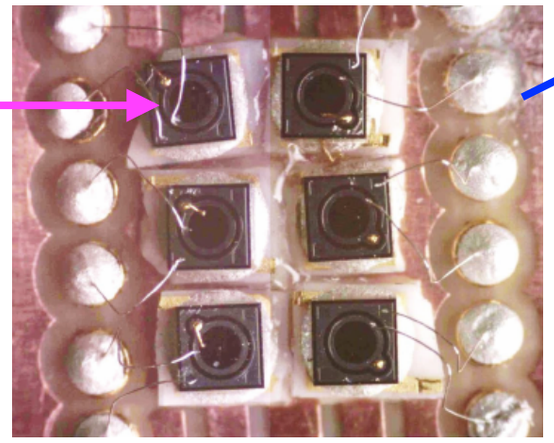


Experimental setup

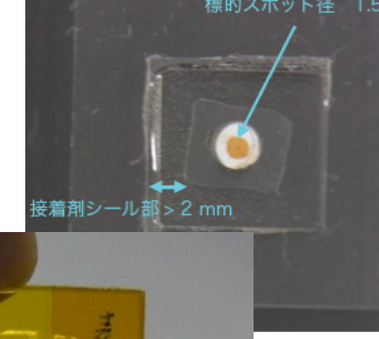


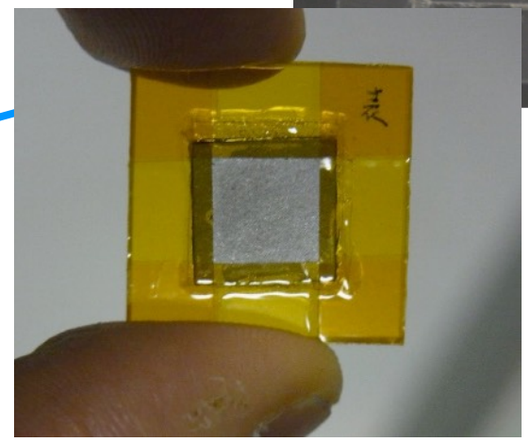
Glass capillary





APD array
HPK S12053-05 (ϕ0.5)





