

# Кафедра квантовой метрологии Института ЛаПлаз

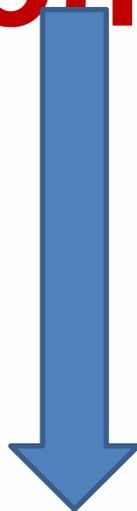
## Ядерные часы: состояние и перспективы

Борисюк Петр Викторович,  
к.ф.-м.н., доцент Института ЛаПлаз  
25.02.2021

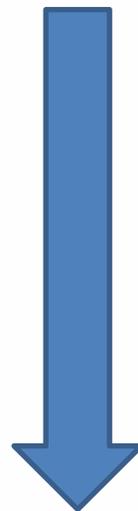
# Квантовые технологии



Кодирование  
Криптография



Computing  
Симуляция



Стандарты  
частоты



Детекторы  
Сенсорика

# СТАНДАРТЫ ВРЕМЕНИ И ЧАСТОТЫ

Государственный эталон времени и частоты РФ работает с точностью на уровне  $5 \times 10^{-16}$ . В результате Глобальная навигационная спутниковая система (ГЛОНАСС) обеспечивает точность **позиционирования объектов** на уровне 1-2 метров.

**Точность  $10^{-15} - 10^{-16}$**



**Точность  $10^{-17} - 10^{-18}$**

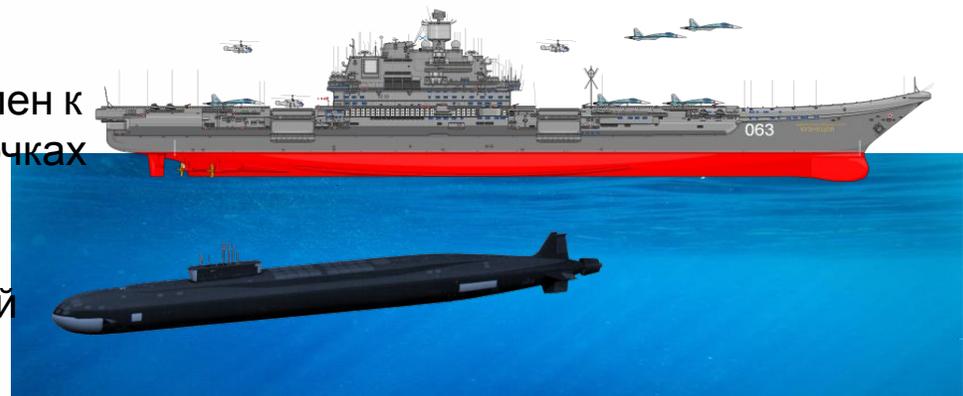
Точность позиционирования достигнет нескольких десятков сантиметров и обеспечит **высокоточное управление объектами в режиме удаленного доступа.**

Стандарт такого уровня чувствителен к величине силы тяжести в разных точках Земли и откроет путь к **созданию гравитационных навигационных карт** как альтернативы сегодняшней спутниковой навигации.



**Точность  $10^{-19} - 10^{-20}$**

Высокоточные измерения гравитационной карты Земли позволят проводить **дистанционное обнаружение полезных ископаемых.** При такой точности (!) можно проверить гипотезу об **изменении фундаментальных физических констант** со временем.

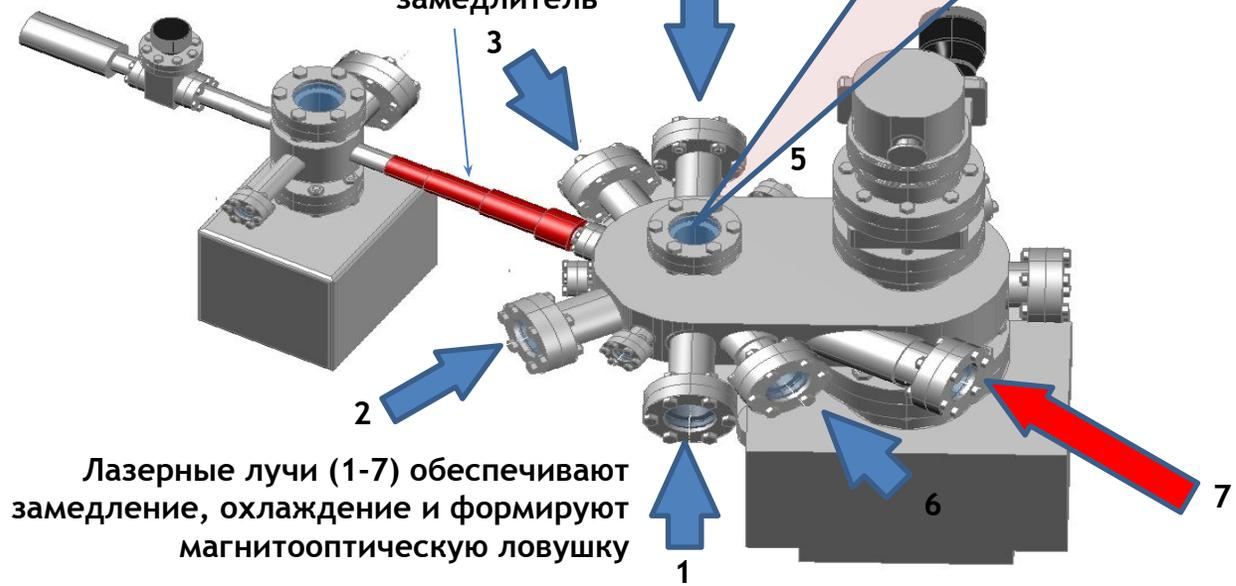


# ОПТИЧЕСКИЕ ЧАСЫ НА ХОЛОДНЫХ АТОМАХ СТРОНЦИЯ

Облако ( $R \sim 1$  мм) из  $10^4$  охлажденных ( $T \sim 1$  мК) атомов  $^{87}\text{Sr}$  в магнитооптической ловушке

Источник атомов стронция

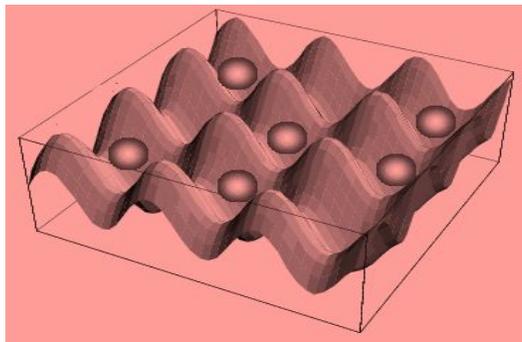
Зеемановский замедлитель



Лазерные лучи (1-7) обеспечивают замедление, охлаждение и формируют магнитооптическую ловушку

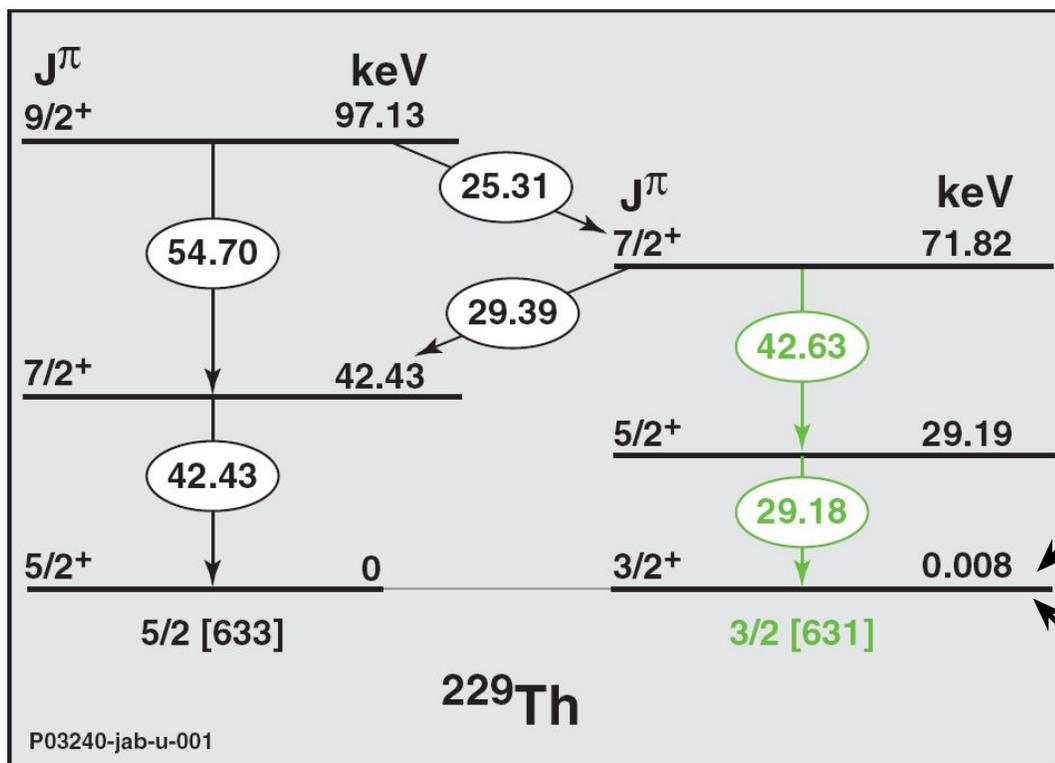


Атомы стронция в оптической решетке, образованной пересекающимися лазерными лучами

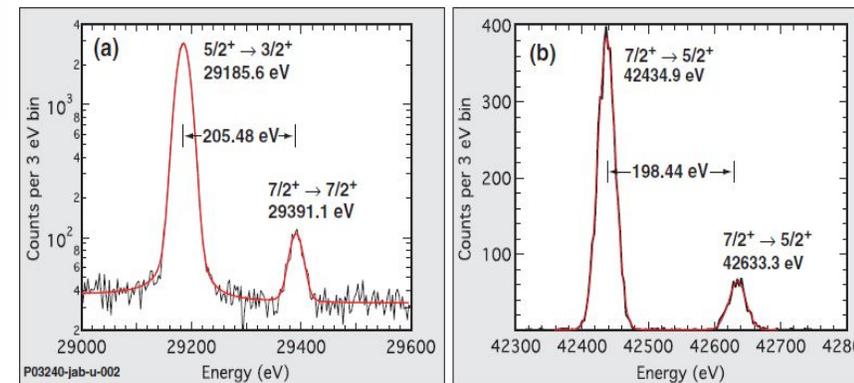


В NIST достигнута точность  $2.1 \times 10^{-18}$  на часовом переходе  $^1S_0 - ^3P_0$

# Измерения энергии ядерного перехода в $^{229}\text{Th}$ гамма- спектроскопией



Partial level scheme of  $^{229}\text{Th}$  with  $E_\gamma$  in keV.



**B. R. Beck et al., Phys. Rev. Lett. 98 (2007)**

$^{229}\text{Th}$  isomer level:

- 7.6(0.5) eV
- $10^3 - 10^5$  s lifetime

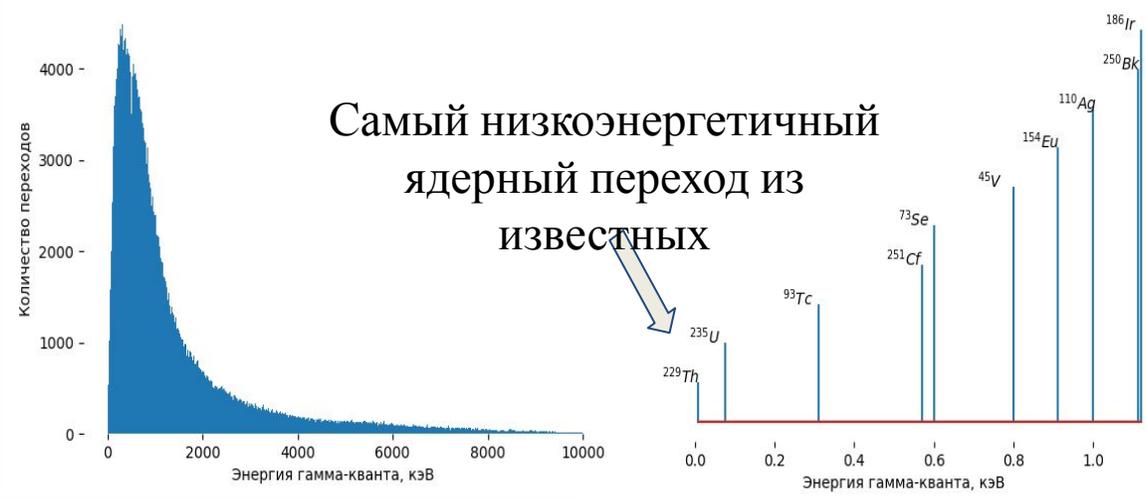
**B. R. Beck et al., Proceedings Materials (2010)**

$^{229}\text{Th}$  isomer level

(improved result):

- 7.8(0.5) eV

## Чем интересен торий?



Evaluated Nuclear Structure Data File (ENSDF), January 2019 snapshot

## Возможные применения:

## Свойства изомерного перехода в ядре $^{229}\text{Th}$ :

- Энергия перехода:
  - $8.09 \pm 0.13$  эВ [1]
  - $8.28 \pm 0.17$  эВ [2]
- Длина волны  $\sim 155$  нм
- Время излучательного распада изомерного состояния  $\sim 1$  час
- Малая естественная ширина  $\sim 1$  мГц
- Экранирование ядра атомными электронами приводит к уменьшению чувствительности ядерного перехода к внешним возмущениям на несколько порядков

[1] *Bestimmung der Isomerenergie von  $^{229}\text{Th}$  mit dem hochauflösenden Mikrokalorimeter-Array maXs30 Geist, Jeschua. - PhD Thesis, Heidelberg, (2020)*

[2] *B. Seiferle, et al, Energy of the  $^{229}\text{Th}$  nuclear clock transition, Nature volume 573, (2019)*

PRL 106, 162501 (2011) PHYSICAL REVIEW LETTERS week ending 22 APRIL 2011

**Proposal for a Nuclear Gamma-Ray Laser of Optical Range**

E. V. Tkalya\*

*Institute of Nuclear Physics, Moscow State University, Moscow, Russia*  
(Received 2 November 2010; published 21 April 2011)

A possibility of the amplification of the 7.6 eV  $\gamma$  radiation by the stimulated  $\gamma$  emission of the ensemble of the  $^{229}\text{Th}$  isomeric nuclei in a host dielectric crystal is proved theoretically. This amplification is a result of (1) the excitation of a large number of  $^{229}\text{Th}$  isomers by laser radiation, (2) the creation of the inverse population of nuclear levels in a cooled sample owing to the interaction of thorium nuclei with the crystal electric field or with an external magnetic field, (3) the emission or absorption of the optical photons by thorium nuclei in the crystal without recoil, and (4) the nuclear spin relaxation through the conduction electrons of the metallic covering.

DOI: 10.1103/PhysRevLett.106.162501 PACS numbers: 23.20.Lv, 27.90.+b, 42.72.Bj

PRL 108, 120802 (2012) PHYSICAL REVIEW LETTERS week ending 23 MARCH 2012

**Single-Ion Nuclear Clock for Metrology at the 19th Decimal Place**

C. J. Campbell,<sup>1,\*</sup> A. G. Radnaev,<sup>1</sup> A. Kuzmich,<sup>1</sup> V. A. Dzuba,<sup>2</sup> V. V. Flambaum,<sup>2</sup> and A. Derevianko<sup>3</sup>

<sup>1</sup>*School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332-0430, USA*  
<sup>2</sup>*School of Physics, University of New South Wales, Sydney 2052, Australia*  
<sup>3</sup>*Department of Physics, University of Nevada, Reno, Nevada 89557, USA*  
(Received 7 October 2011; published 22 March 2012)

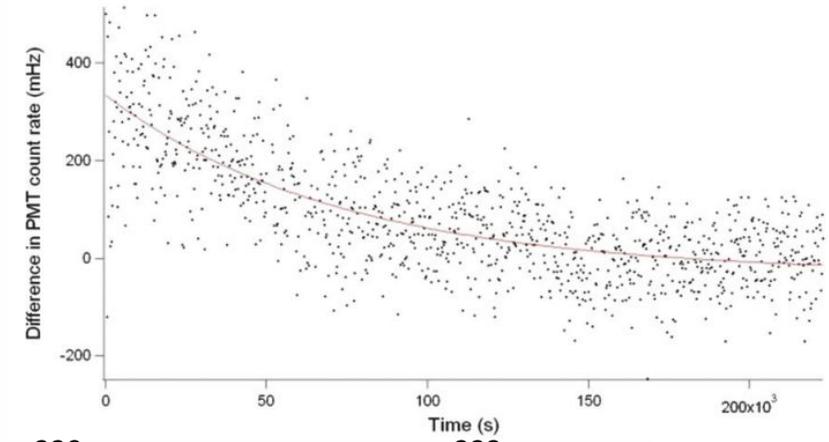
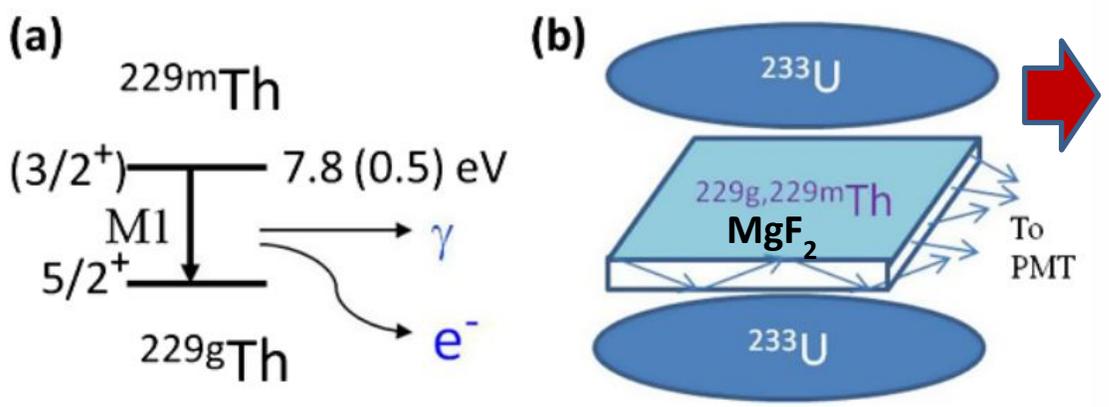
The 7.6(5) eV nuclear magnetic-dipole transition in a single  $^{229}\text{Th}^{3+}$  ion may provide the foundation for an optical clock of superb accuracy. A virtual clock transition composed of stretched states within the  $5F_{5/2}$  electronic ground level of both nuclear ground and isomeric manifolds is proposed. It is shown to offer unprecedented systematic shift suppression, allowing for clock performance with a total fractional inaccuracy approaching  $1 \times 10^{-19}$ .

