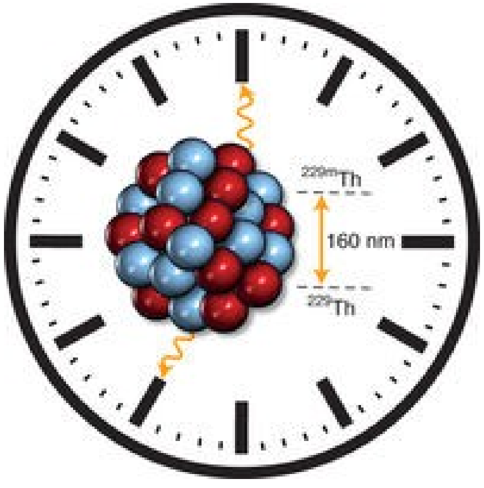
Что известно об изомерном состоянии тория ^{229m}Th из атомных экспериментов?

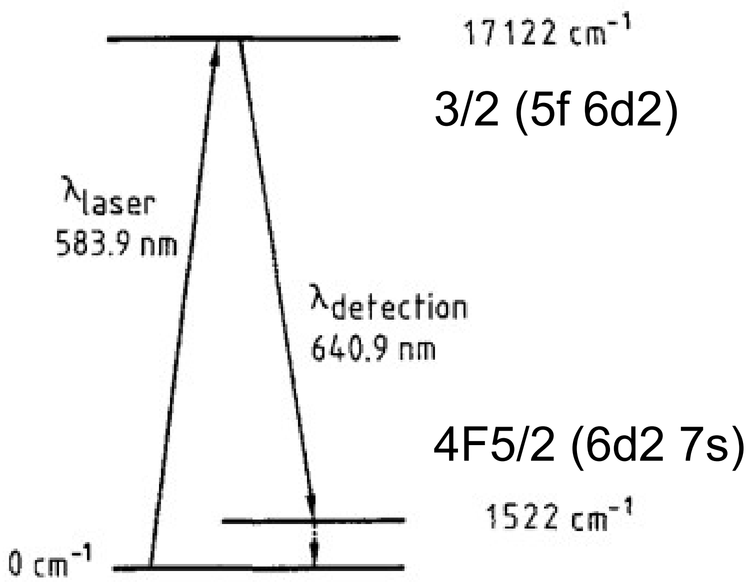


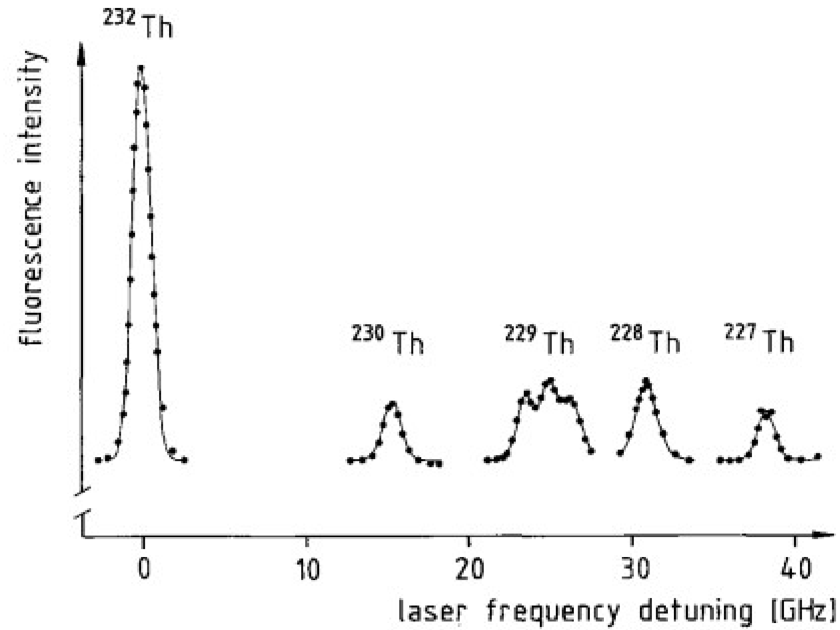
Семинар ОФВЭ-ОТФ
14 июня 2018

Z. Phys. A – Atomic Nuclei 334, 103–108 (1989)

Nuclear Radii of Thorium Isotopes from Laser Spectroscopy of Stored Ions*

W. Kälber[1], J. Rink[1], K. Bekk[1], W. Faubel[2], S. Göring[1], G. Meisel[1], H. Rebel[1], and R.C. Thompson[3]





(a)

(a) Isotope structure of the 583.9 nm transition in Th II ion.