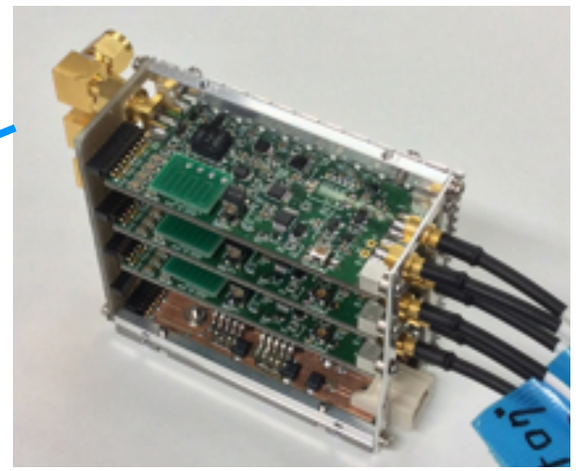
Th-229 Target
ϕ1.5

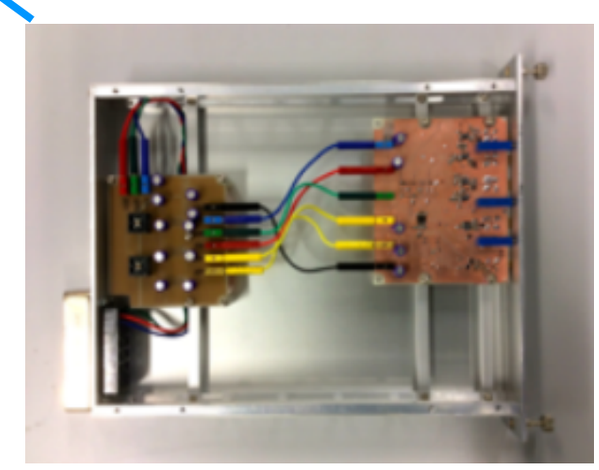
PreAmp

CFD

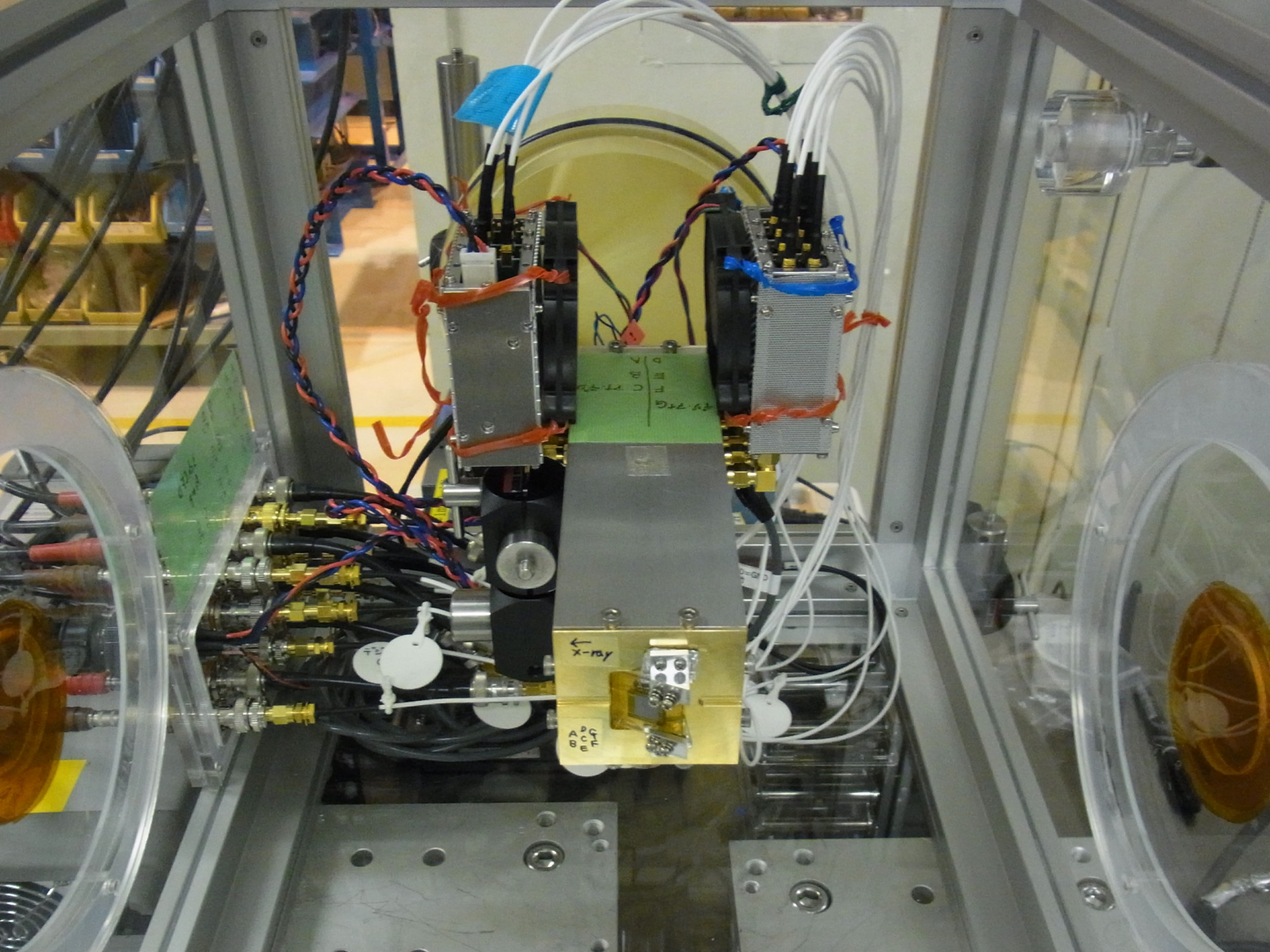
ATC

Multi-hit TDC



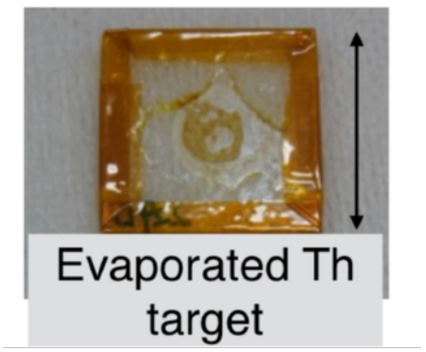


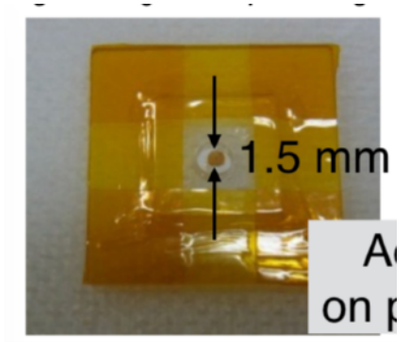
- MAX DAQ rate ~ 7 Mcps
- Acceptance 0.7 %