DOI: 10.1103/PhysRevLett.108.120802 PACS numbers: 06.20.fb, 06.20.Jr, 21.10.Tg, 24.80.+y

# Общепринятый метод Исследование ядер отдачи $^{229}\text{Th}$ при распаде $^{233}\text{U}$ Содержат 2% ядер заселенных в изомерное состояние

X. Zhao, Y. N. Martinez de Escobar, R. Rundberg, E.M. Bond, A. Moody, and D.J. Vieira  
Los Alamos National Laboratory, Los Alamos, USA

PRL **109**, 160801 (2012)

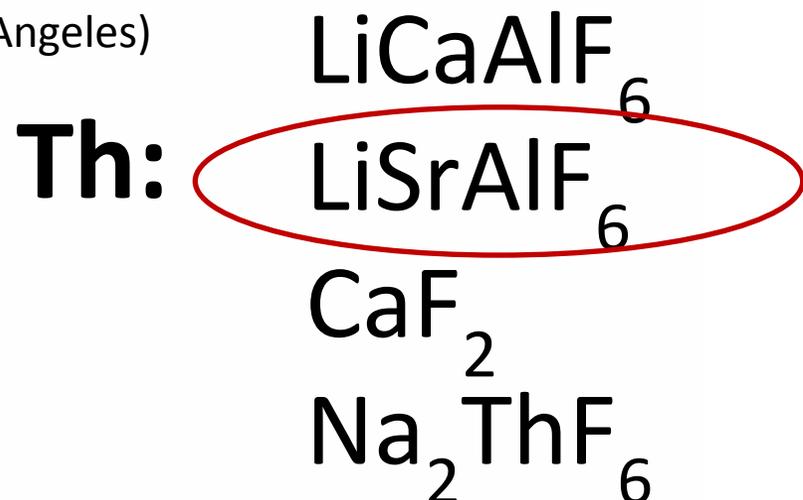
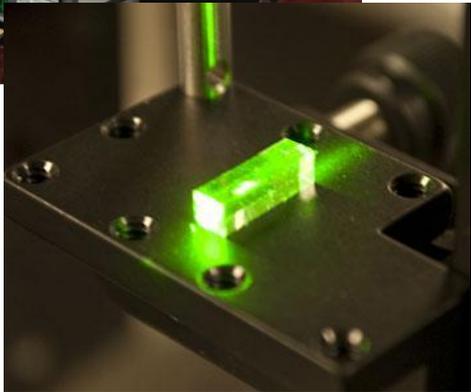


Измерения  $\gamma$ -распада изомера  $^{229}\text{mTh}$ : ядра отдачи  $^{229}\text{Th}$  от  $\alpha$ -распада  $^{233}\text{U}$  имплантируют в  $\text{MgF}_2$  в течение нескольких часов. Источники  $^{233}\text{U}$  затем удаляют, регистрируется эмиссия фотонов с поверхности  $\text{MgF}_2$  с помощью ФЭУ.

**Оказалось, что метод неэффективен!** Сигнал определяется фоном от короткоживущих дочерних продуктов распада U-233 [E. Peik, K. Zimmermann, Phys. Rev. Lett. 111, 018901 (2013)](comment)

# Исследование широкополосных кристаллов с <sup>229</sup>Th на источниках СИ в ультрафиолетовом спектре

Hudson's group (The University of California, Los Angeles)



*Для данной системы группой Хадсона не обнаружено подтверждений существования ядерного измерного перехода в ядрах тория в диапазоне энергий 7.3-8.8 эВ с временем жизни 2000-5600 с.*

Results of a direct search using synchrotron radiation for the low-energy <sup>229</sup>Th nuclear isomeric transition // PRL 114 (2015)

**Th:LiSAF**

# In 2015, within the framework of the FET project (Future and Emerging Technologies) The European consortium "nuClock" was created

The consortium includes 8 partners  
focused on the study of the nuclear  
transition in thorium-229:

- PTB (Germany)**
- LMU (Germany)**
- University of Juvaskylä (Finland)**
- Max Planck Institute of Nuclear Physics  
(Germany)**
- University of Vienna (Austria)**
- Max Planck Institute (Germany)**
- Toptica Photonics**

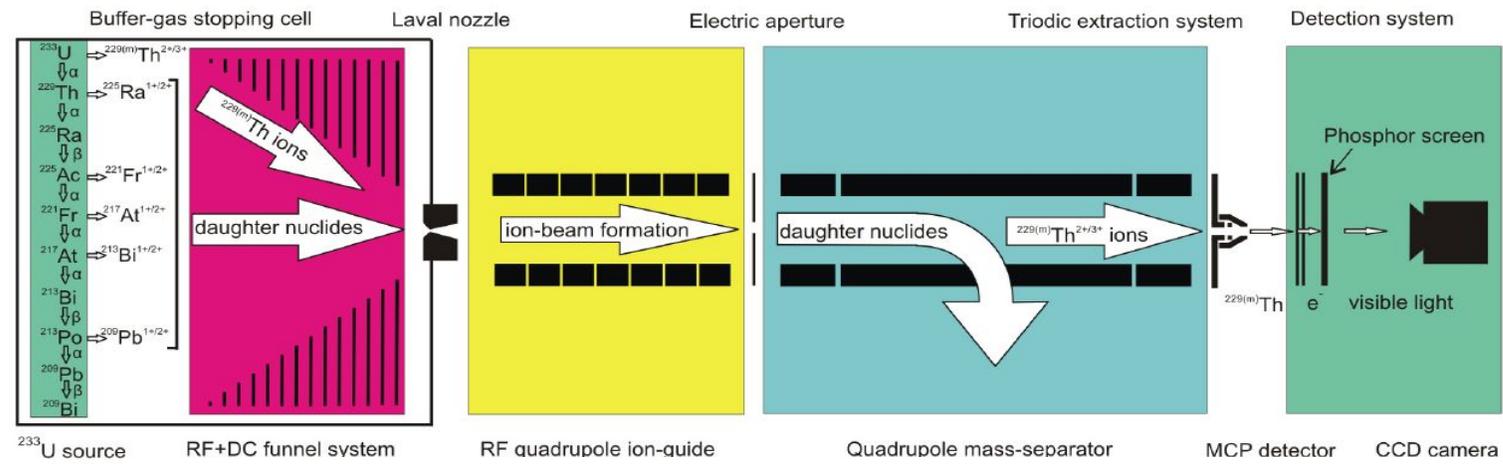


**Participants of the consortium for 2015-2020  
a number of breakthrough results were obtained**

**The transition energy remains "Terra Incognita" !**

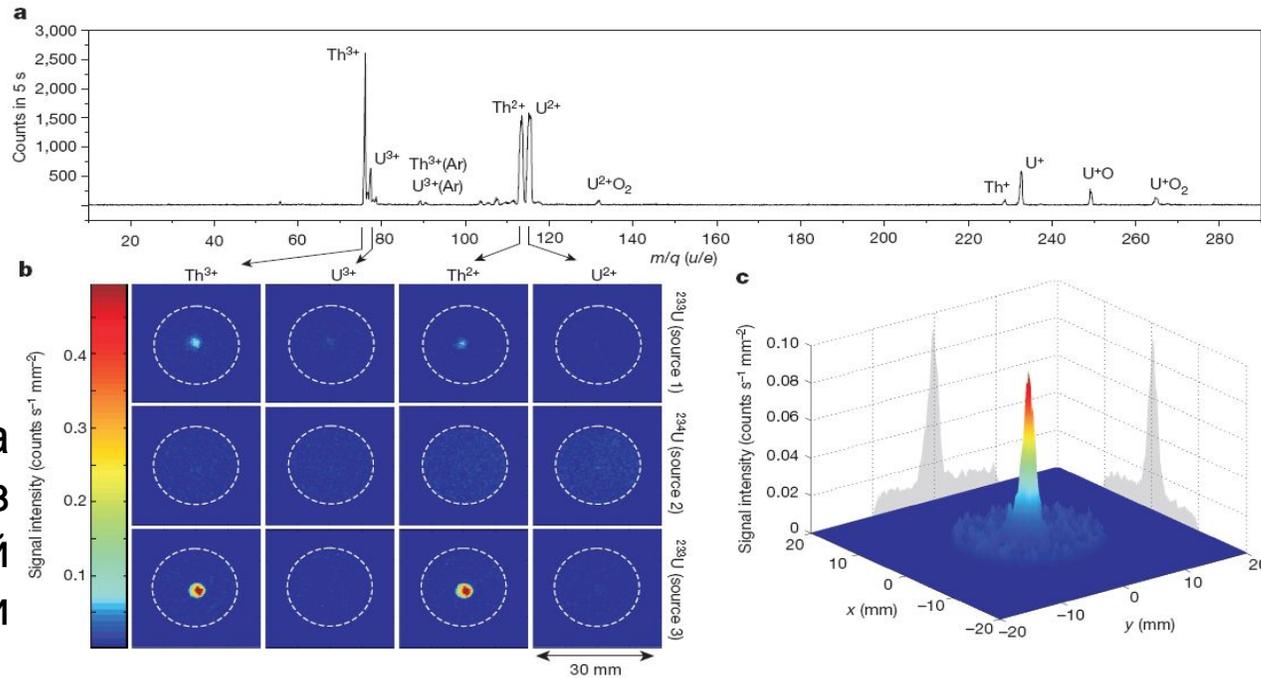
# The Munich $^{229m}\text{Th}$ recoil ion experiment

L. v. d. Wense, P. Thierolf et al., Nature 533, 47 (2016)



«Доказательство  
теоремы о  
существовании»

Регистрация распада  
изомерных ядер через  
канал электронной  
конверсии



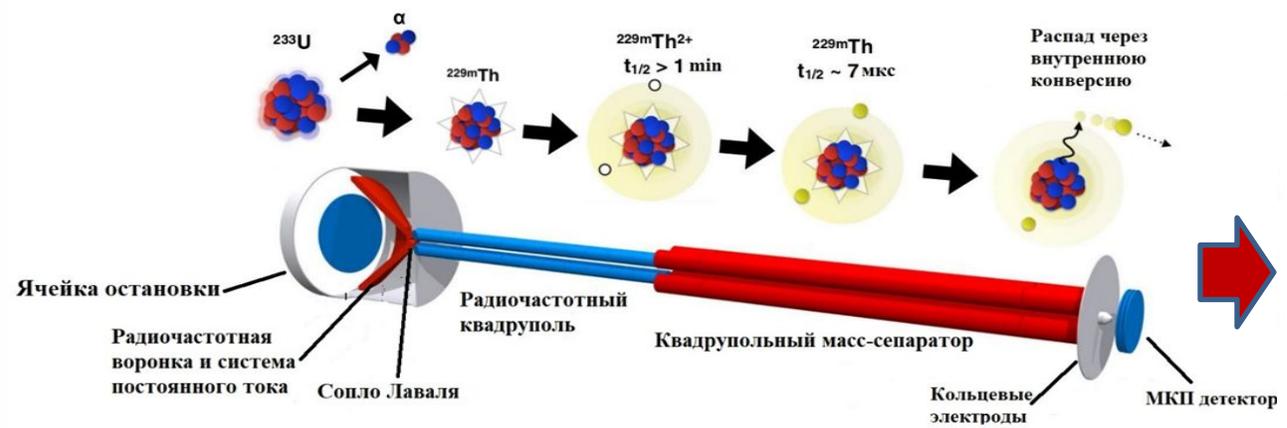
Продолжение работы  
Nature

Lifetime Measurement of the  $^{229m}\text{Th}$  nuclear isomer

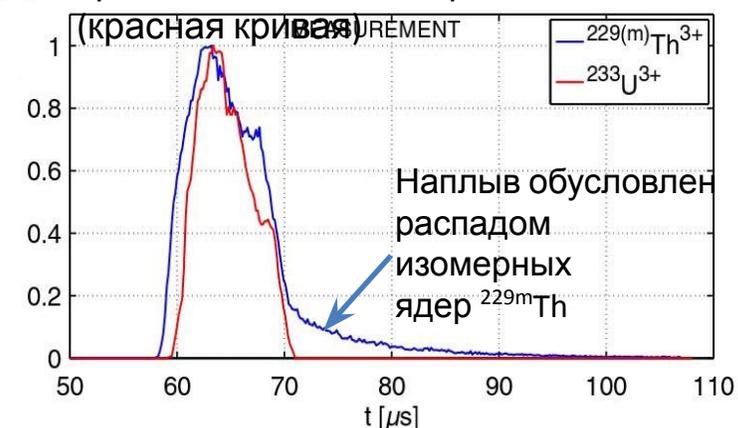
Benedict Seiferle, Lars von der Wense, and Peter G. Thirolf

Ludwig-Maximilians-Universität München, Am Coulombwall 1, 85748 Garching bei München, Germany

(Received 23 November 2016; published 26 January 2017)



Измерение характеристик  
изомерного распада пучка ионов  
 $^{229m}\text{Th}^{3+}$  (синяя кривая) и  
сравнительное измерение с  $^{233}\text{U}^{3+}$   
(красная кривая)



**Период полураспада изомерных ядер на поверхности твердого тела:  $7 \pm 1 \mu\text{s}$**

Согласуется с оценками Ткаля Е.В. [Sov. Phys. JETP 72, 387 (1991); PRC 92, 054324 (2015)]

Важное наблюдение: время жизни изомерных ядер для ионов в ловушке зависит от зарядности ионов  
тория

$\text{Th}^+$ :  $< 10 \text{ ms}$  - возможно ограничено распадом через канал электронного моста (?)

$\text{Th}^{2+}$ :  $< 60 \text{ s}$  - ограничено химическими реакциями с атомами остаточного газа

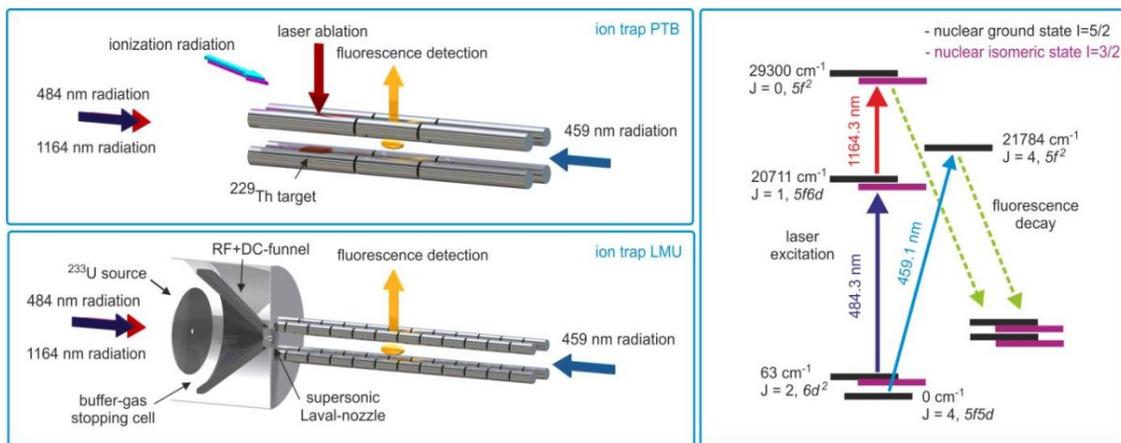
(время удержания ионов в ловушке)

## Laser spectroscopic characterization of the nuclear clock isomer $^{229m}\text{Th}$

Johannes Thielking, Maxim V. Okhapkin, Przemyslaw Glowacki, David M. Meier, Lars von der Wense, Benedict Seiferle, Christoph E. Düllmann, Peter G. Thirolf, Ekkehard Peik

(Submitted on 15 Sep 2017)

Сравнение результатов лазерной спектроскопии ионов тория-229 в 2-х ловушках:  
 1 - Physikalisch-Technische Bundesanstalt (PTB) загружается  $^{229}\text{Th}^{2+}$  методом лазерной абляции;  
 2 - Ludwig-Maximilians-Universität (LMU) загружается  $^{229}\text{Th}^{2+}$  ионами отдачи от  $\alpha$ -распада  $^{233}\text{U}$

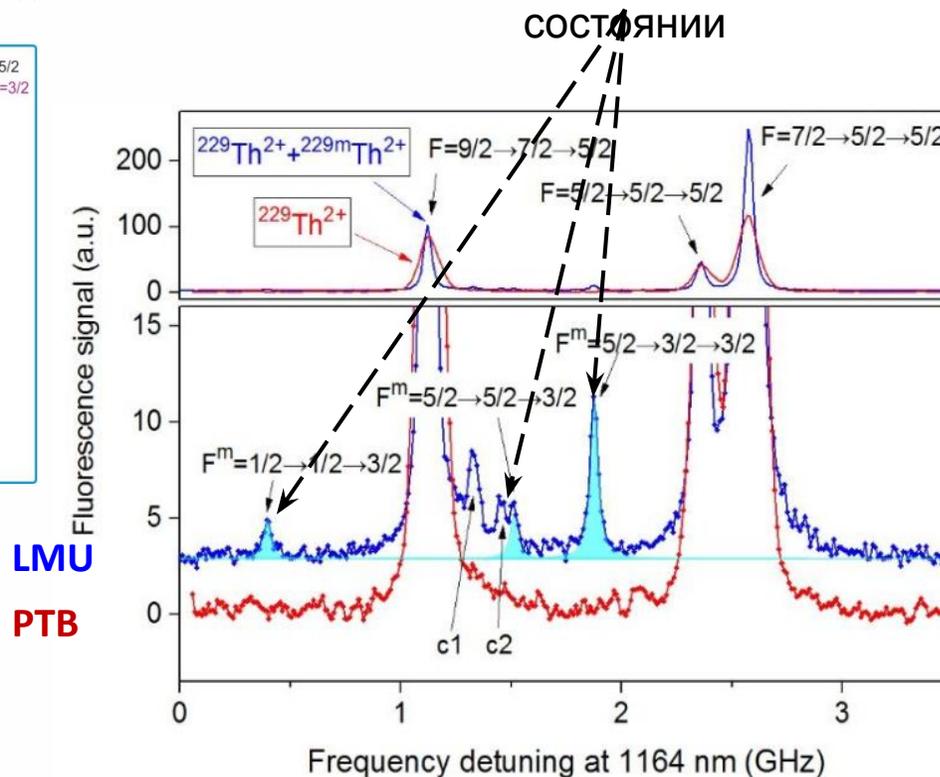


**По сверхтонкому расщеплению  
измерены:**  
 магнитный дипольный момент  
 изомерного состояния  $\mu^m = -0,37 (6) \mu_N$

квадрупольный момент  
 изомерного состояния  $Q_0^m = 8.7 (3) \text{ eb}$

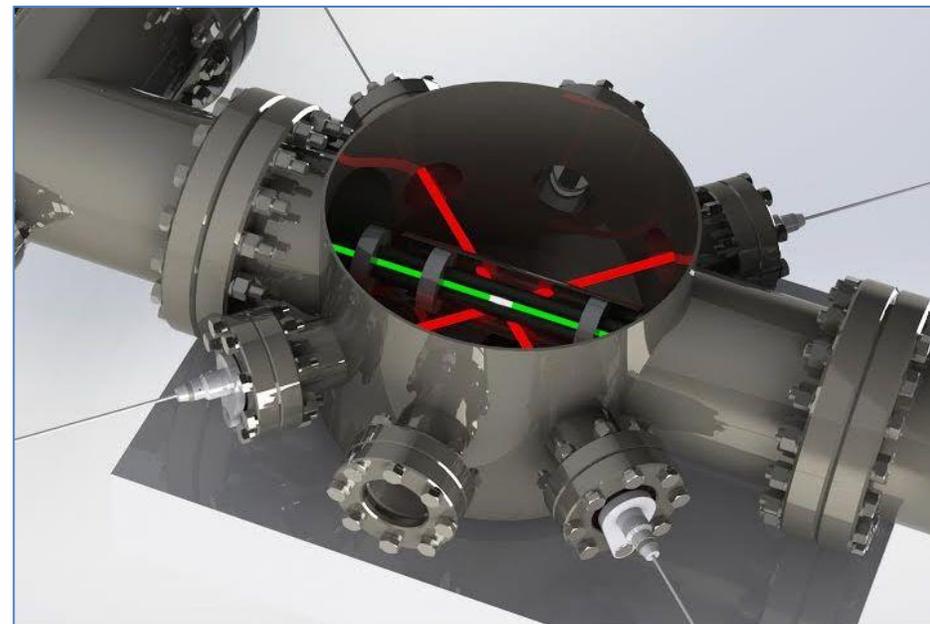
**Энергия перехода остается «Terra  
Incognita»!**