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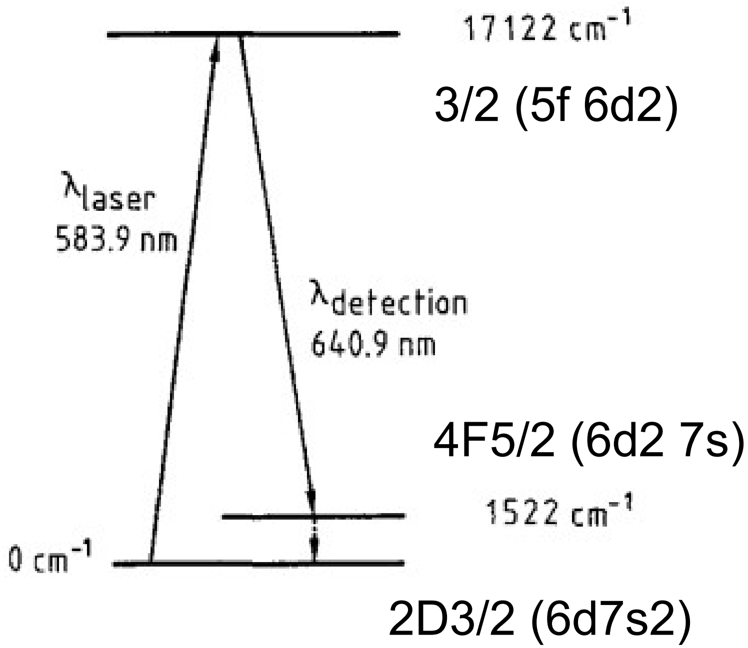
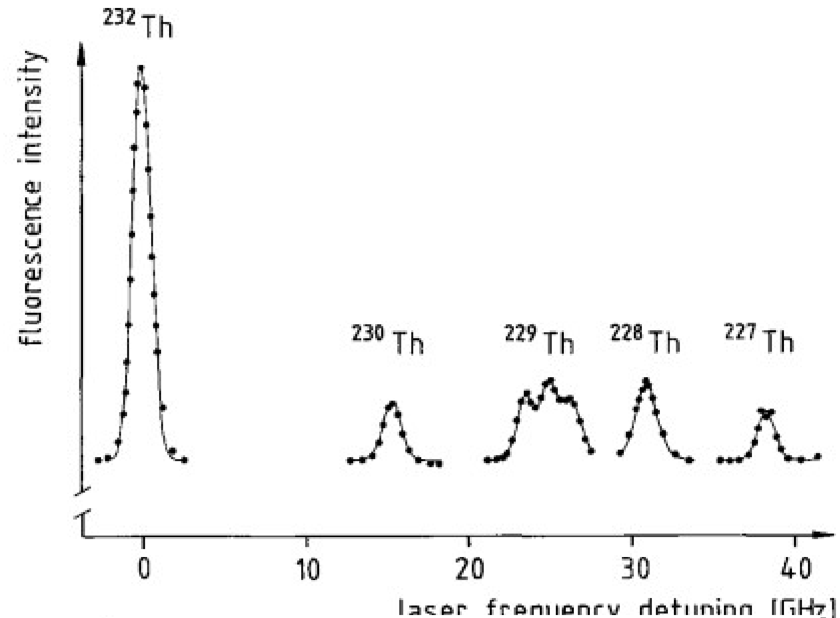
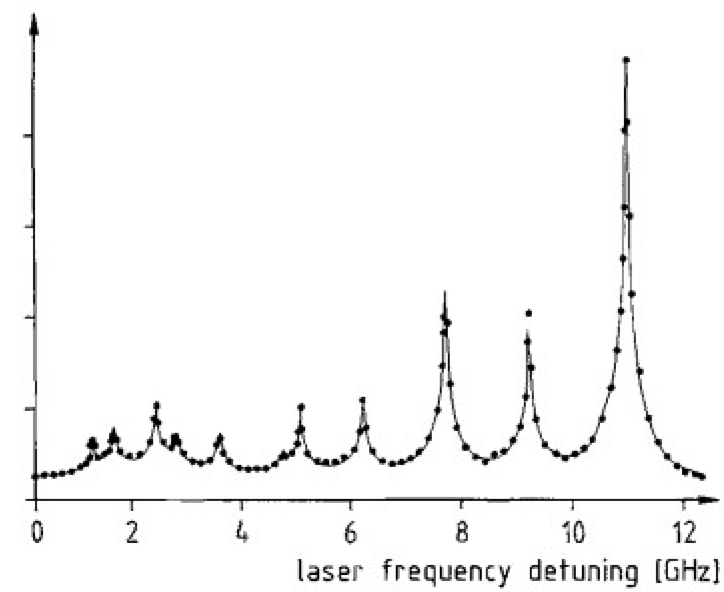