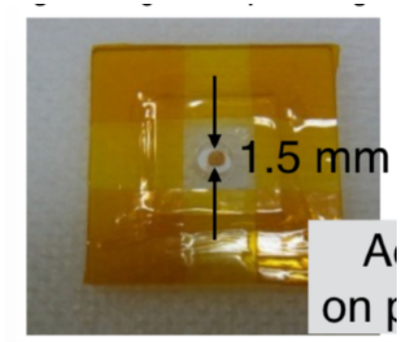

X-ray

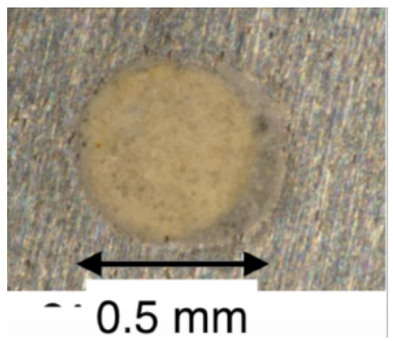
4 年間の技術的進展

標的

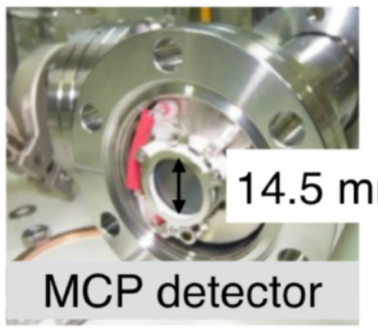


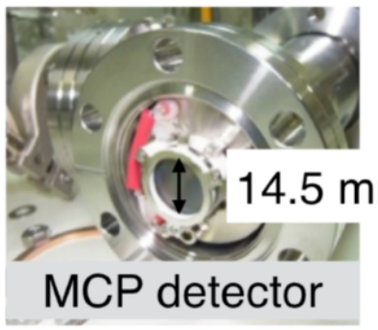


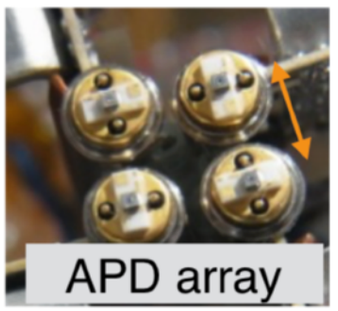


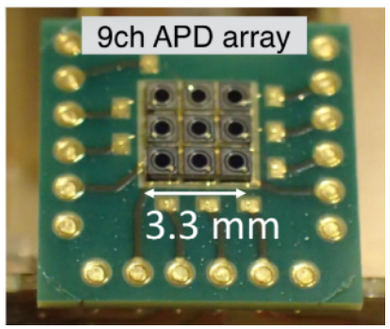


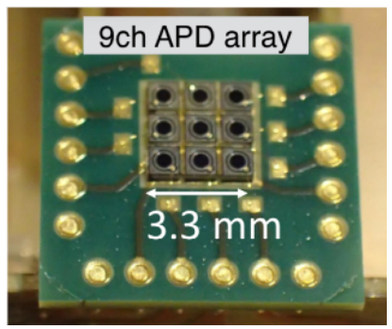
検出器



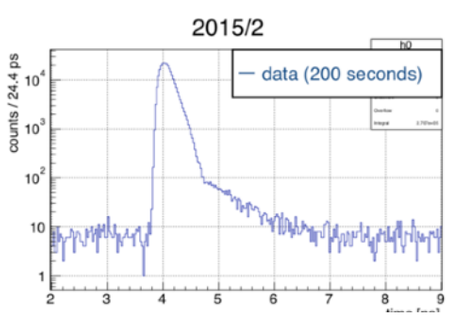


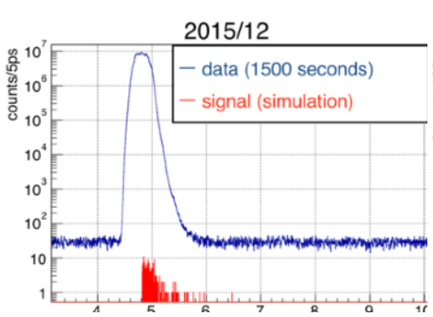


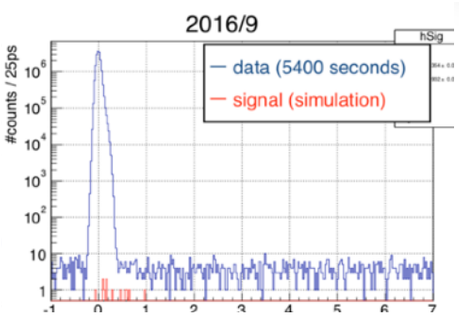


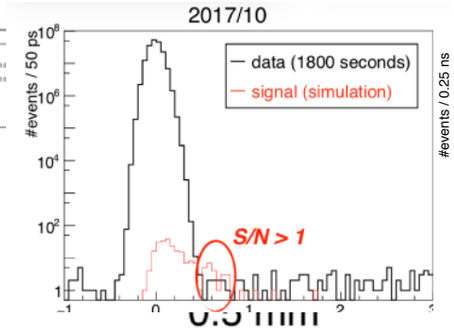