2% ионов в ловушке LMU  
находятся в изомерном  
состоянии

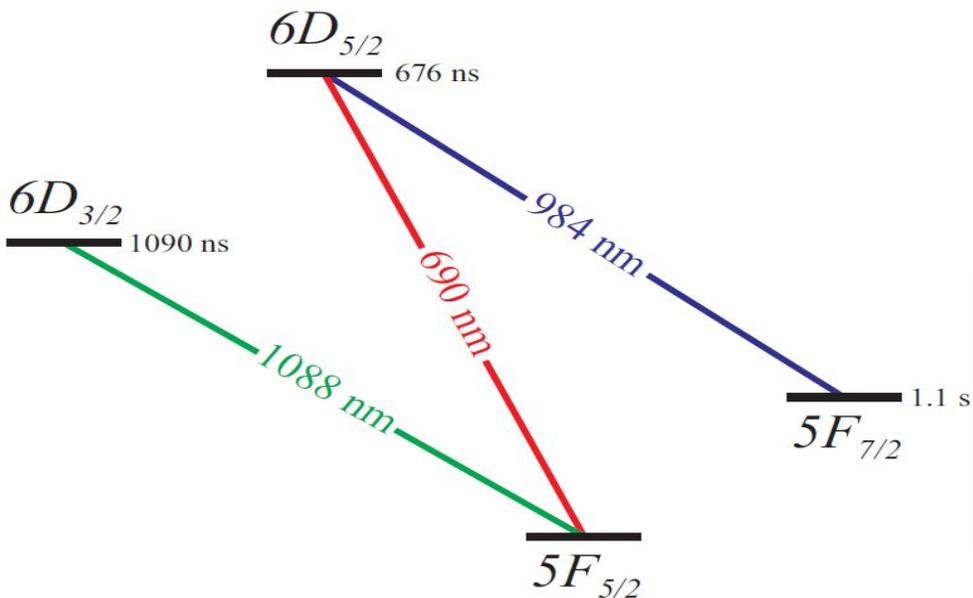


# Подготовка чистых кристаллов $^{229}\text{Th}^{3+}$

Исследование ядерного перехода  
оптического диапазона и перспективы  
создания квантового регистра на  
ионах с использованием  
квадрупольной ловушки Пауля



Цепочка охлажденных ионов тория



**nature**  
International journal of science

Letter | Published: 29 November 2017

## Observation of a many-body dynamical phase transition with a 53-qubit quantum simulator

J. Zhang , G. Pagano, P. W. Hess, A. Kyprianidis, P. Becker, H. Kaplan, A. V. Gorshkov, Z.-X. Gong & C. Monroe

*Nature* **551**, 601–604 (30 November 2017) | [Download Citation](#) 



# TRAPPED ION QUANTUM INFORMATION

CHRISTOPHER MONROE, Principal Investigator. University of Maryland Department of Physics, Joint Quantum Institute, and Center for Quantum Information and Computer Science

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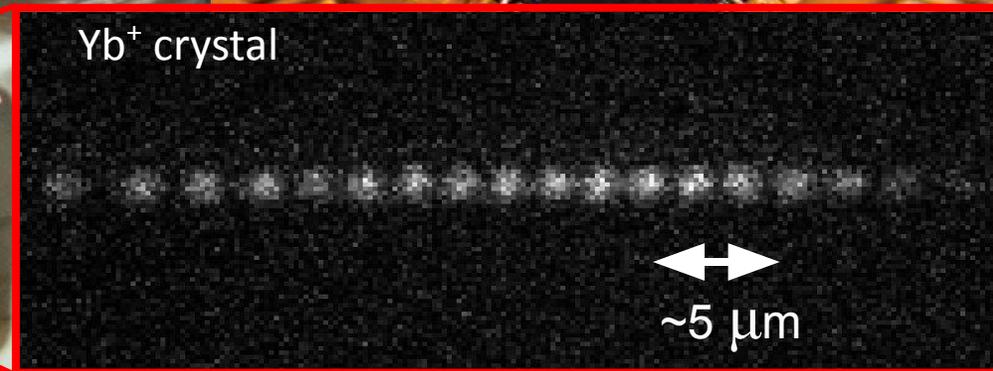
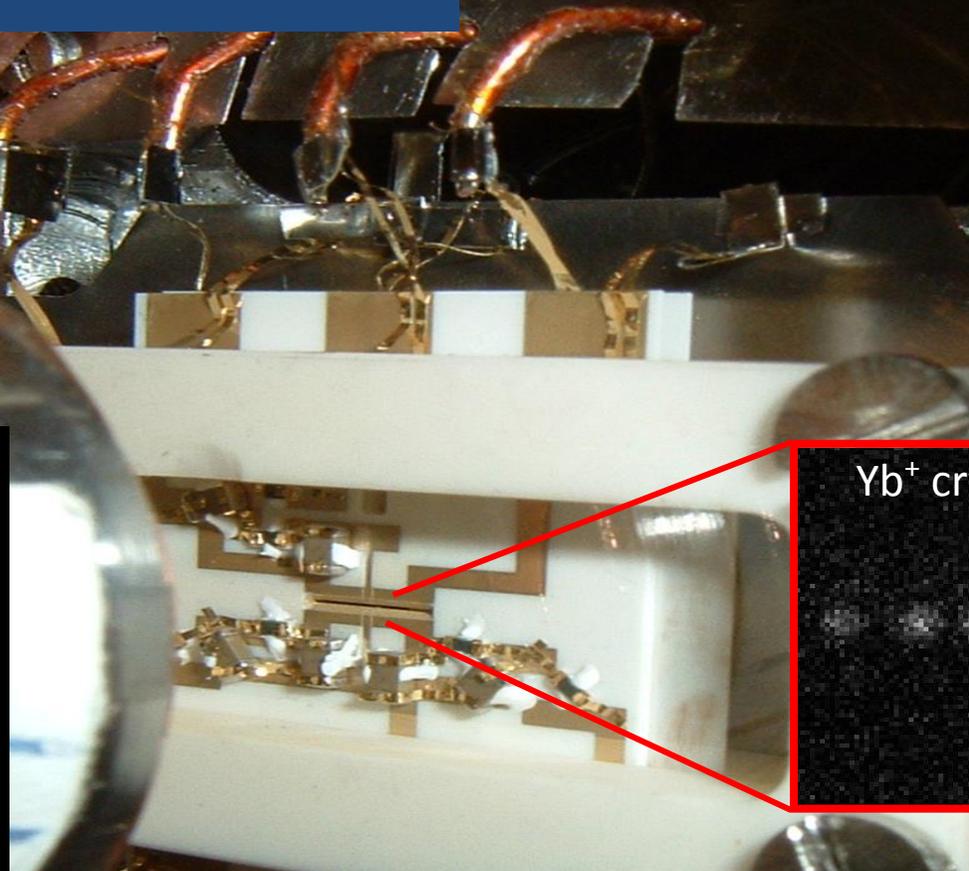
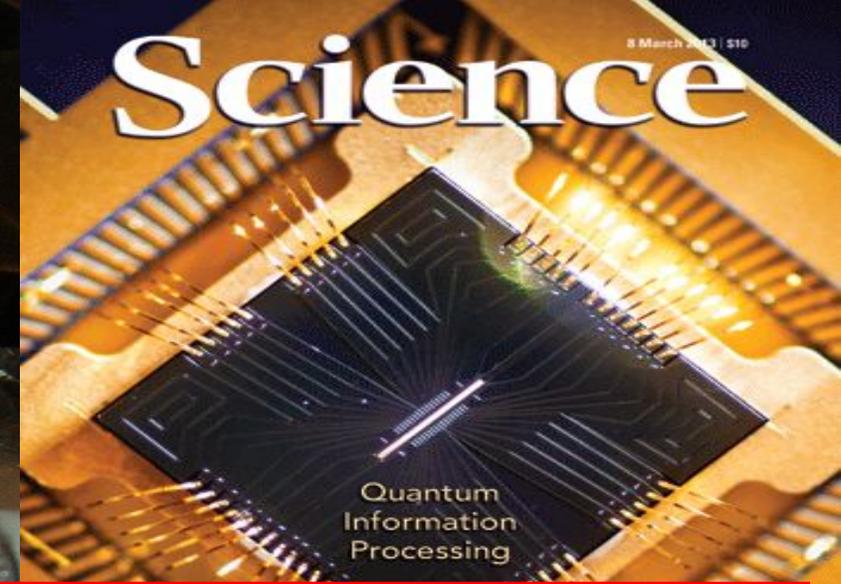
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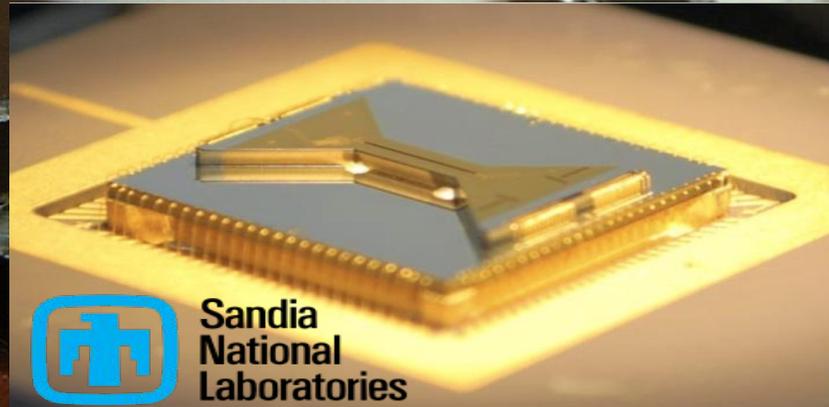
[Popular Press](#)



# Trapped Atomic Ions



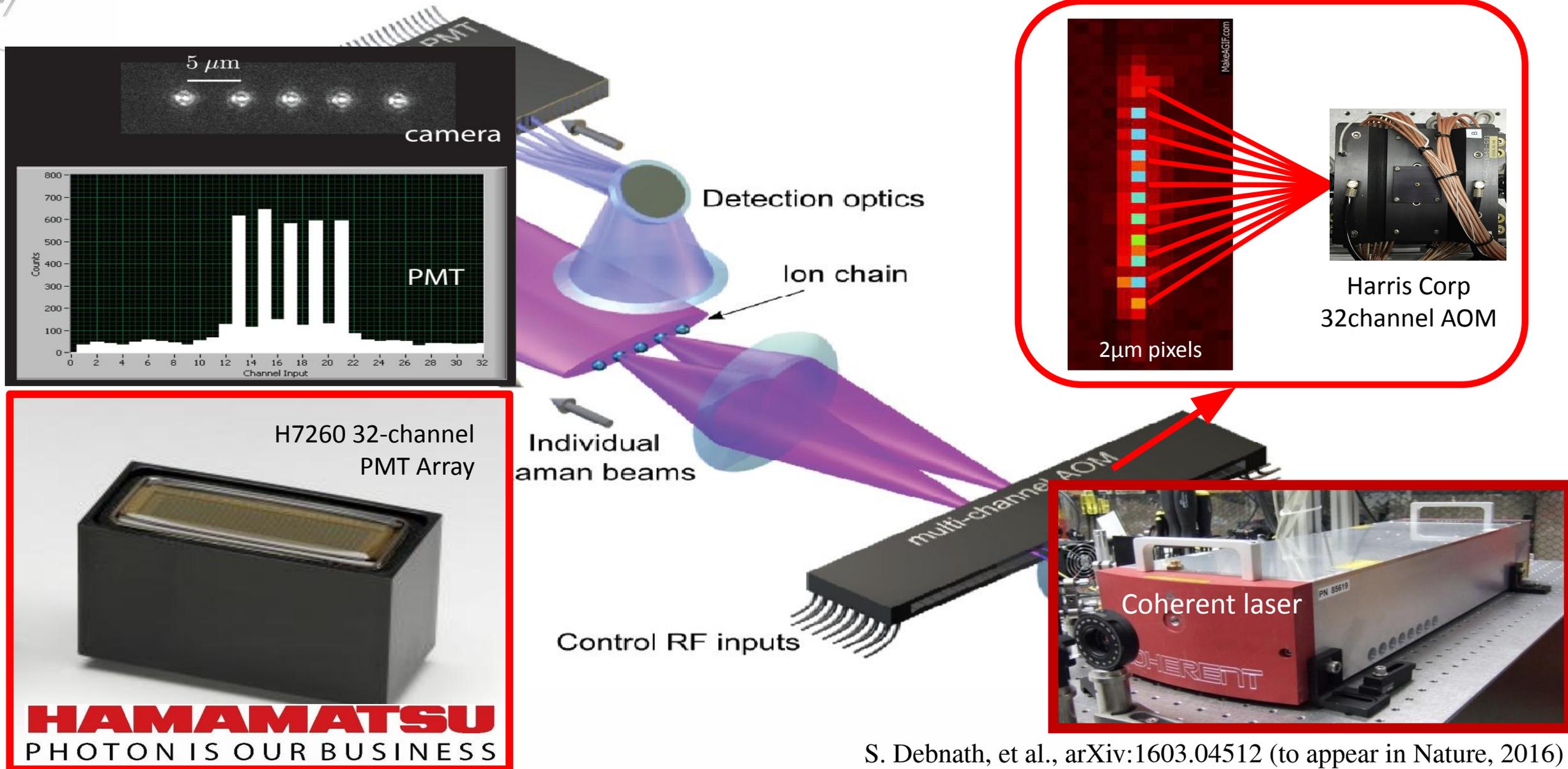
- Aarhus
- Amherst
- Basel
- Berkeley
- Bonn
- Citadel
- Clemson
- Denison
- Duke
- Erlangen
- ETH-Zurich
- Freiburg
- Georgia Tech
- Griffith
- Hannover
- Honeywell
- Indiana
- Innsbruck
- Lincoln Labs
- Lockheed
- Maryland/JQI
- Mainz



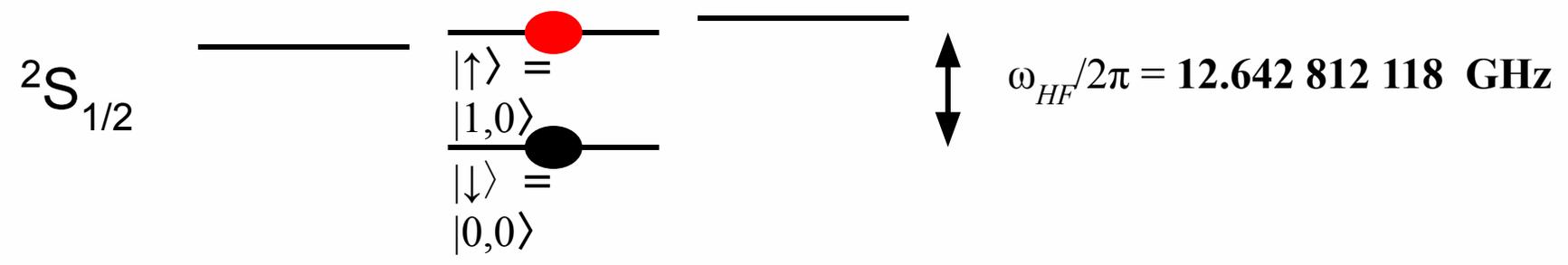


75 ЛЕТ  
АТОМНОЙ  
ПРОМЫШЛЕННОСТИ

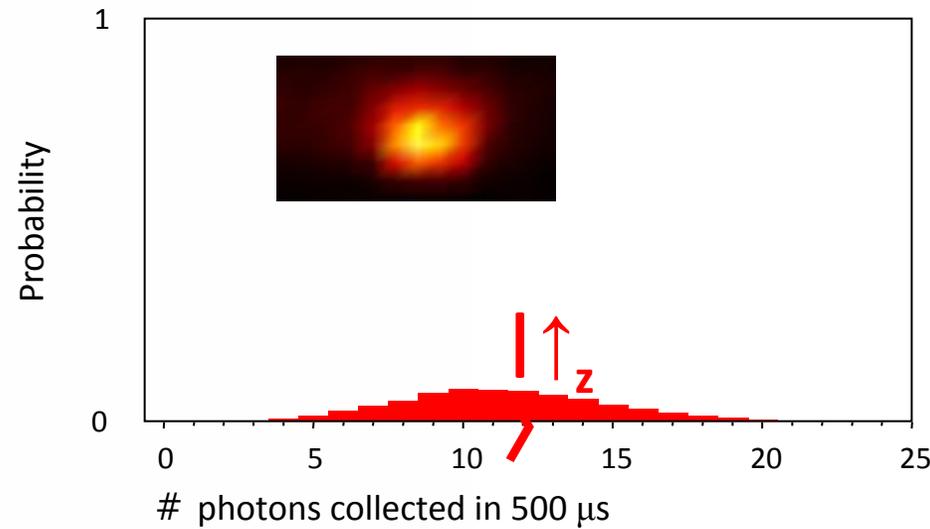
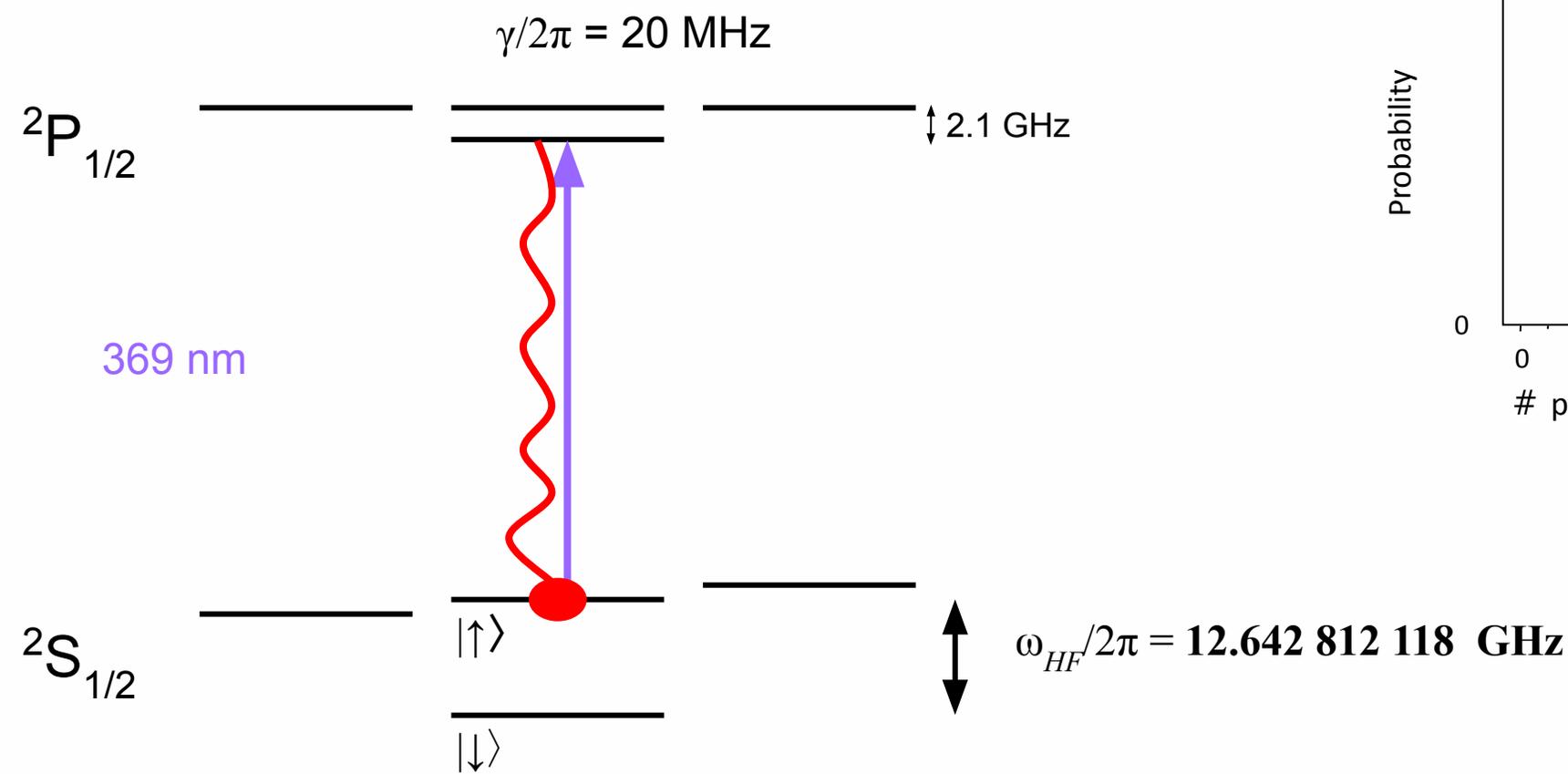
# Программируемый квантовый компьютер на