(a)



(b)

(a) Isotope structure of the 583.9 nm transition in Th II ion.

(b) High resolution hyperfine structure for ^{229}Th ($I^{\pi}=5/2^{+}$)

Direct detection of the ^{229}Th nuclear clock transition

L von der Wense, B Seiferle, M Laatiaoui, J B Neumayr, H Maier, H Wirth, C Mokry, J Runke, K Eberhardt, C E Düllmann, N G Trautmann & P G Thirolf. Nature, **533**, 47 (2016)

Today's most precise time and frequency measurements are performed with optical atomic clocks. However, it has been proposed that they could potentially be outperformed by a nuclear clock, which employs a nuclear transition instead of the atomic shell transitions used so far. By today there is only one nuclear state known which could serve for a nuclear clock using currently available technology, which is the isomeric first excited state in ^{229}Th. **Here we report the direct detection of this nuclear state, which is a further confirmation of the isomer's existence and lays the foundation for precise studies of the isomer's decay parameters. Based on this direct detection the isomeric energy is constrained to lie between 6.3 and 18.3 eV, and the half-life is found to be longer than 60 s for $^{229m}Th^{2+}$.** More precise determinations appear in reach and will pave the way for the development of a nuclear frequency standard.

IP(Th I) = 6.3 eV < E(^{229m}Th)
IP(Th III) = 18.3 eV > E(^{229m}Th)