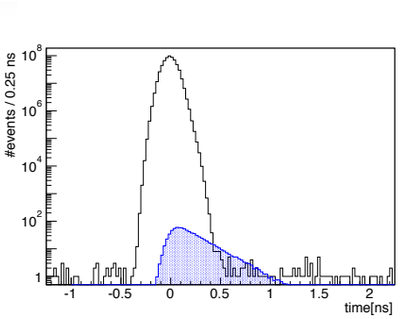
S/N











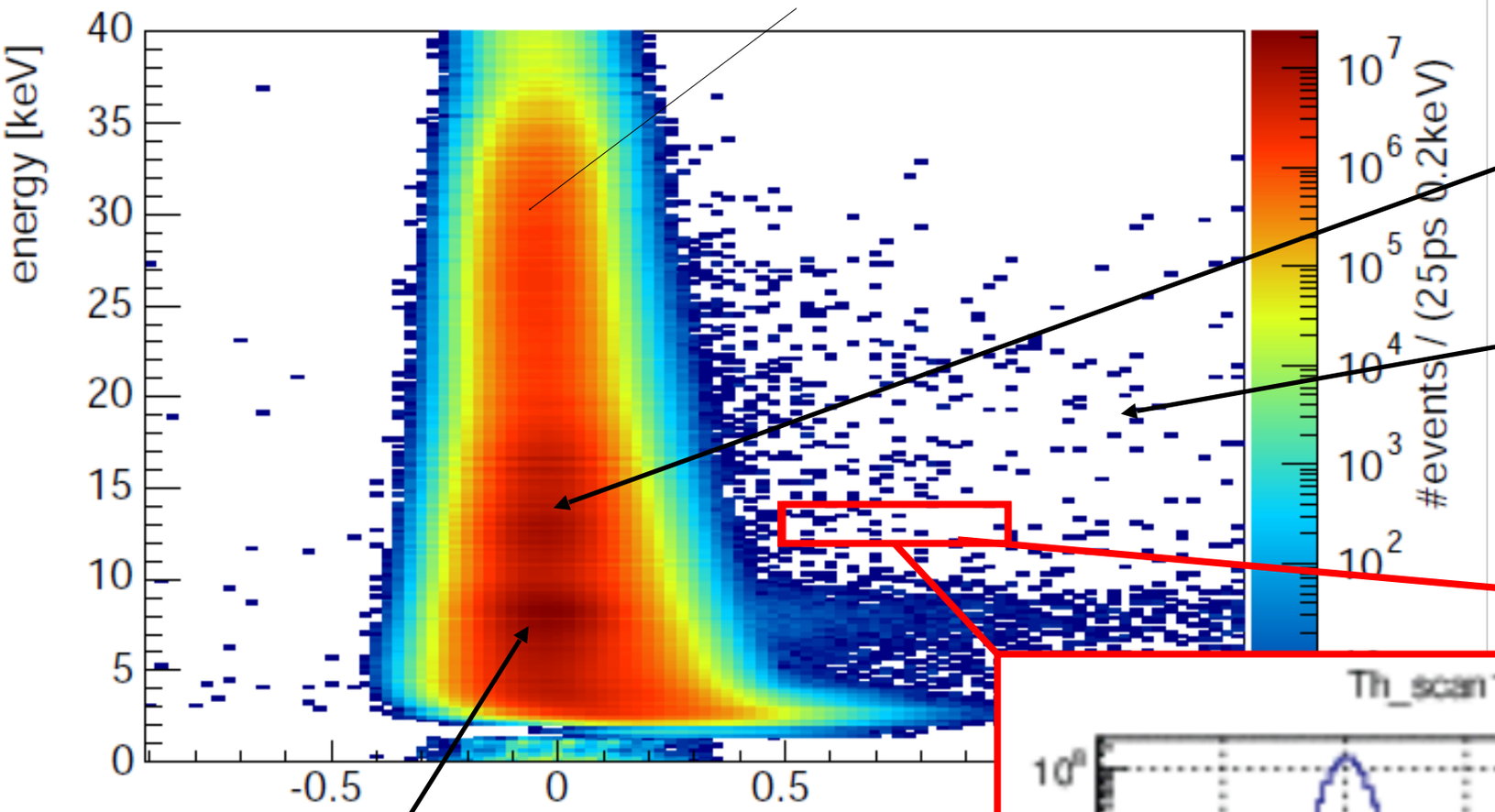
	2015/2	2015/12	2016/9	2017/10	2018/4, 7
Detector	14.5mmϕ MCP	14.5mmϕ MCP	0.5mmϕ **APD 4ch**	0.5mmϕ APD 9ch	0.5 mmϕ APD 9ch
Th target	0.06 μg/mm2 × 5mmϕ	**1.7 μg/mm2** × 1.5mmϕ	1.7 μg/mm2 × 1.5mmϕ	**3.0 μg/mm2** × 0.5mmϕ	**4, 10μg/ mm2** x 0.4 mm
Beam size (FWHM)	~1×1 mm2	1.0×0.8 mm2	**0.2×0.1 mm2**	**0.2×0.05 mm2**	**0.2 x 0.05 mm2**
count rate	1.3 kHz	300-400 kHz	22 kHz	310 kHz	500 kHz, 1 MHz