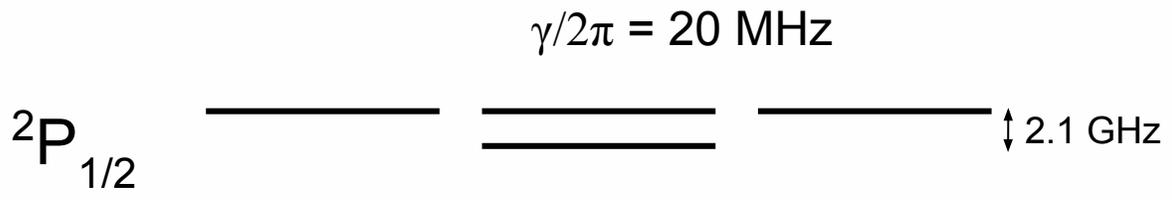
# •Atomic Qubit ( $^{171}\text{Yb}^+$ )



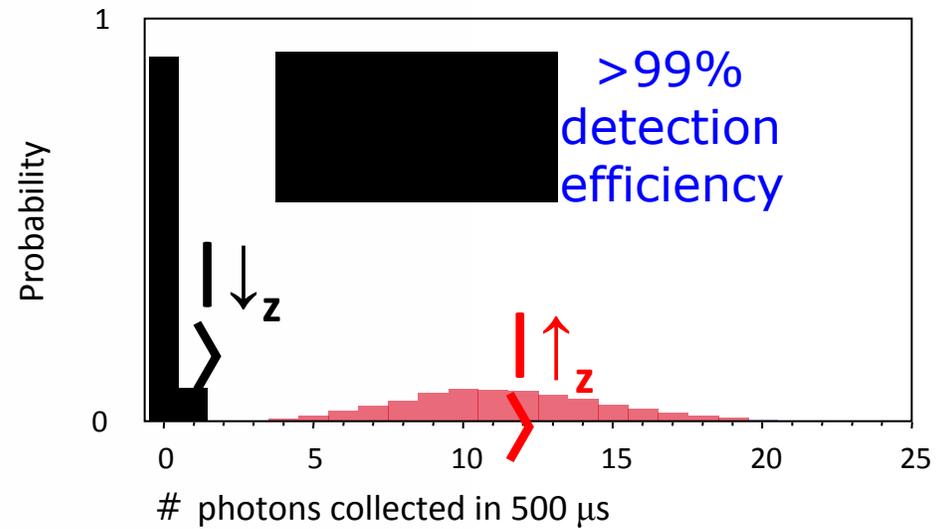
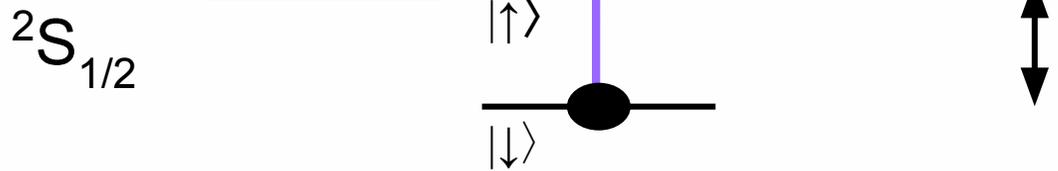
# Atomic Qubit Detection



# Atomic Qubit Detection

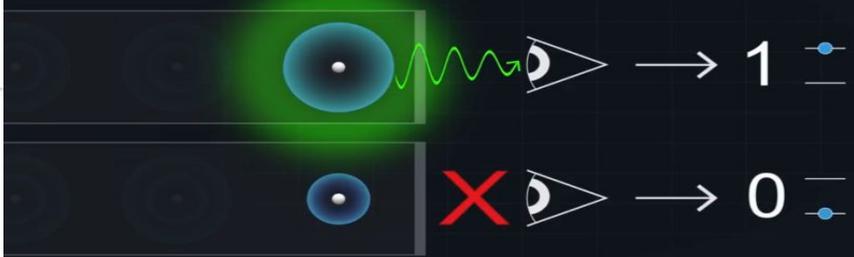


369 nm

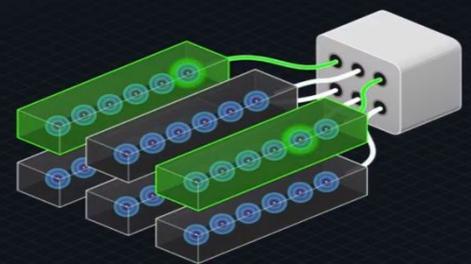




A quantum computer must:  
Get information from the qubits



A quantum computer must:  
Scale to many qubits

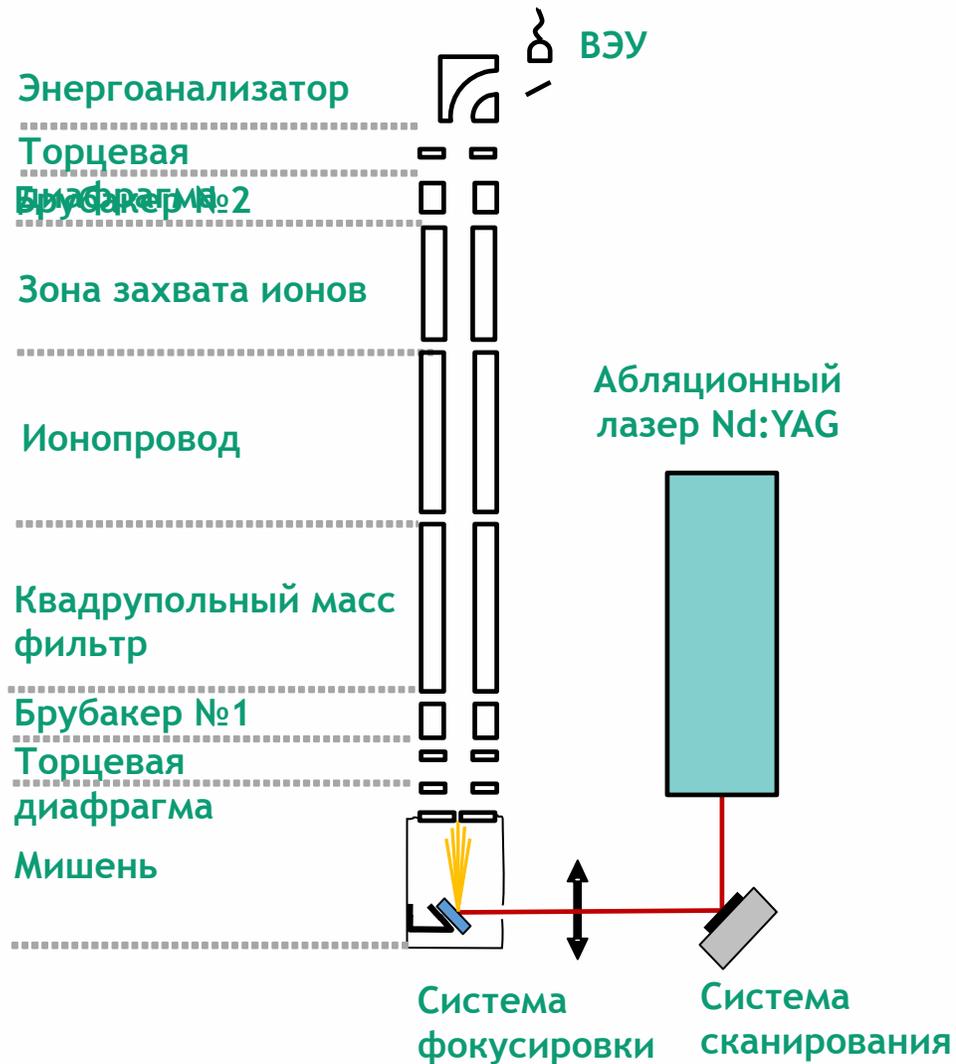


Quantum simulation with individual control of 53 qubits



Complex qubit organization: each row is a separate image of 53 trapped ion qubits, with each qubit fluorescing (state 1) or dark (state 0) upon measurement.,

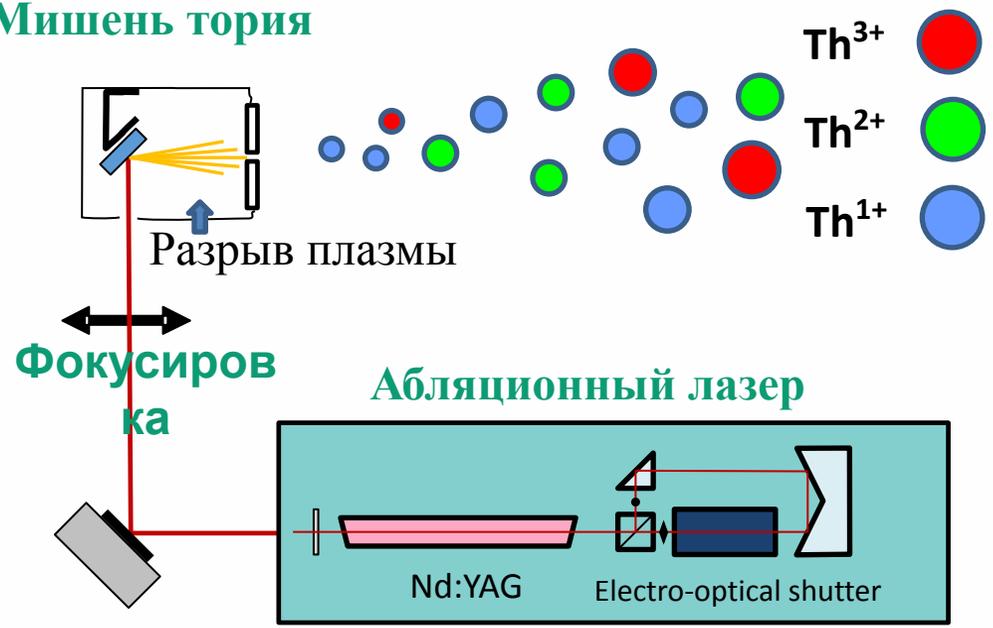
## Многосекционная квадрупольная ловушка Пауля



# НАУЧНО-ТЕХНИЧЕСКИЙ ЗАДЕЛ

## 2. Получение ионов $^{229}\text{Th}^{n+}$

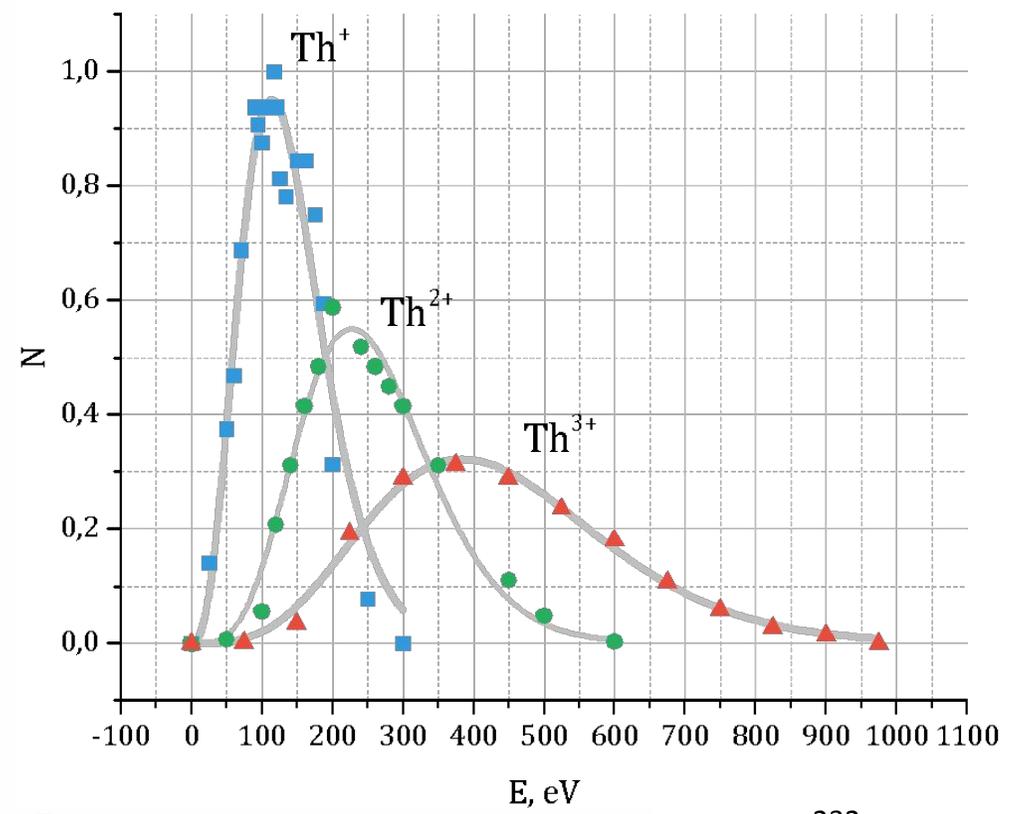
Мишень тория



Сканирующая  
система

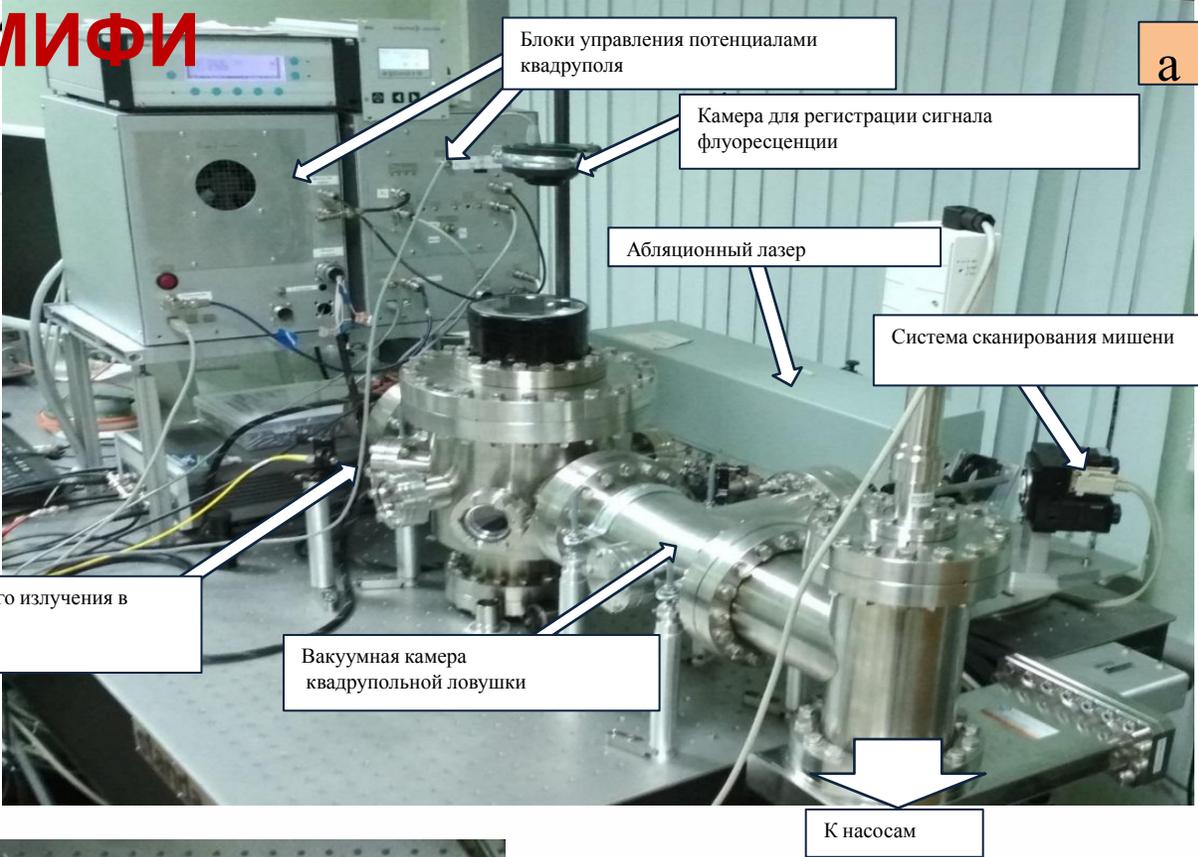
Laser parameters :

- Ширина импульса ~ 25 нс
- Мах. энергия в импульсе ~ 300 мДж
- Пятно фокусировки ~ 100 мкм



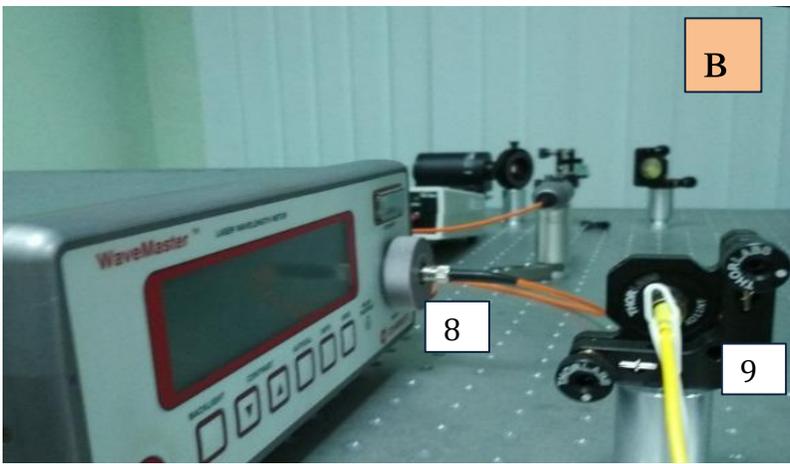
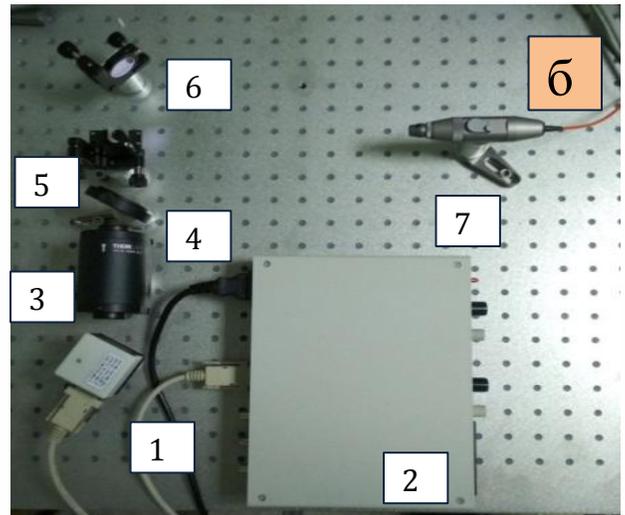
Распределение по энергиям ионов  $^{232}\text{Th}^+$ ,  $^{232}\text{Th}^{2+}$ ,  $^{232}\text{Th}^{3+}$ , сформированных при лазерной абляции твердотельной мишени металлического  $^{232}\text{Th}$