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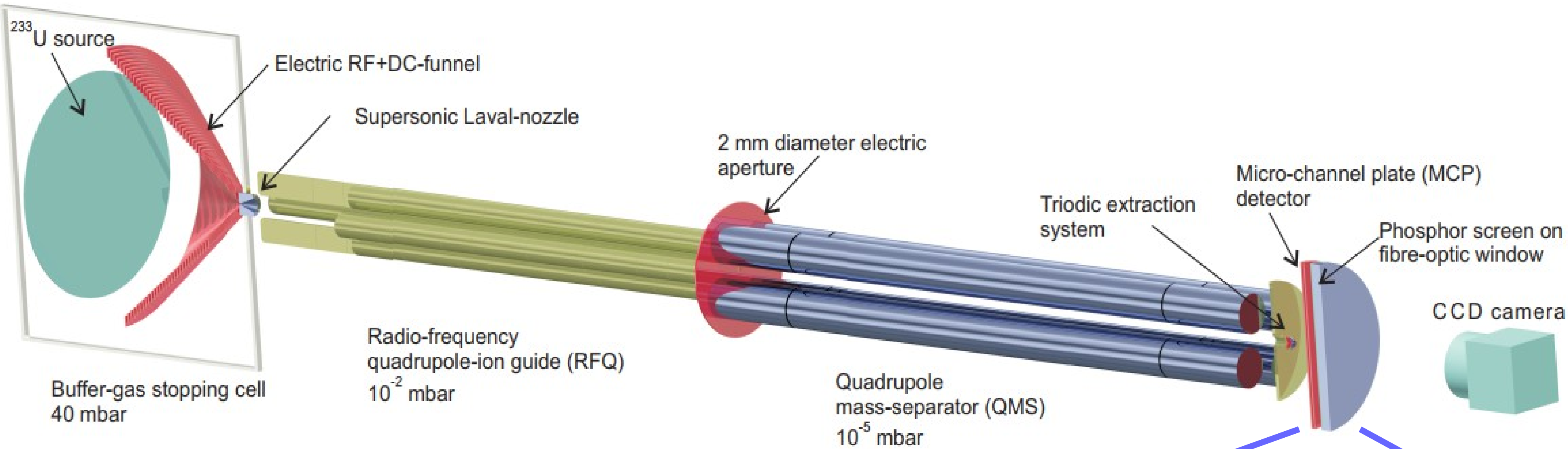
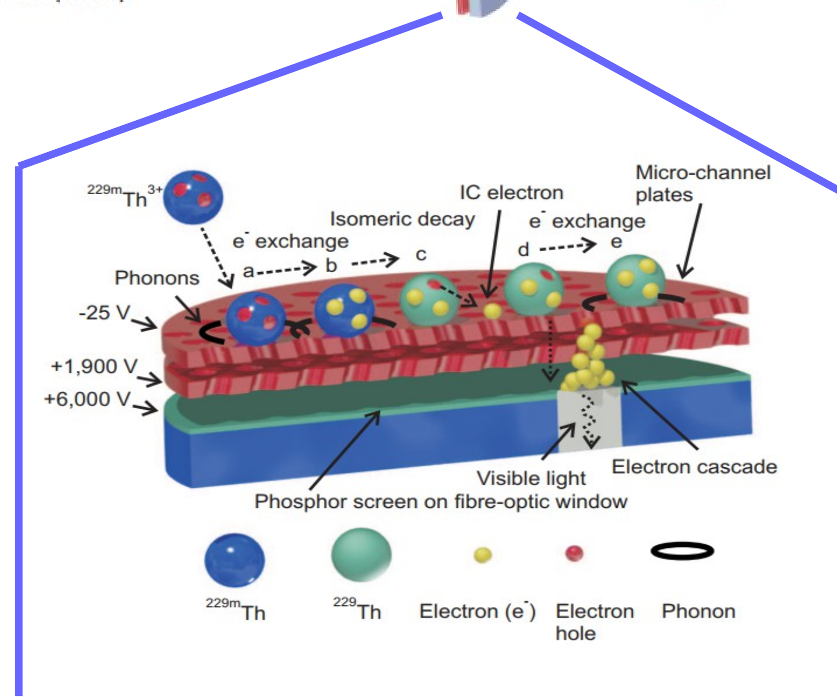


IP(Th I) = 6.3 eV < E(^{229m}Th)

IP(Th III) = 18.3 eV > E(^{229m}Th)

^{233}U → $^{229(m)}$Th + He

(recoil energy 84 keV)