Th collaboration

- 岡山大学
  - S.Okubo, H.Hara, T.Hiraki, T. Masuda, Y.Miyamoto, K.Okai, N.Sasao, S. Uetake, A.Yoshimi, K.Yoshimura, M.Yoshimura
- 理化学研究所
  - A.Yamaguchi, H. Haba, Yokokita
- 大阪大学
  - Y.Kasamatsu, Y.Yasuda, Y.Shigekawa
- 東北大学・金研大洗センター
  - K.Konashi, M.Watanabe
- SPring-8
  - Y.Yoda, K. Tamasaku
- 京大原子炉
  - M.Seto, K.Kitao, Y.Kobayashi, R.Masuda
- 産総研
  - H.Fujii, T. Watanabe, Y. Ueyama
- ウィーン工科大学
  - T. Schumm, S.Stellmer

2018.7 実験　　229Th 標的からの散乱データ

コンプトン、レイリー散乱

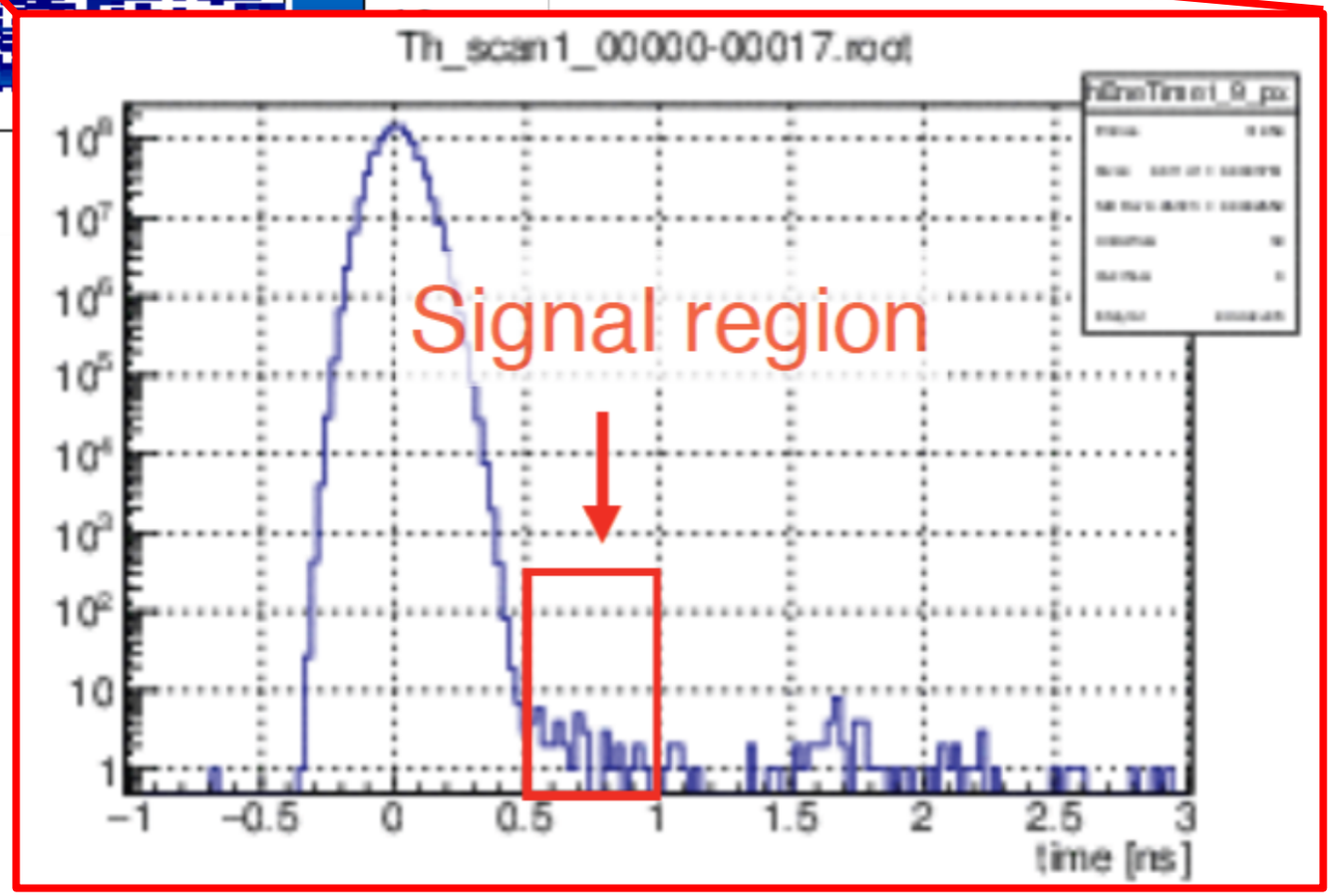


Th からの信号

特性X線：12-14 keV

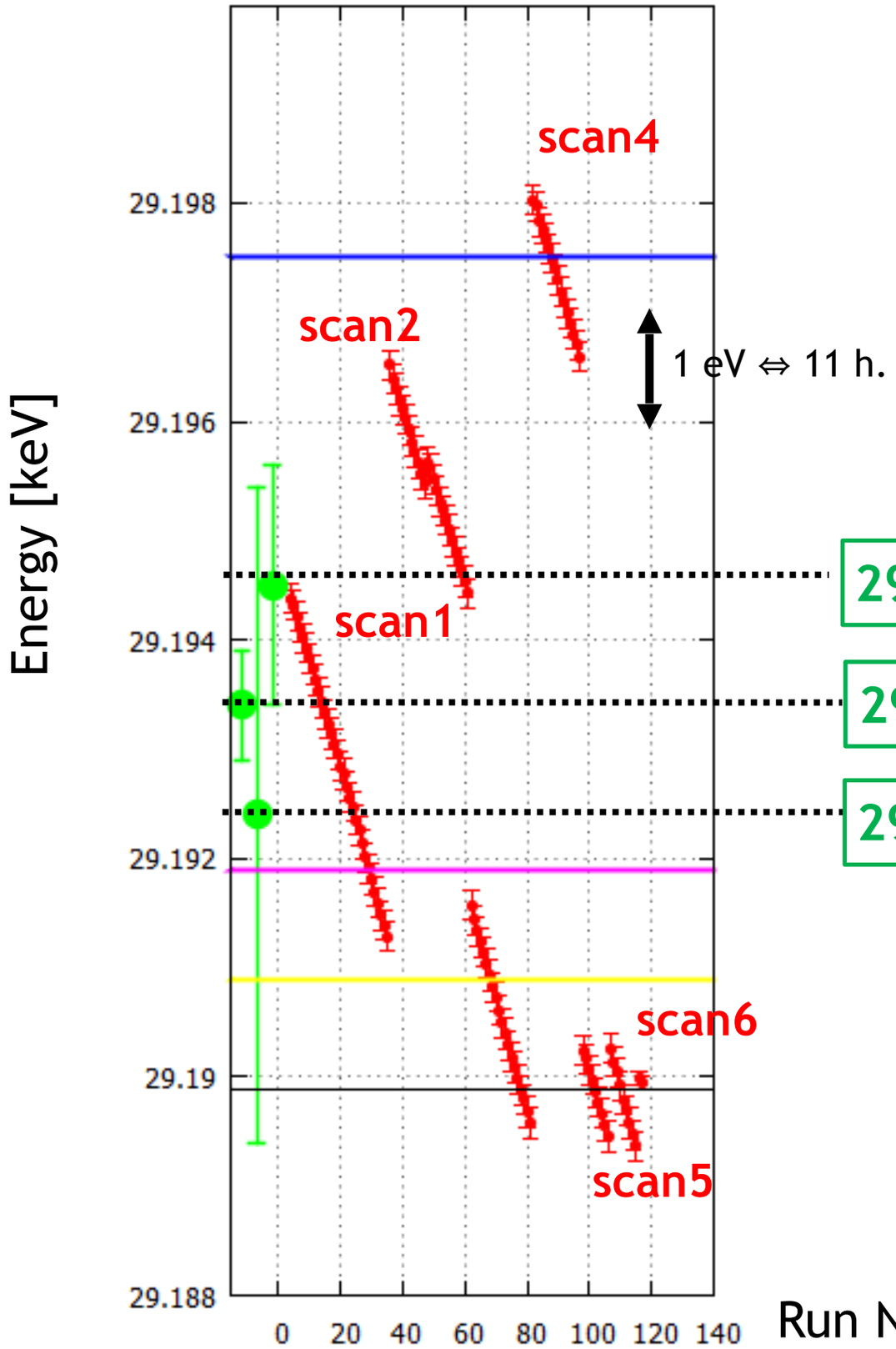
放射性B.G.

周辺部(Cu) からの散乱



Monochromator: Si(440)
Accumulation time : 1,800 s.

^{229}Th NRS 共鳴エネルギー探索



単色化モノクロメータ: Si(440)

Bandwidth = 0.28 eV

Si(440) step設定：0.10 eV-step

≈ 0.16”-step (角度)

29.1945(11) keV

V.Barci et al, PRC(2003).

= 29.1867(11)+0.0078(5)

29.1934(5?) keV

B.R.Beck et al. PRL(2007)