# Установка каф.78 Института ЛаПлаз НИЯУ



**а** Фотографии экспериментальной установки.  
**а.** Обзорная фотография установки по получению, захвату и охлаждению ионов тория;  
**б, в** Фотографии оптической схемы;  
**г.** Фотография, демонстрирующая ввод лазерного излучения в вакуумную камеру через окно во фланце

1. Перестраиваемый диодный лазер,
2. Блок управления лазером,
3. Оптический изолятор,
4. Пластика  $\lambda/2$ ,
5. Светоделительный кубик,
6. Зеркало,
7. Входной сенсор измерителя длин волн,
8. Измеритель длин волн,
9. Коллиматор для ввода излучения в оптоволокно



**Институт ЛаПлаз реализует программу:  
Квантовая метрология**

**Спец.курсы по квантовой информатике**

**Каф.78**

Введение в квантовую информатику

Прецизионные измерения

Атомная спектроскопия

**Каф.32**

Введение в теорию квантовых вычислений

(Методы квантовой механики в кибернетике)

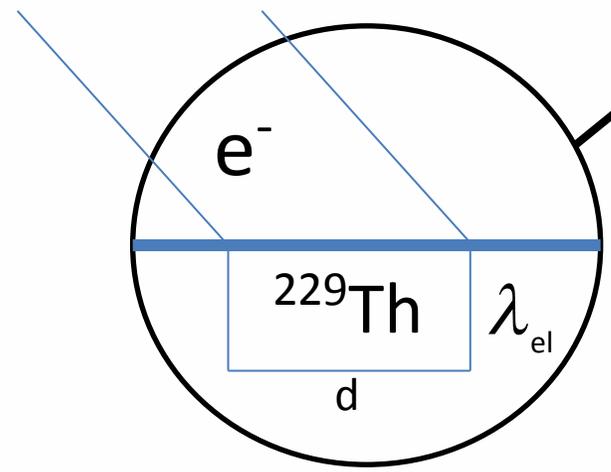
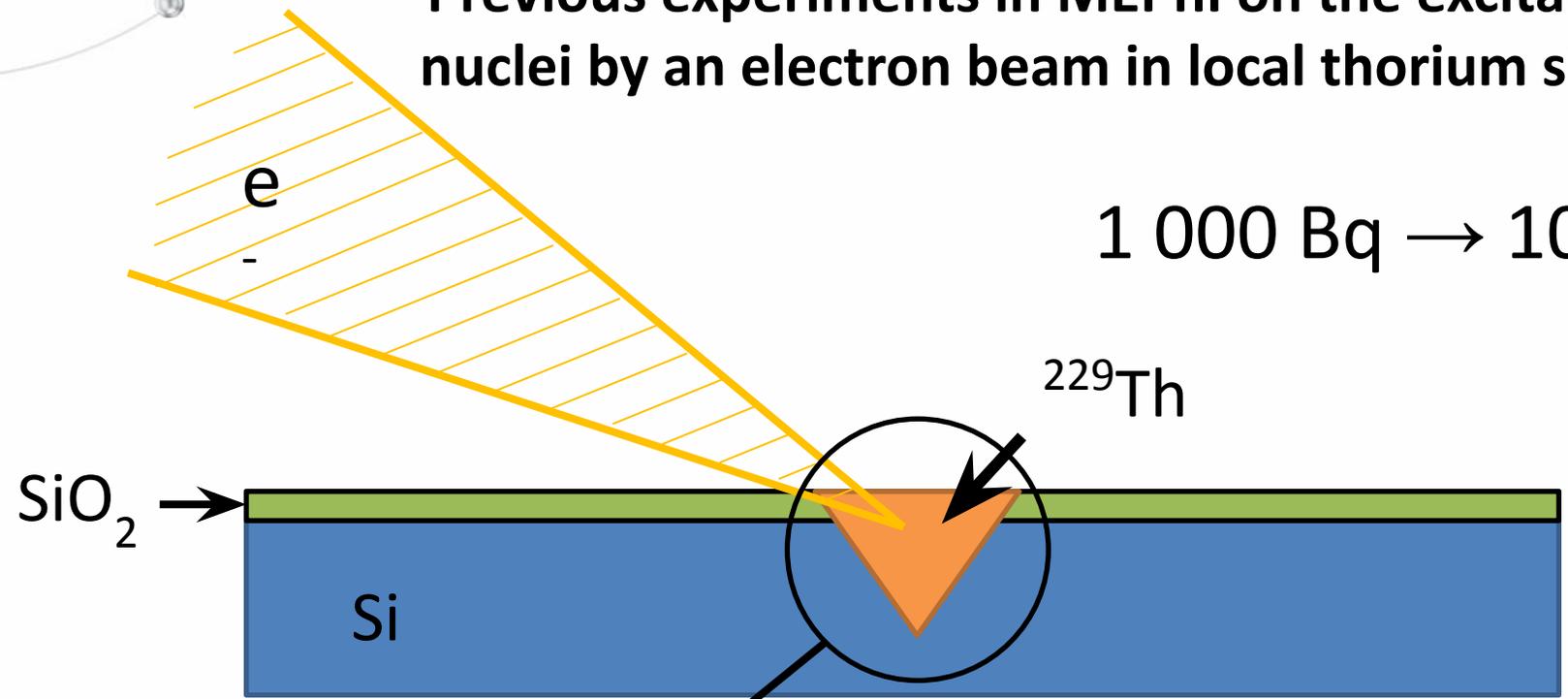
Элементы квантовой информатики

**Каф.37**

Лазерная спектроскопия и охлаждение атомов

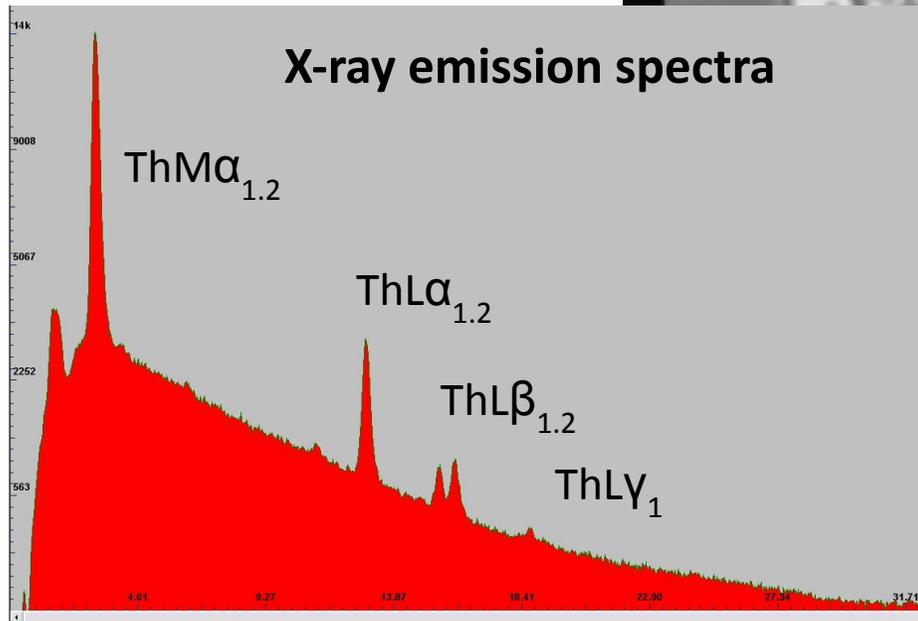
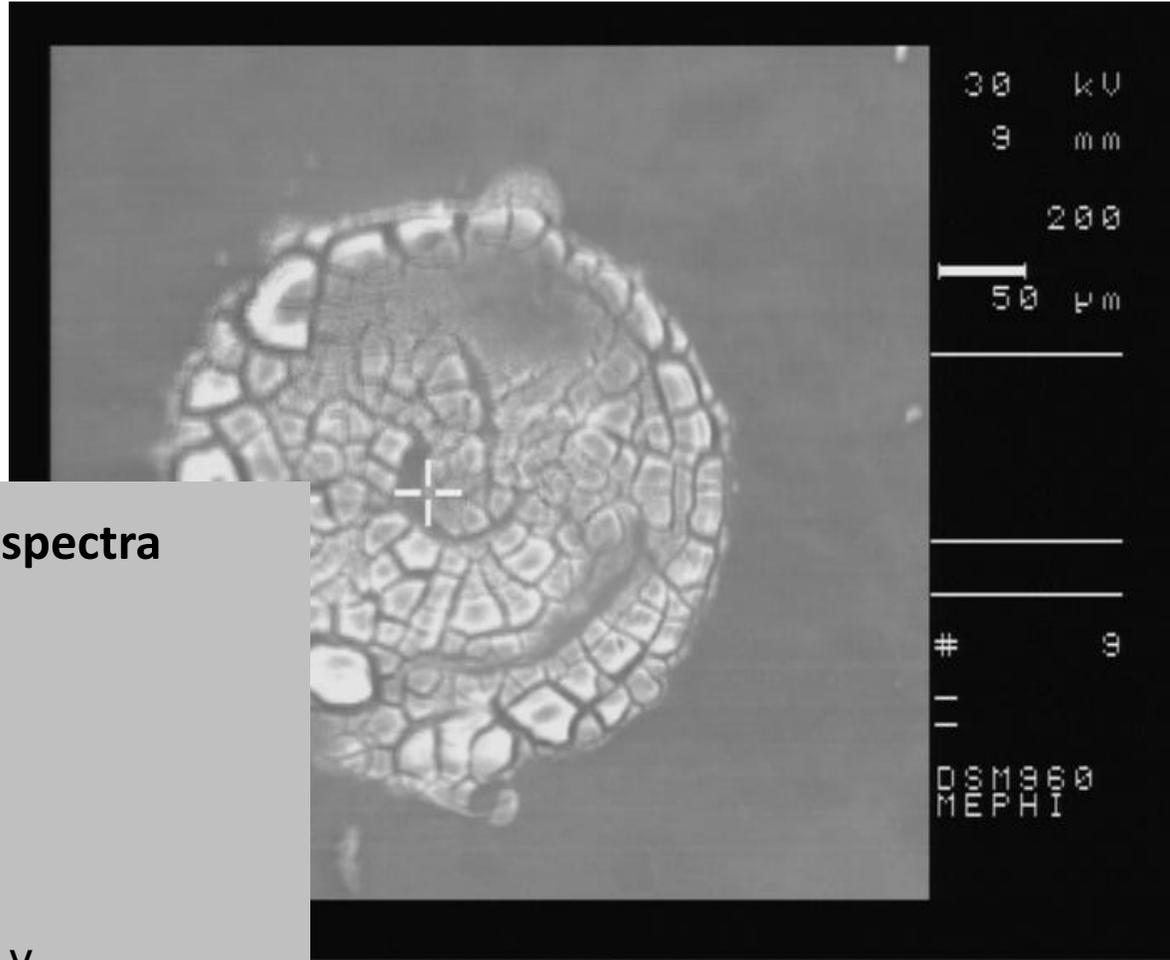
Previous experiments in MEPhI on the excitation of isomeric  $^{229m}\text{Th}$  nuclei by an electron beam in local thorium silicon oxide compound

1 000 Bq  $\rightarrow$   $10^{15}$  atoms



$d=10^{-2}$  cm – diameter of thorium spot  
 $S \approx 10^{-4}$  cm<sup>2</sup> – square of electron beam  
 $n_{\text{Th}} \approx 10^{23}$  cm<sup>-3</sup> – atomic density  
 $\lambda_{\text{el}} \approx 10^{-4}$  cm – IMFP in ThSiO4 for 30 keV electrons  
 $N(^{229}\text{Th}) \approx n_{\text{Th}} \cdot S \cdot \lambda_{\text{el}} \sim 10^{15}$  atoms

# Local electrochemical deposition of thorium-229 compound



## Production of isomeric thorium-229 nuclei by electron beam irradiation

TABLE I. Average energy of primary  $\varepsilon_{pe}$  and secondary  $\varepsilon_{se}$  electrons, effective penetration depth  $Z_{eff}$ , average length of trajectory of primary electrons  $L_{eff}$ , multiplication factor  $\kappa$  (ratio of secondary electrons to primary electrons), average time of flight of primary electrons  $\tau$ , and parameter  $\lambda$ , which is the output speed of isomeric thorium-229 nuclei related to the current of the primary beam, calculated for different energy values of incident electrons  $E_0$  in the  $\text{ThSi}_{10}\text{O}_{22}$  compound.

$E_0$ , keV	$\varepsilon_{pe}$ , keV	$\varepsilon_{se}$ , eV	$Z_{eff}$ , $\mu\text{m}$	$L_{eff}$ , $\mu\text{m}$	$\kappa$	$\tau, \times 10^{-13}\text{c}$	$\lambda$ , isomeric nuclei/(mA c)
1.0	0.6	20	0.01	0.05	30	0.3	42
5.0	3.6	25	0.08	0.46	140	1.9	$1.6 \times 10^3$
10.0	7.4	27	0.25	1.44	260	5.7	$9.7 \times 10^3$
15.0	11.2	28	0.51	2.84	370	9.9	$2.5 \times 10^4$
20.0	15.1	28	0.77	4.44	440	14.9	$4.5 \times 10^4$
25.0	19.6	29	1.07	5.80	560	16.7	$6.7 \times 10^4$

AIP Advances 6, 095304 (2016);  
doi:10.1063/1.4962661

If electron beam is 1 mA  
the expected level of the desired signal is  
**1-10 counts/second**



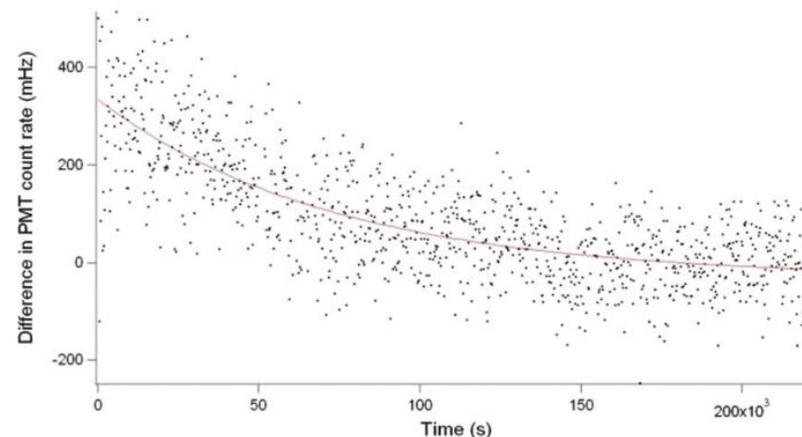
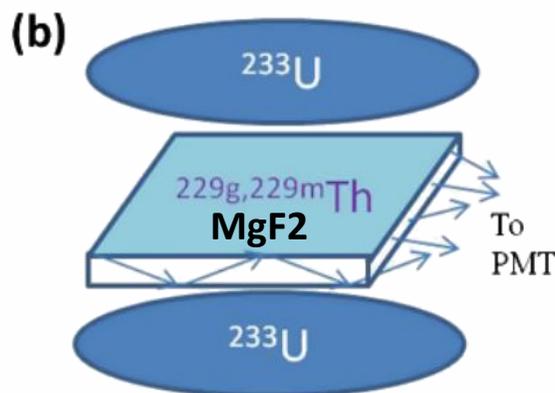
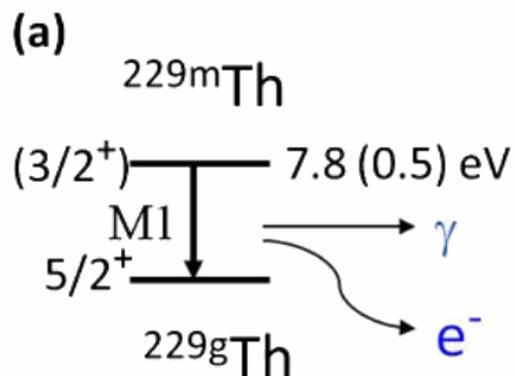
# The conventional method

## Investigation of recoil nuclei $^{229}\text{Th}$ in the decay of $^{233}\text{U}$

### Contain 2% of the nuclei populated in the isomeric state

X. Zhao, Y. N. Martinez de Escobar, R. Rundberg, E.M. Bond, A. Moody, and D.J. Vieira  
Los Alamos National Laboratory, Los Alamos, USA

PRL **109**, 160801 (2012)



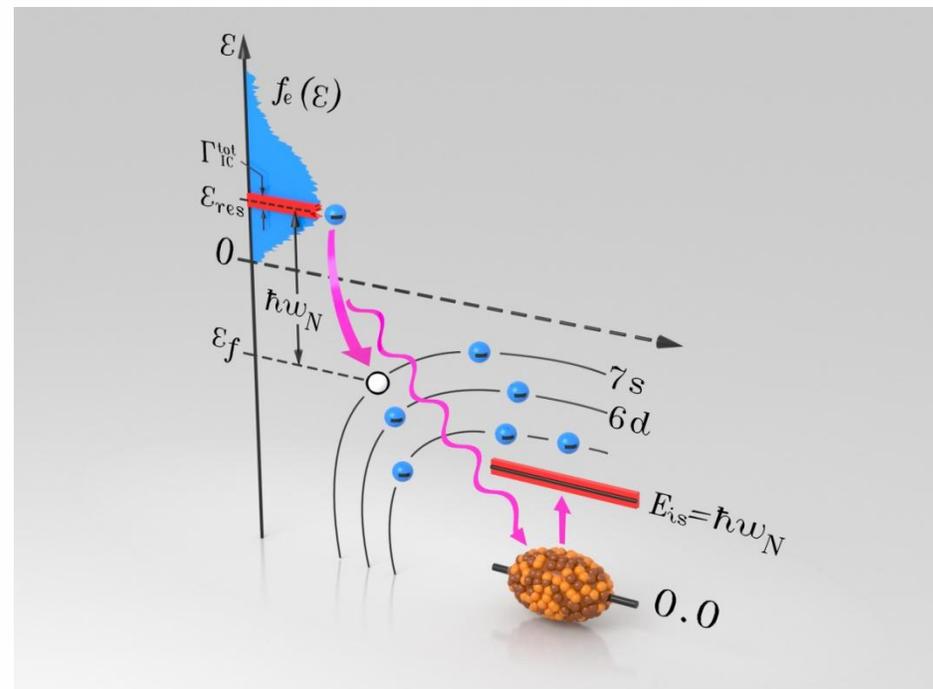
Measurements of the  $\gamma$ -decay of the isomer  $^{229m}\text{Th}$ : the recoil nuclei  $^{229}\text{Th}$  from the  $\alpha$ -decay of  $^{233}\text{U}$  are implanted in MgF2 for several hours. The  $^{233}\text{U}$  sources are then removed, and photon emission from the MgF2 surface is detected with a PMT.

It turned out that the method is ineffective! The signal is determined by the background from the short-lived daughter products of U-233 decay  
[E. Peik, K. Zimmermann, Phys. Rev. Lett. **111**, 018901 (2013)](comment)

## Pioneer work [V.F. Strizhov and E.V. Tkalya, Sov. Phys. JETP 72, 387 (1991)]

When intense laser radiation is applied to thorium-containing targets, the electrons of the laser plasma from states of the continuous spectrum with energy  $E$  populate the levels of the  $\text{Th}^+$  ion, that is, they enter the states of the discrete spectrum with energy  $E_b$ . The nucleus is then excited by a virtual photon, which is produced at this transition. The process in consideration is the inverse of the process of decay of the isomeric nuclear state through the internal electron conversion channel of gamma rays and has an extremely high cross section as compared to direct excitation by electrons or plasma photons.

**$\sim 10^8$  cores  $^{229\text{m}}\text{Th}$   
for one laser pulse**



**Questions for the experimental implementation:**

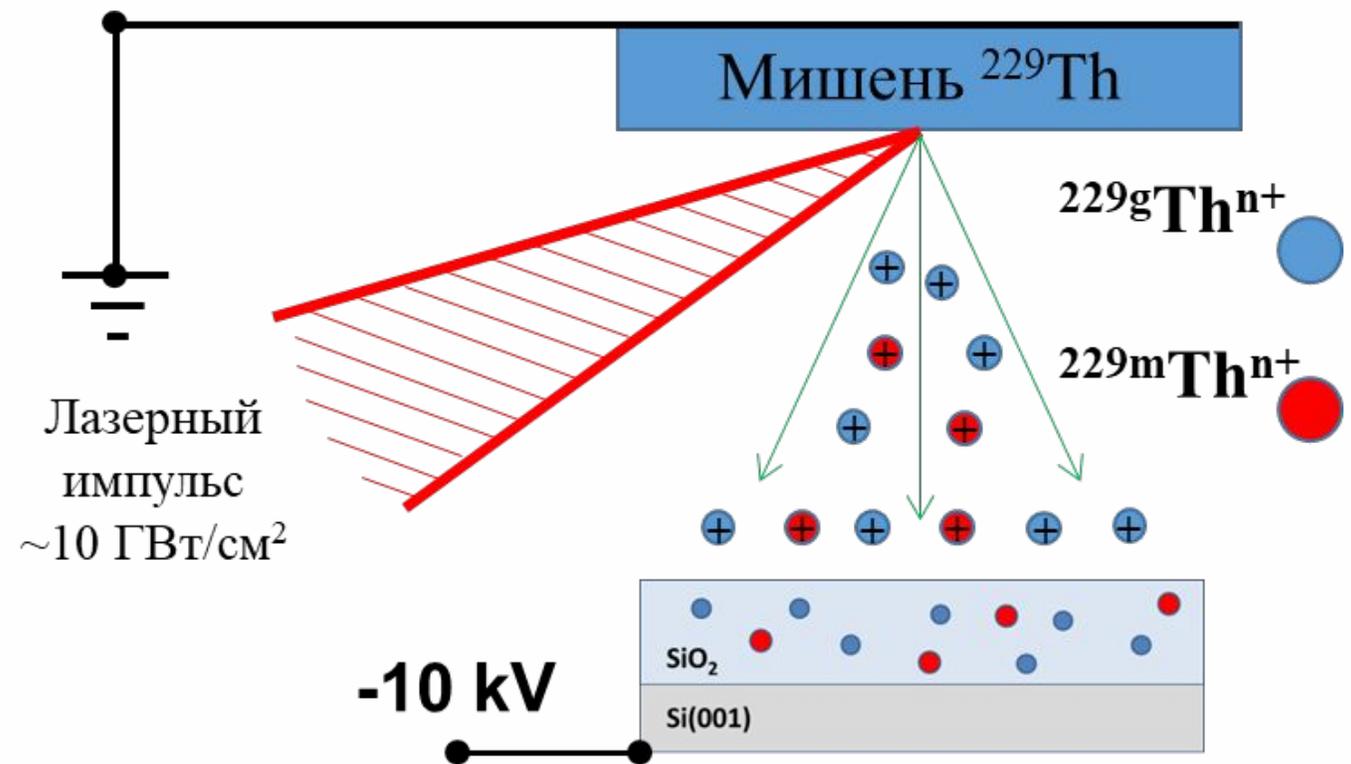
**How to obtain information about the isomeric state from the complex spectrum of a laser plasma?**

**How to exclude conversion channels of decay?**

**How to measure energy?**

# We have refined a UNIQUE METHOD!

Excitation of isomeric thorium-229 nuclei in a laser plasma by the inverse electron conversion mechanism and their injection into the near-surface region of a thin SiO<sub>2</sub> / Si (001) layer

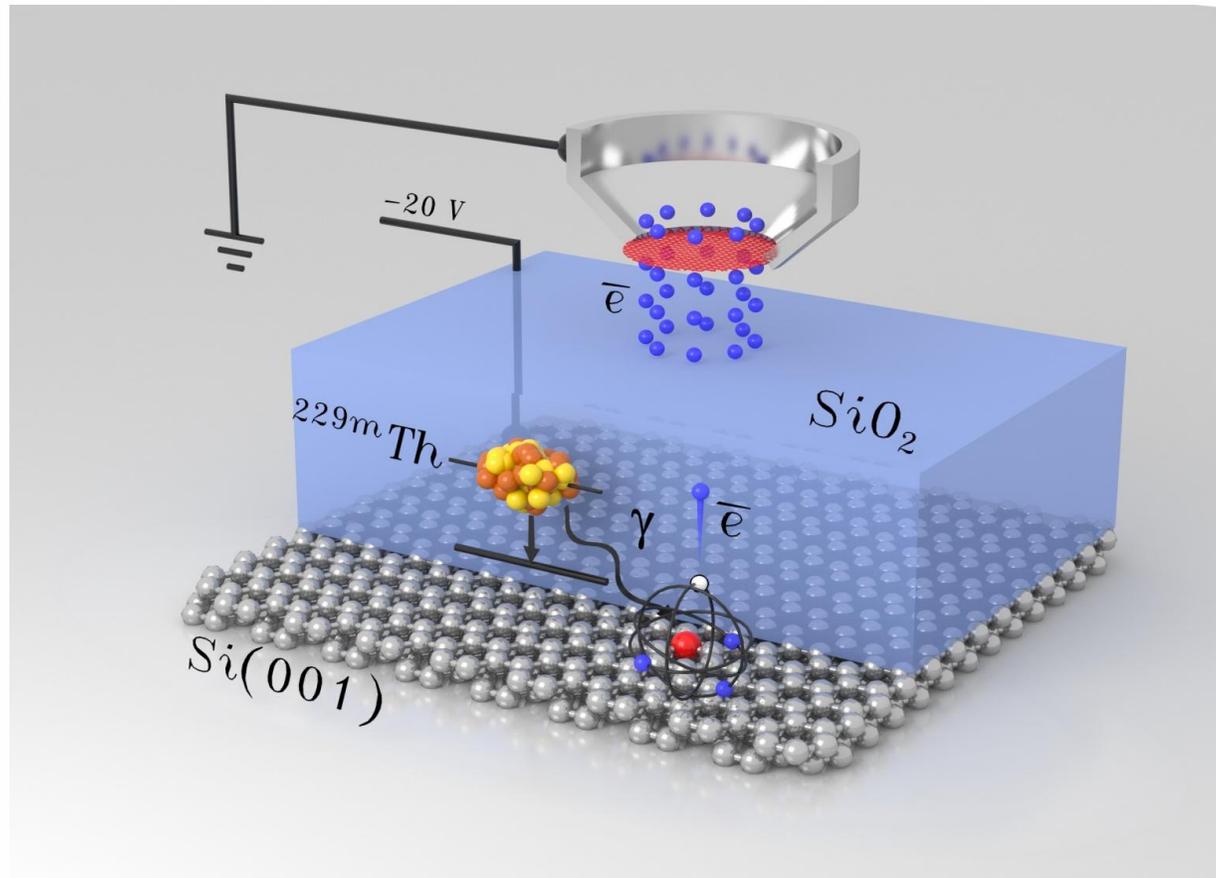


**Important:**  
Flight time <sup>229m</sup>Th<sup>n+</sup> < 1 us  
Life time <sup>229m</sup>Th > 7 us

The overwhelming majority of <sup>229m</sup>Th nuclei remain in the excited state after implantation

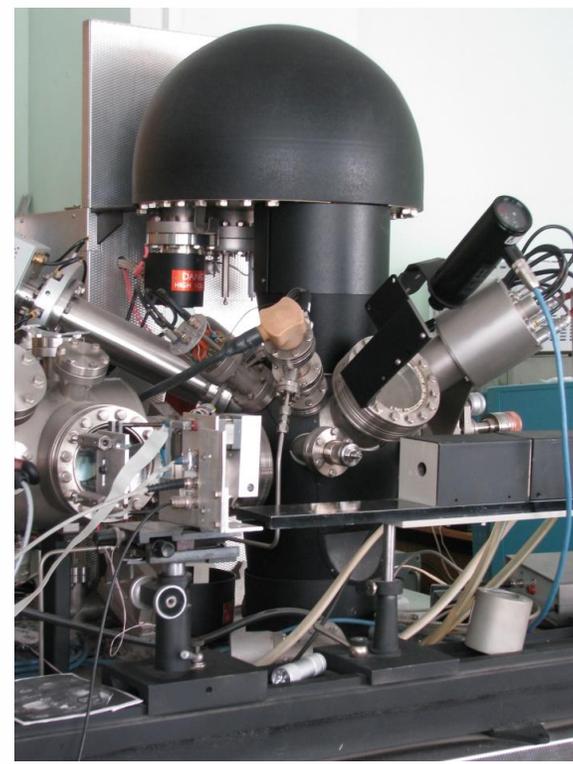
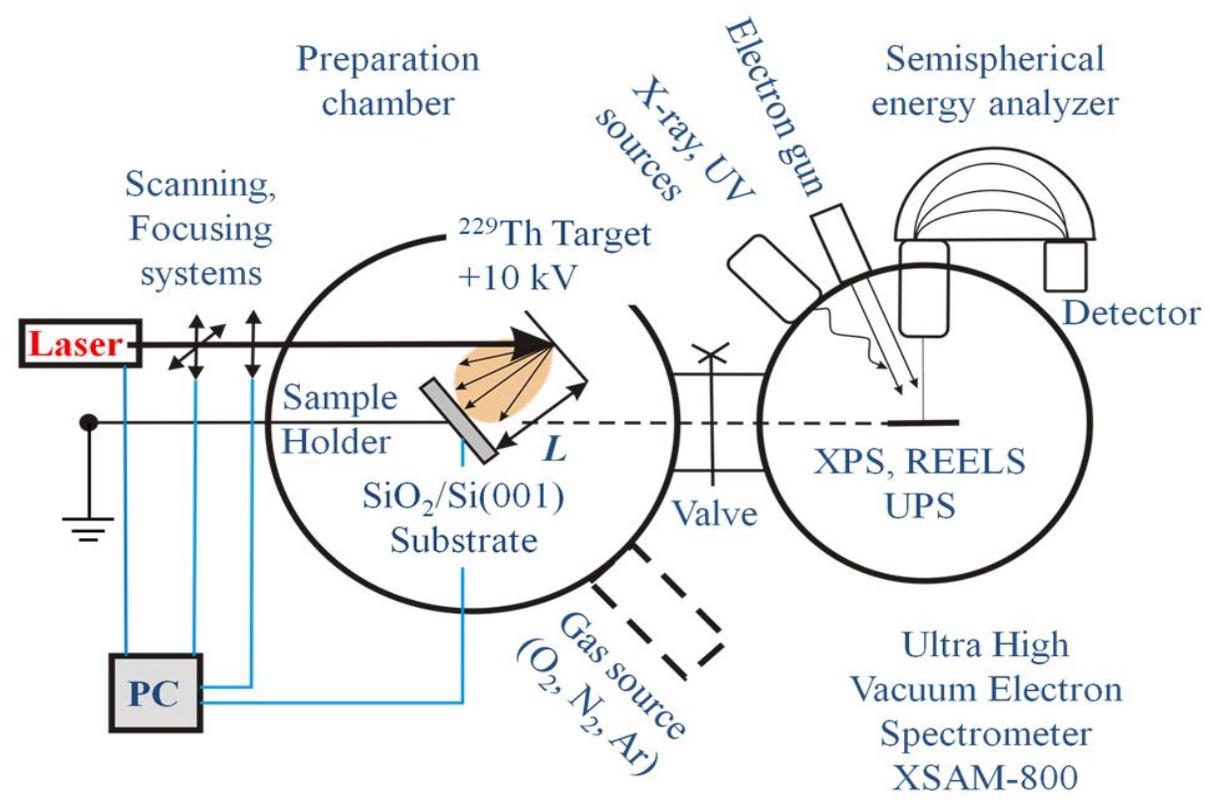
The wide-gap (E<sub>gap</sub> ≈ 9.0 eV) dielectric crystal doped with <sup>229m</sup>Th<sup>n+</sup>

## Detection system for a single-photon signal in the vacuum ultraviolet range. Conducting spectral analysis



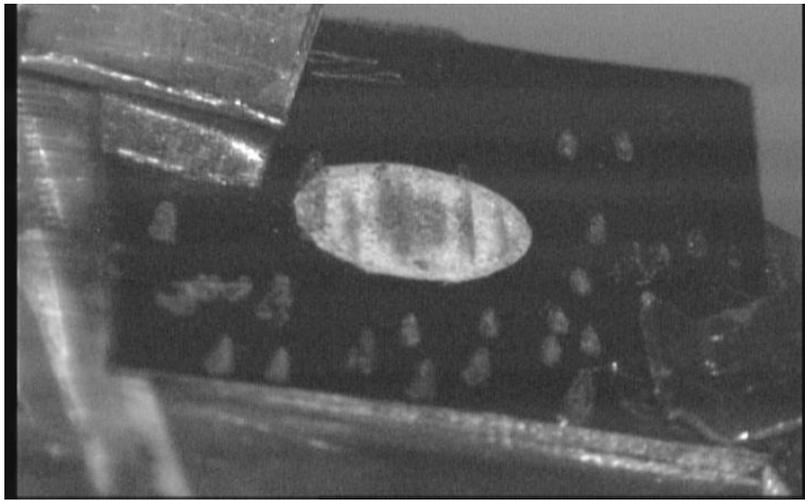
Schematic of the system for analyzing the spectral characteristics of secondary electrons, the emission of which is recorded during the decay of excited thorium-229 nuclei implanted in a thin-film silicon oxide matrix. The silicon wafer acts as a photocathode.

# ELECTRONIC SPECTROMETER NRNU MEPhI

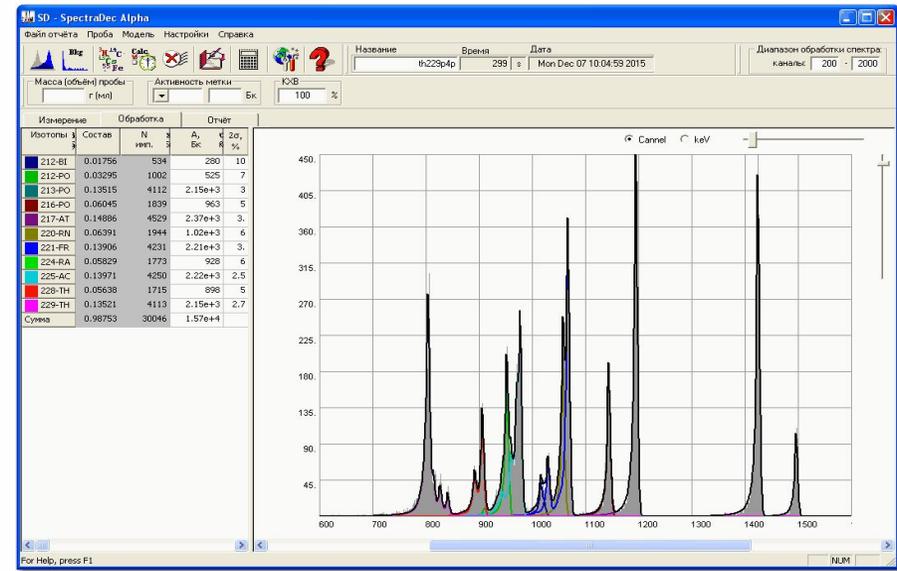


The schematic of the device and the appearance of the UHV complex for pulsed laser deposition and in situ studies of the electronic structure of the surface, ultrathin layers by the methods of XPS AES, UPS, and REELS, created in NRNU MEPhI based on the XSAM-800 Kratos electronic spectrometer.

# Target 229Th

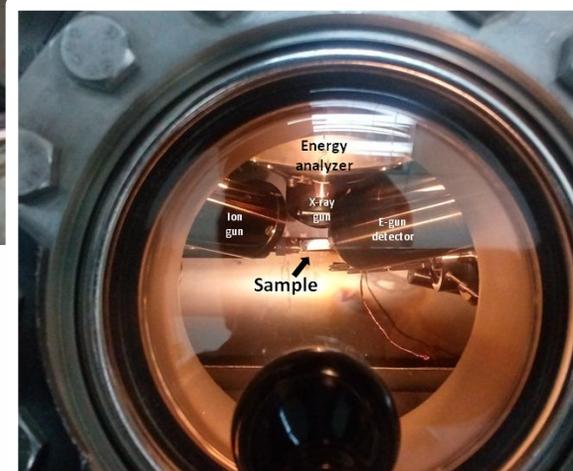
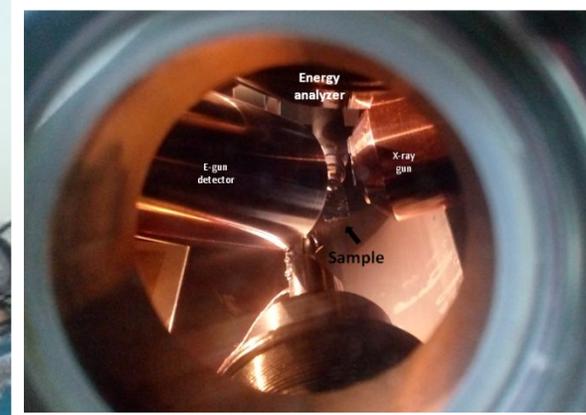
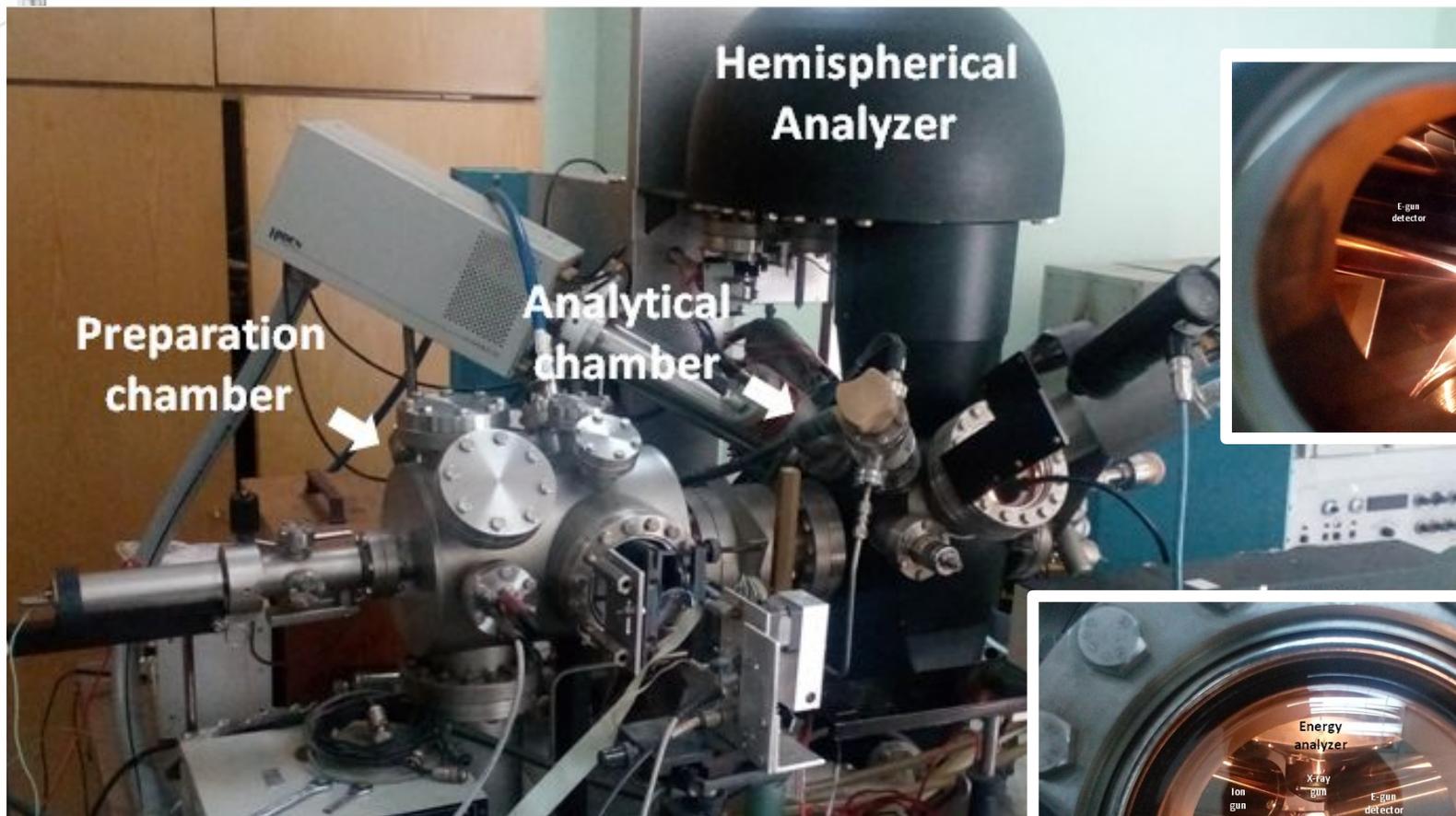