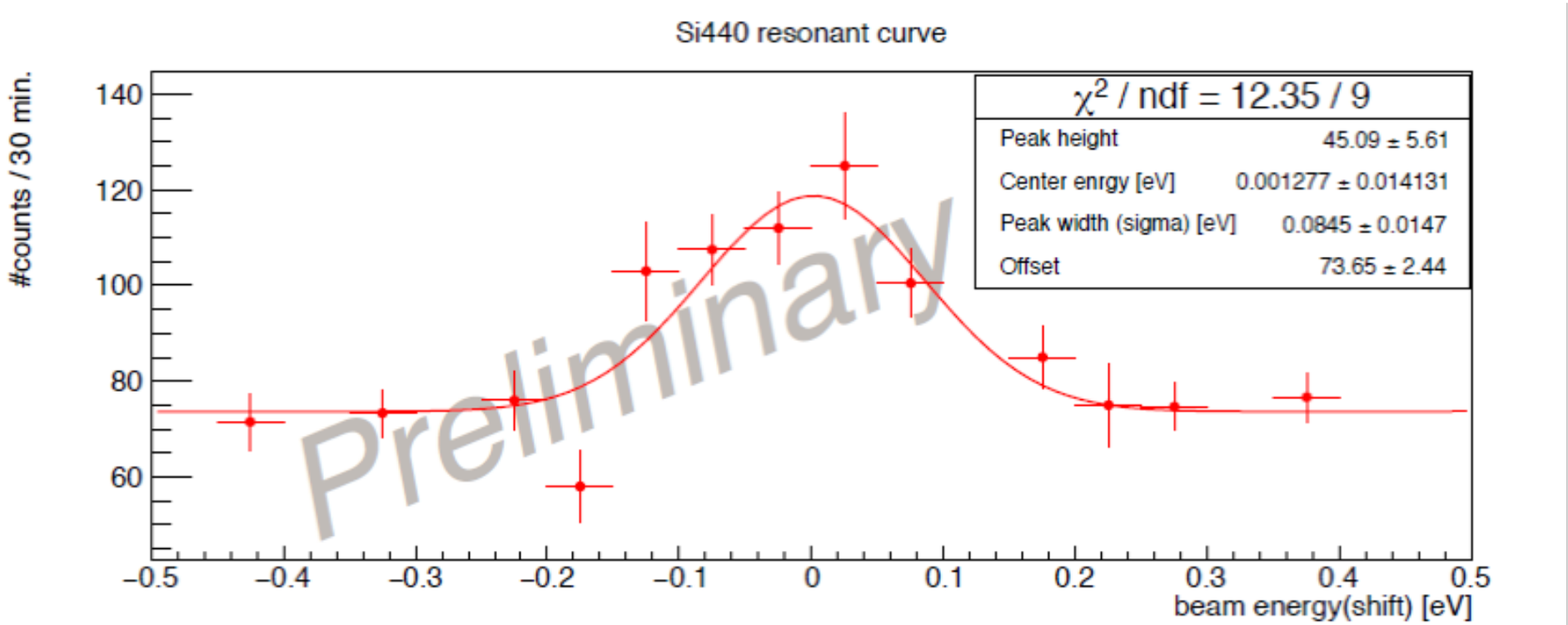
= 29.1856(?)+0.0078(5)

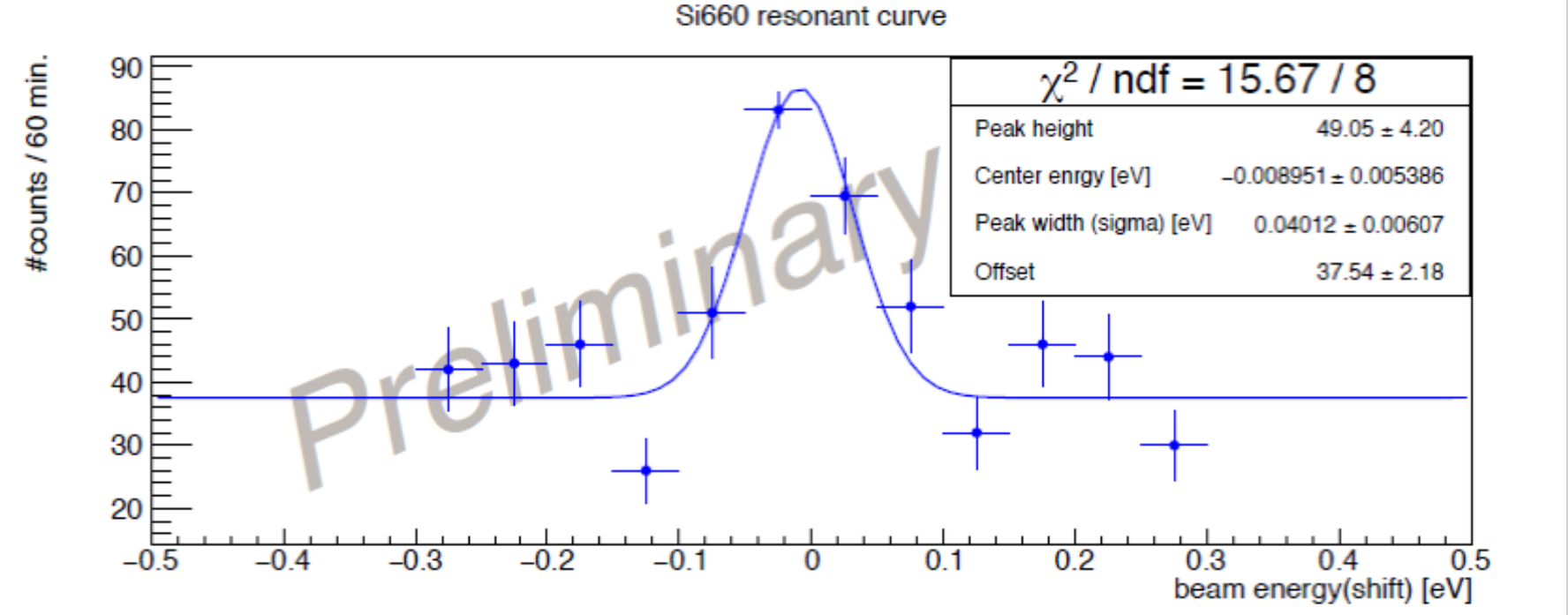
29.1924(30) keV

Helmer-Reich (1994)/ Gulda et al. (2002) / E. Ruchowska et al. (2006)