# α-spectrum



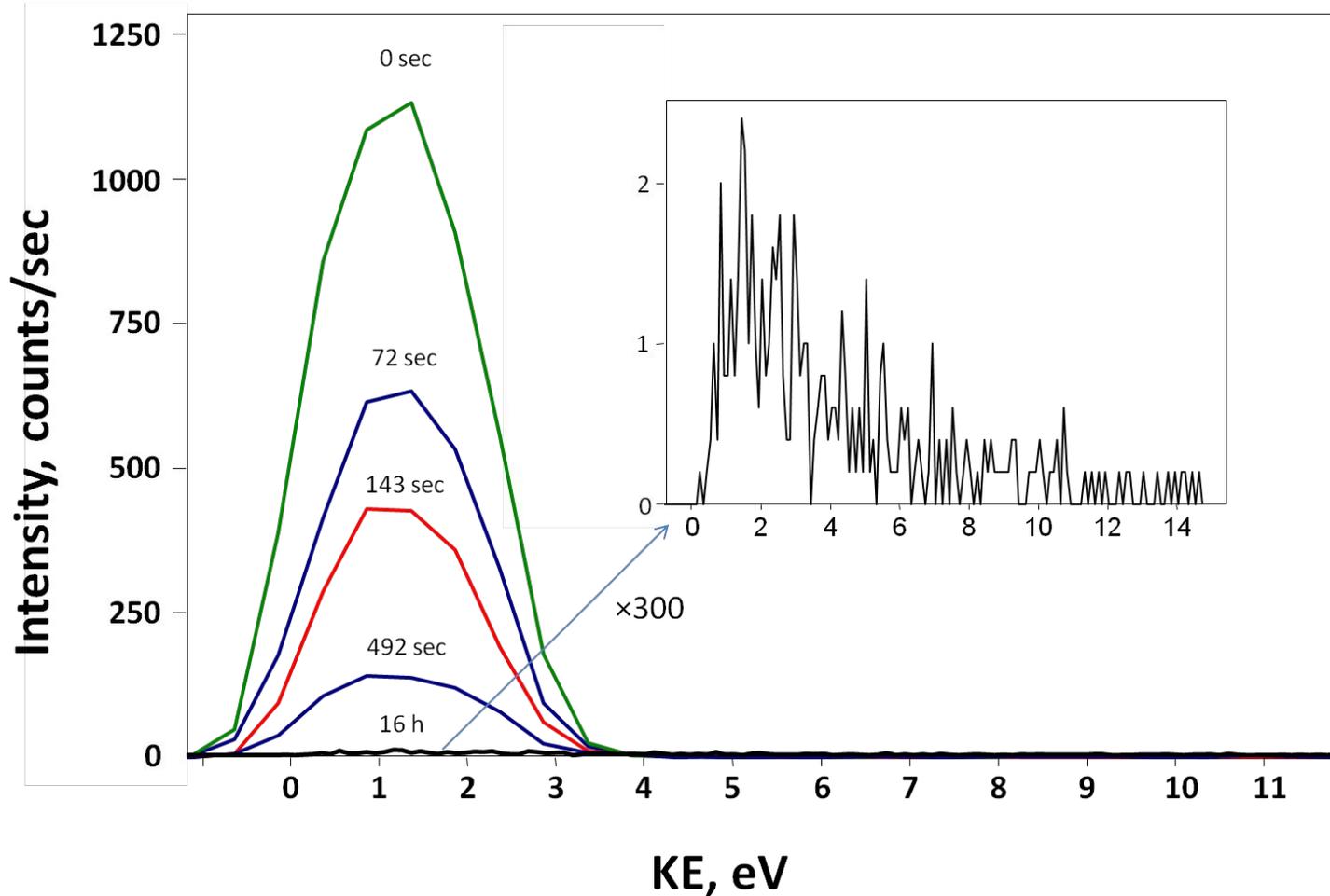
Th/SiO2/Si(001)  
A=100 kBq  
232Th/ 229Th=13.6

Isotope	Number of atoms	Atomic mass		Mass Portion, %
Th-228	7.81E+10	228	3.4259E+08	0.01092
Ra-224	4.12E+08	224	1.8388E+06	0.00005862
Rn-220	7.24E+04	220	3.2923E+02	0.00000001049
Po-216	1.89E+02	216	8.7454E-01	0.000000002788
Pb-212	4.99E+07	212	2.3552E+05	0.000007508
Bi-212	4.74E+06	212	2.2340E+04	0.000007121
Po-212	2.50E-04	212	1.1778E-06	0.000000000000003755
Th-229	7.18E+14	229	3.1367E+12	99.98806
Ra-225	4.00E+09	225	1.7756E+07	0.0005660
Ac-225	2.68E+09	225	1.1916E+07	0.0003798
Fr-221	9.12E+05	221	4.1281E+03	0.0000001316
At-217	1.00E+02	217	4.6129E-01	0.0000000001470
Bi-213	8.49E+06	213	3.9845E+04	0.000001270
Po-213	1.30E-02	213	6.1033E-05	0.000000000000001946
Tl-209	8.56E+03	209	4.0957E+01	0.00000001306
Pb-209	3.64E+07	209	1.7402E+05	0.000005547
			3.1371E+12	



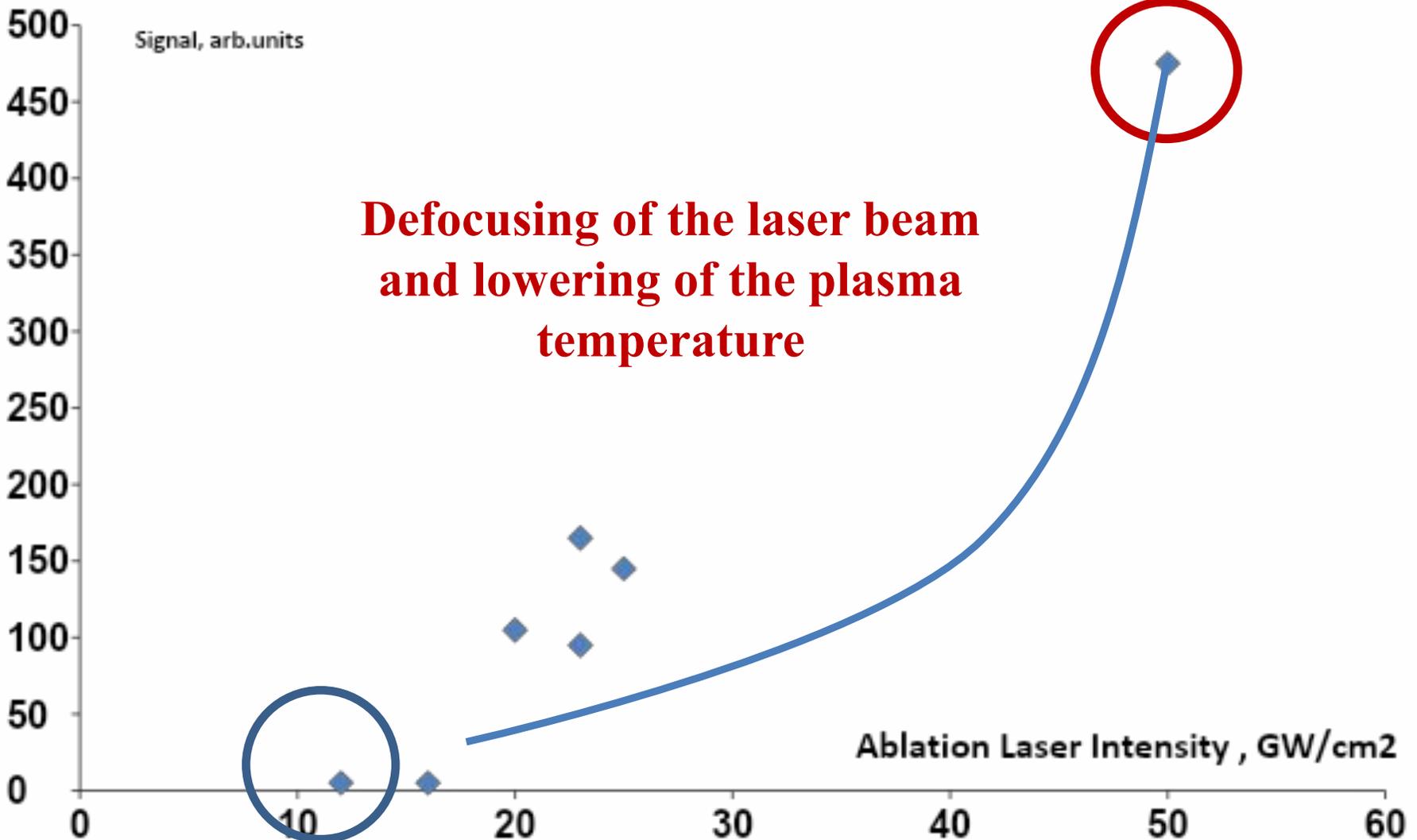
**SAMPLE WITH THORIUM-229 AFTER  
IMPLANTATION IN THE ELECTRONIC  
ENERGY ANALYZER CHAMBER**

## SIGNAL DETECTION!

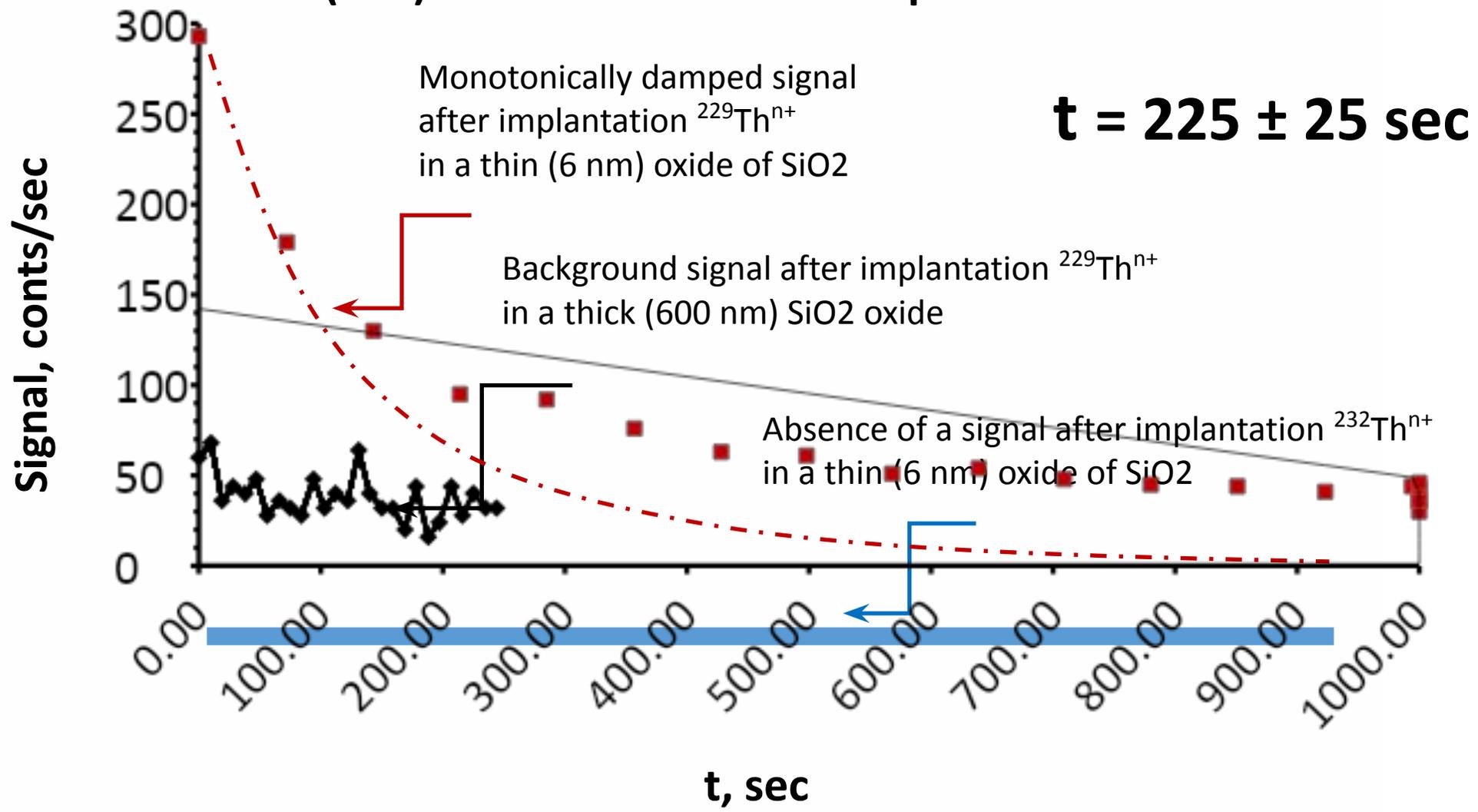


Energy spectra of electrons, the emission of which is recorded after laser implantation of thorium-229 nuclei. The inset shows an enlarged image of the radioactive background, measured 16 hours after implantation. The intensity of the background corresponds to the number of nuclei  $^{229}\text{Th} \sim 10^{12}$

## Decreasing of the laser ablation intensity



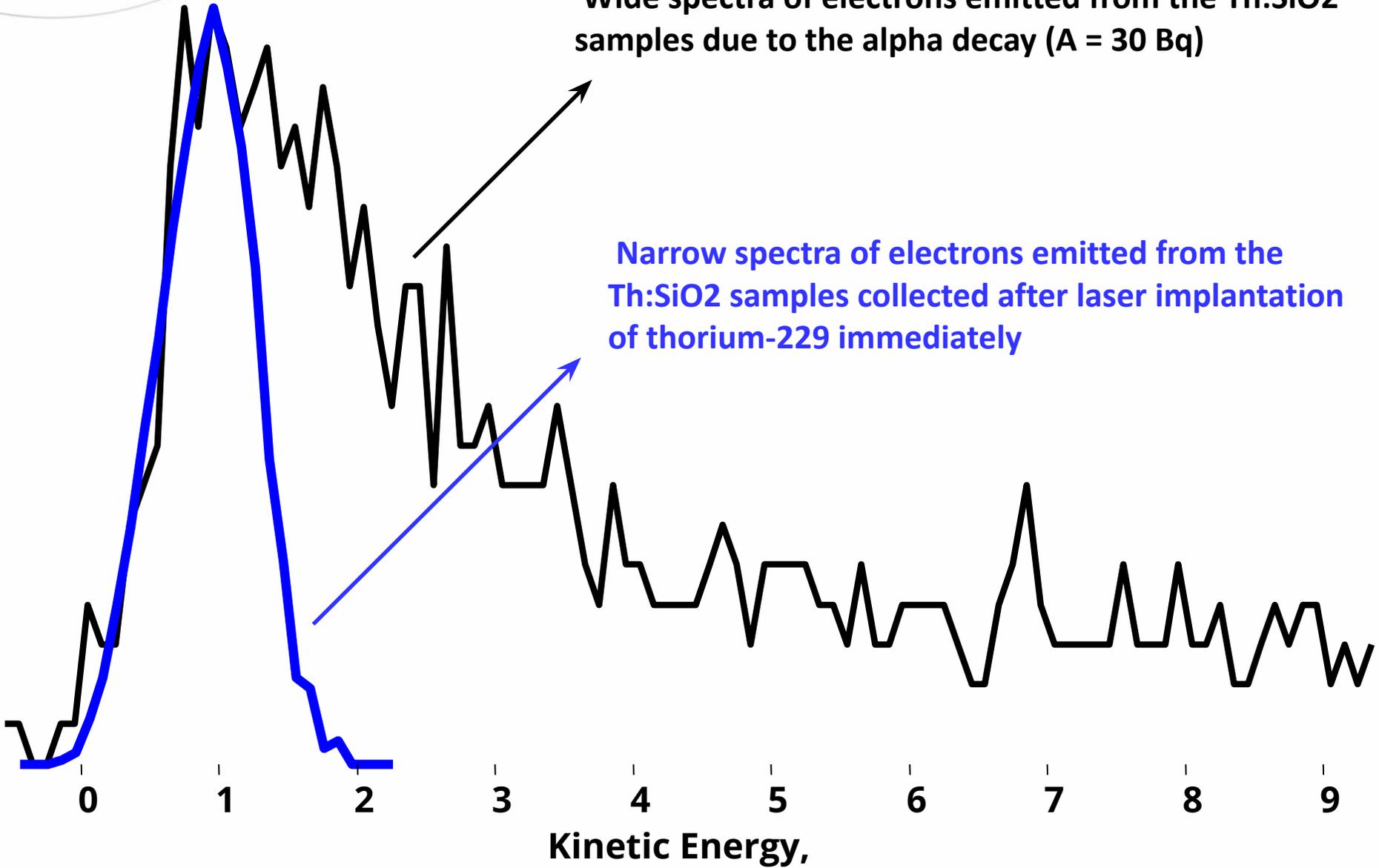
# The decay of a long-lived state in the near-surface region of the SiO<sub>2</sub> / Si (001) substrate after laser implantation of thorium-229



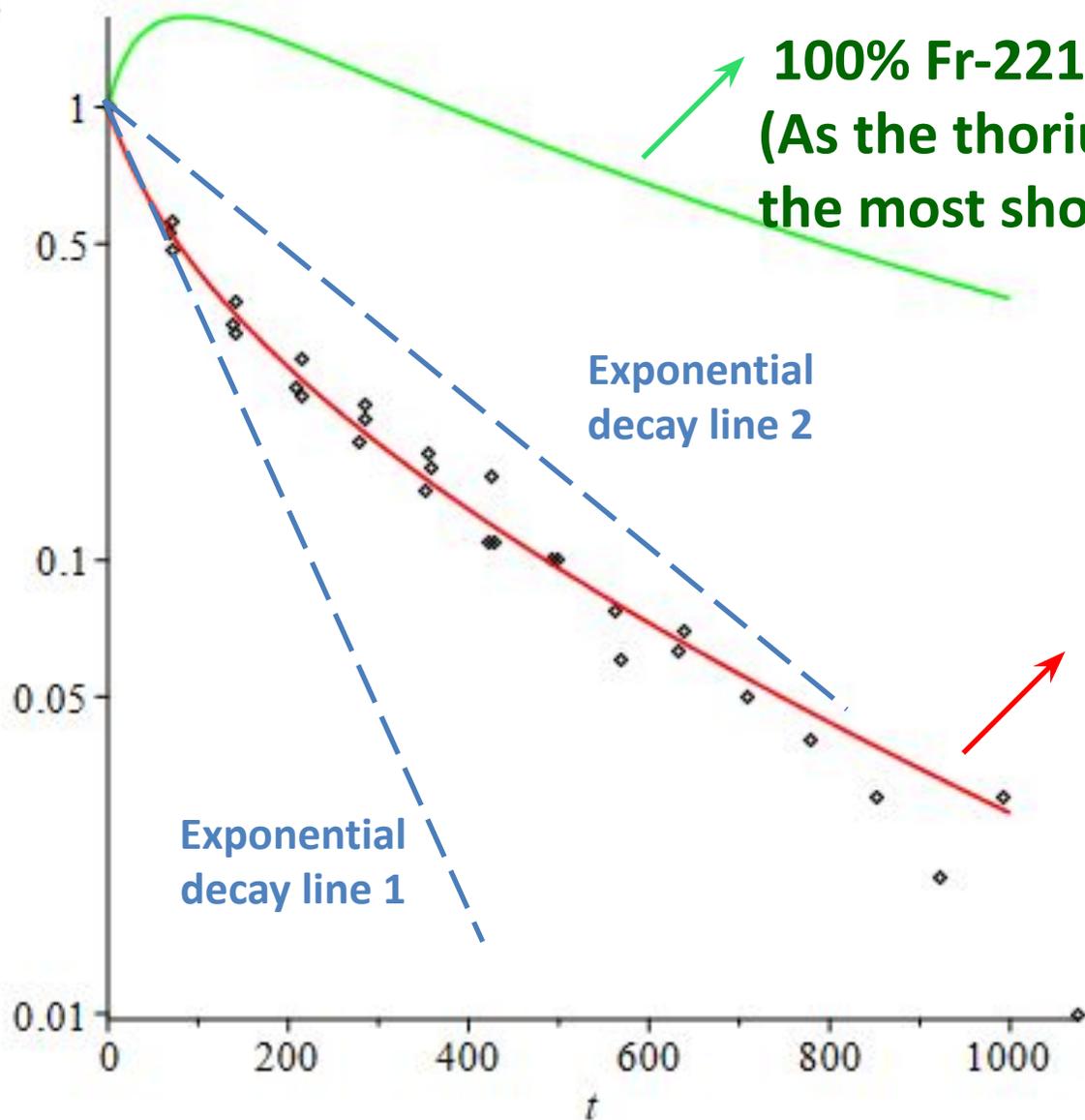
# Comparison of Spectra

Wide spectra of electrons emitted from the Th:SiO<sub>2</sub> samples due to the alpha decay (A = 30 Bq)

Narrow spectra of electrons emitted from the Th:SiO<sub>2</sub> samples collected after laser implantation of thorium-229 immediately



# Decreasing of the laser ablation intensity



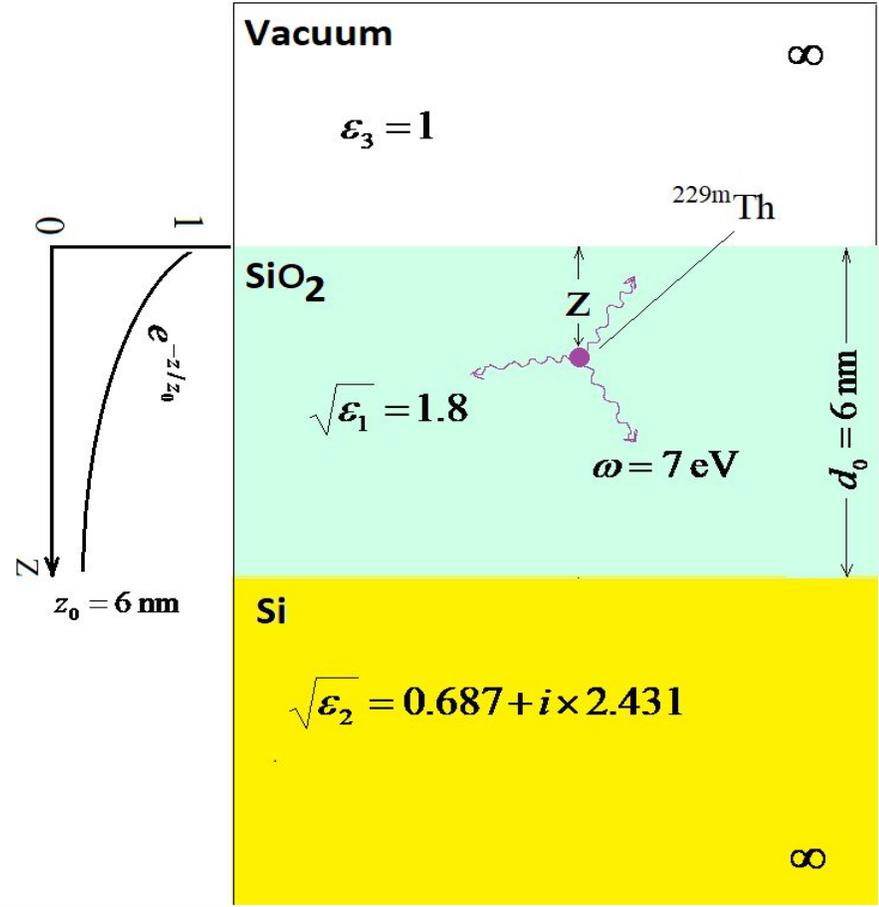
100% Fr-221 decay shifted on 30 seconds  
(As the thorium-229 decay daughter with  
the most shorten half-time)

The decay of a long-lived  
state in the near-surface  
region of the SiO<sub>2</sub> /Si (001)  
substrate after laser  
implantation of thorium-229

Not exponential decay!

# The Purcell Effect

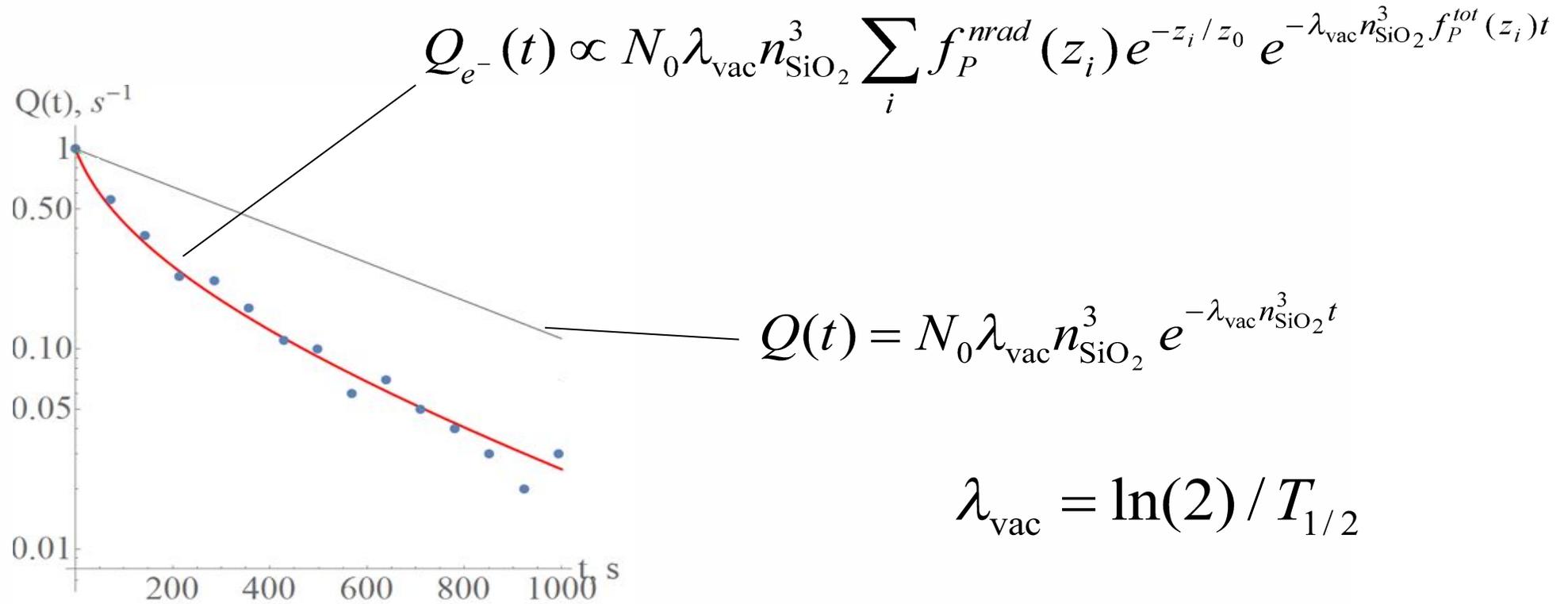
An increase or decrease in the probability of spontaneous emission in the presence of boundaries (for example, in a resonator) as compared with the speed of spontaneous emission in a space without boundaries

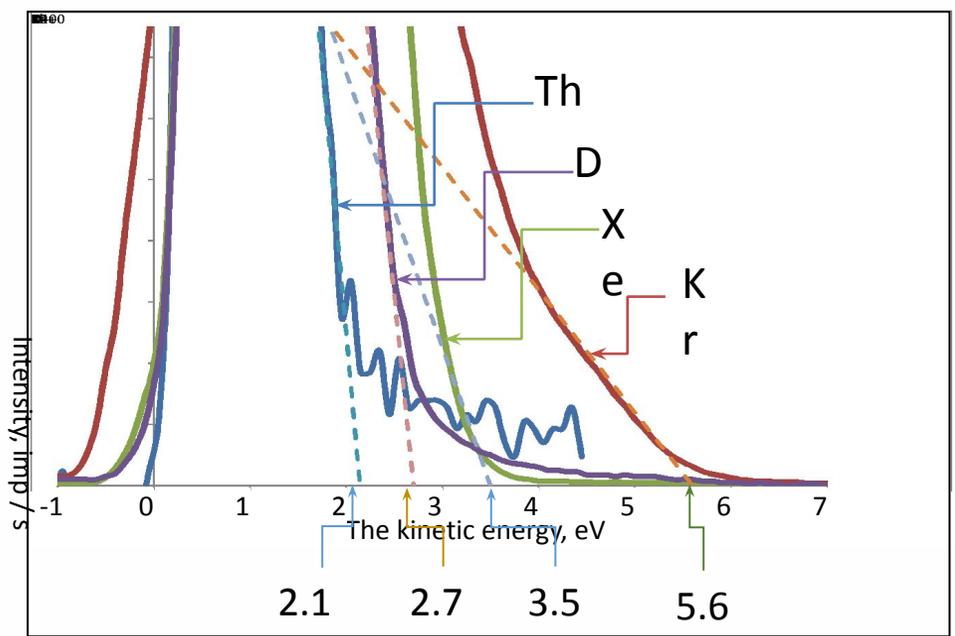
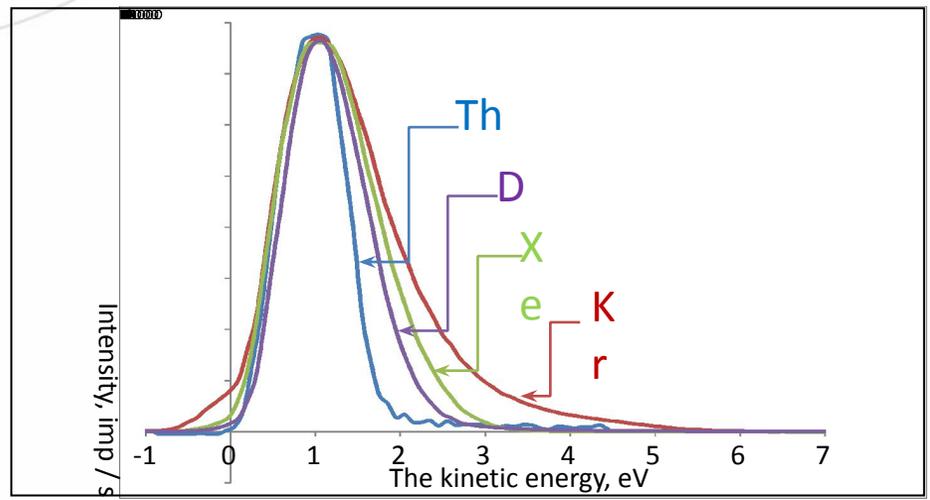


Sample

# Half-life

The experimental data are described by a single free parameter - the half-life of an isomeric state in a bare nucleus in a vacuum  $T_{1/2} = 1850$  s





## Calibration of photoelectron spectra when working with ultraviolet sources

	$h\nu,$	$KE_{max}$
D	7.	x 2.
X	8.	3.
R	10.	5.
r	6.	2.

$$KE_{max} = h\nu - WF_{Si}$$

$$h\nu_{Th} = 7.1 \text{ eV}$$

**The initial analysis of the electron spectra and band structure shows that the detected signal is due to the decay of isomeric thorium-229 nuclei**

**The cross-check shows that the signal is not recorded when:**

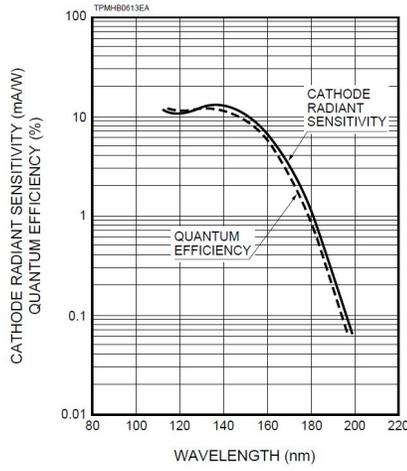
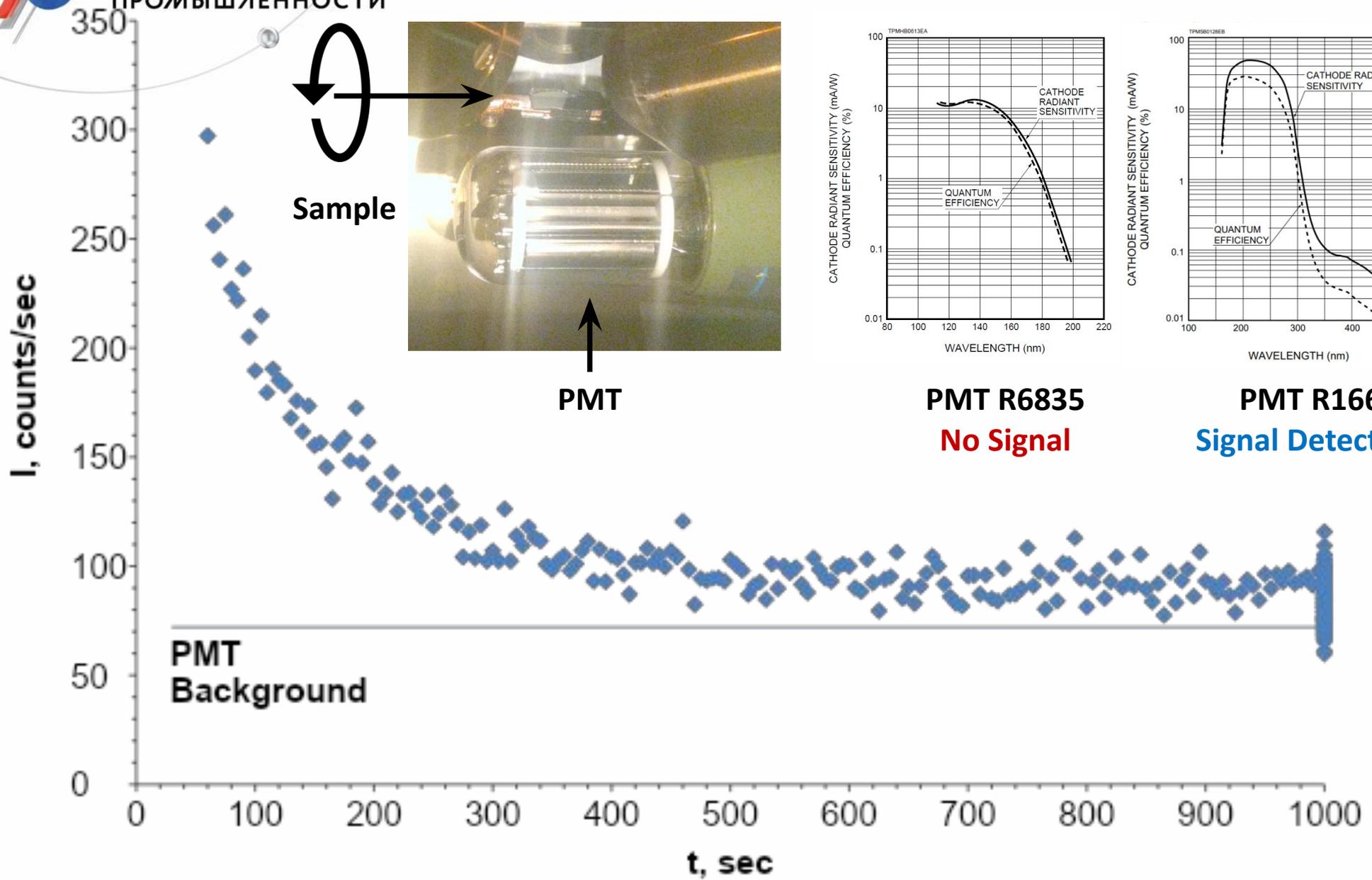
- Defocusing of the laser beam and lowering of the plasma temperature
- Implantation of thorium-232 ions
- Implantation of thorium-229 ions in pure silicon
- Implantation of thorium-229 ions in thick oxide
- Implantation of graphite, silicon, silicon oxide

**The transition energy: 7.1 (+0.1/- 0.2) eV**

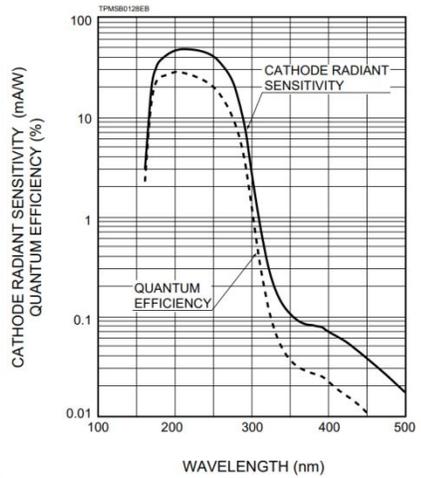
**Half-life: 1850 +/- 150 sec**

**NECESSARY UPDATE BY METHODS OF PRECISION OPTIC  
SPECTROSCOPY**

# Preliminary Study of Photons



**PMT R6835**  
**No Signal**



**PMT R166**  
**Signal Detected!**