= 29.1846(30)+0.0078(5)

共鳴確認に成功



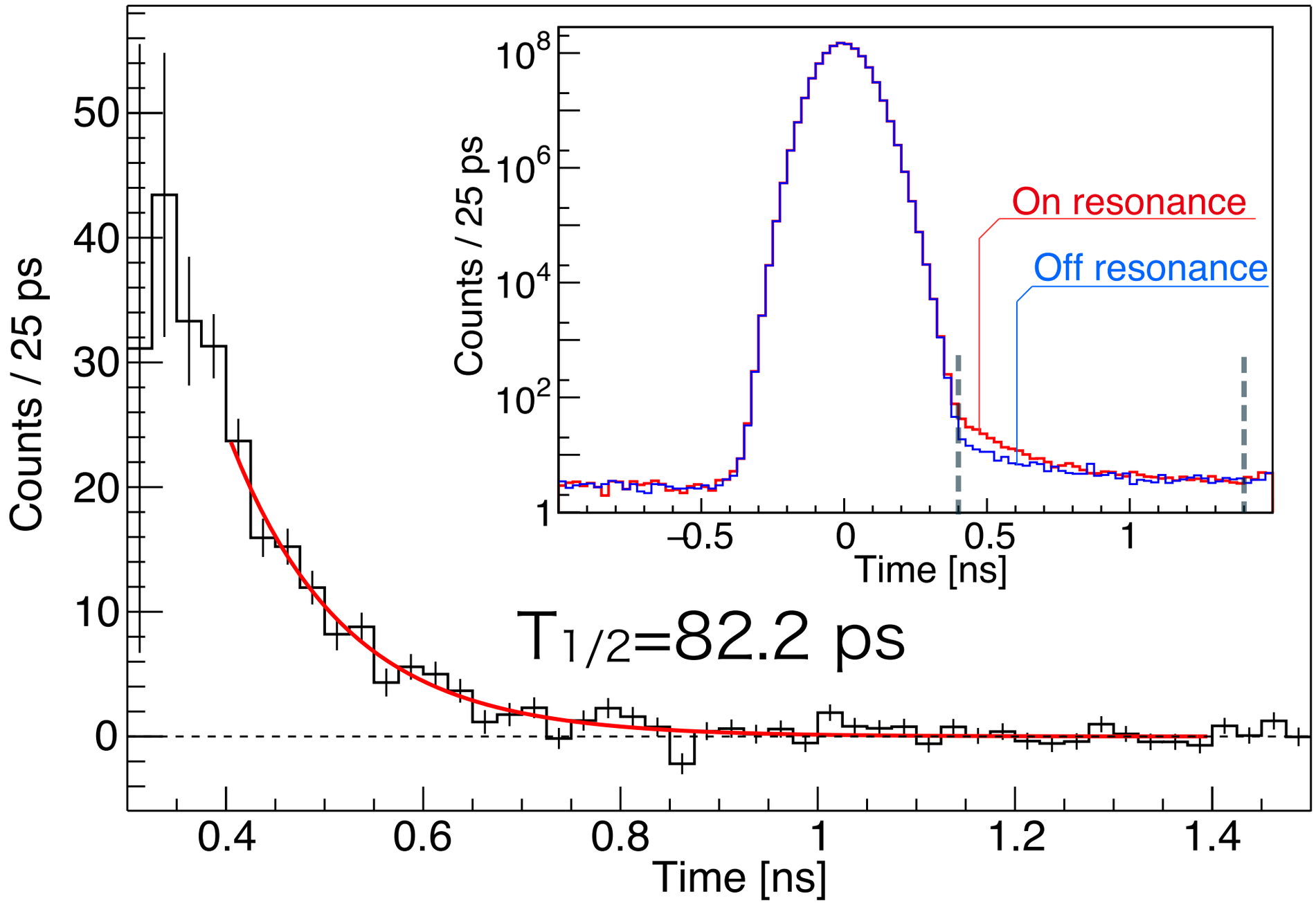


現在、生成アイソマーレート(O(10KHz))、第2励起状態の半減期、第2励起状態のエネルギー値、基底状態とアイソマー状態への分岐比に関する詳細解析進行中

paper in preparation

※画面はハメコミ合成

半減期測定



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

まとめ

- X線による核共鳴散乱を利用したTh-229アイソマー探索方法を確立
  - 標的技術，X線検出，X線集光，X線エネルギーの精密測定
- 第２励起状態核共鳴散乱信号の観測に成功
- 今後アイソマーからの真空紫外光の探索を行う