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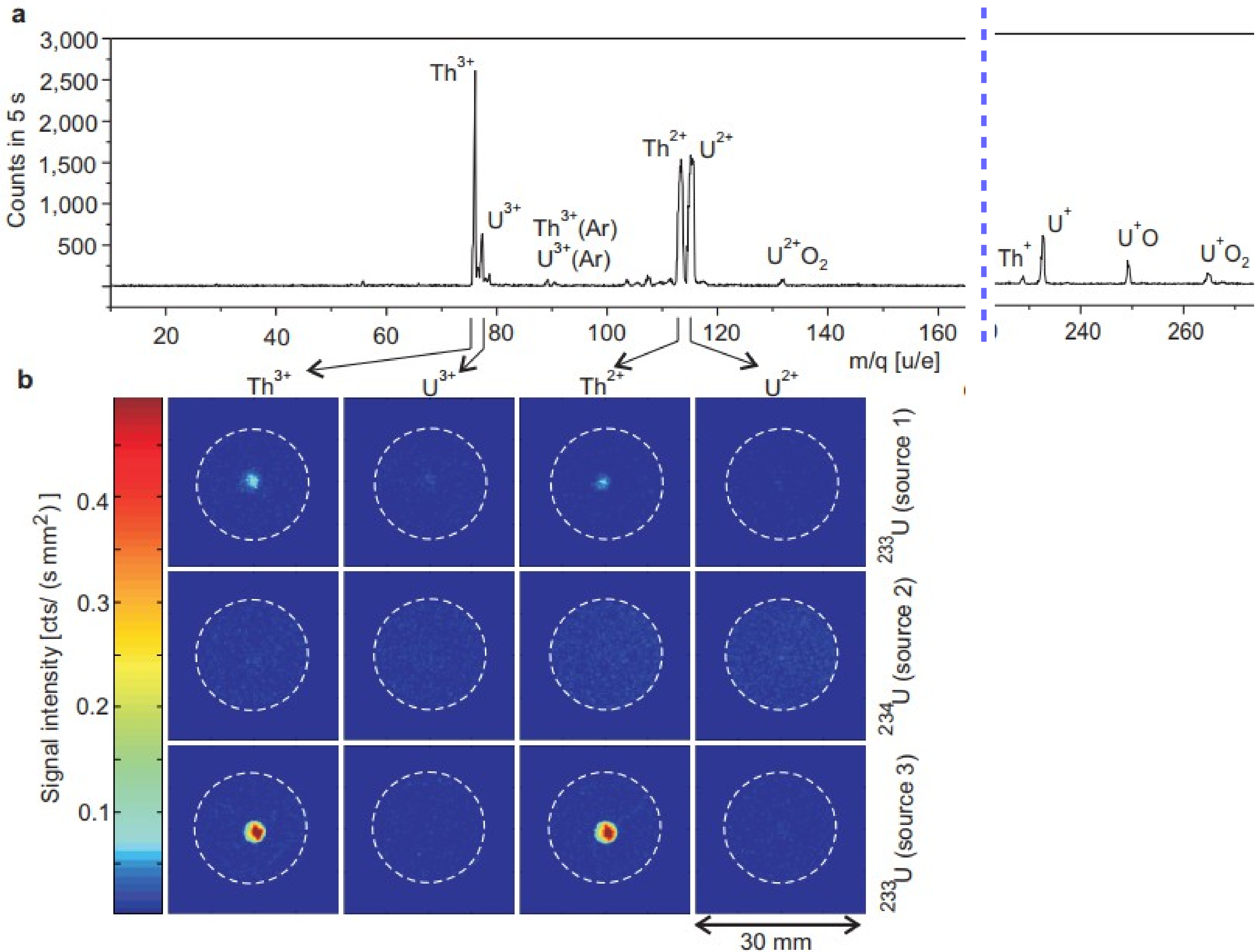

Laser spectroscopic characterization of the nuclear clock isomer ^{229m}Th

J Thielking, M V Okhapkin, P Głowacki, D M Meier, L von der Wense, B Seiferle, C E Düllmann, P G Thirolf, & E Peik. Nature, **556**, 321 (2018)

The isotope ^{229}Th is the only nucleus known to possess an excited state ^{229m}Th in the energy range of a few electron volts, a transition energy typical for electrons in the valence shell of atoms, but about four orders of magnitude lower than common nuclear excitation energies. A number of applications of this unique nuclear system, which is accessible by optical methods, have been proposed. Most promising among them appears a highly precise nuclear clock that outperforms existing atomic timekeepers. **Here we present the laser spectroscopic investigation of the hyperfine structure of $^{229m}Th^{2+}$, yielding values of fundamental nuclear properties, namely the magnetic dipole and electric quadrupole moments as well as the nuclear charge radius.** After the recent direct detection of this long-searched-for isomer, our results now provide detailed insight into its nuclear structure and present a method for its non-destructive optical detection, an important step towards the development of a nuclear clock

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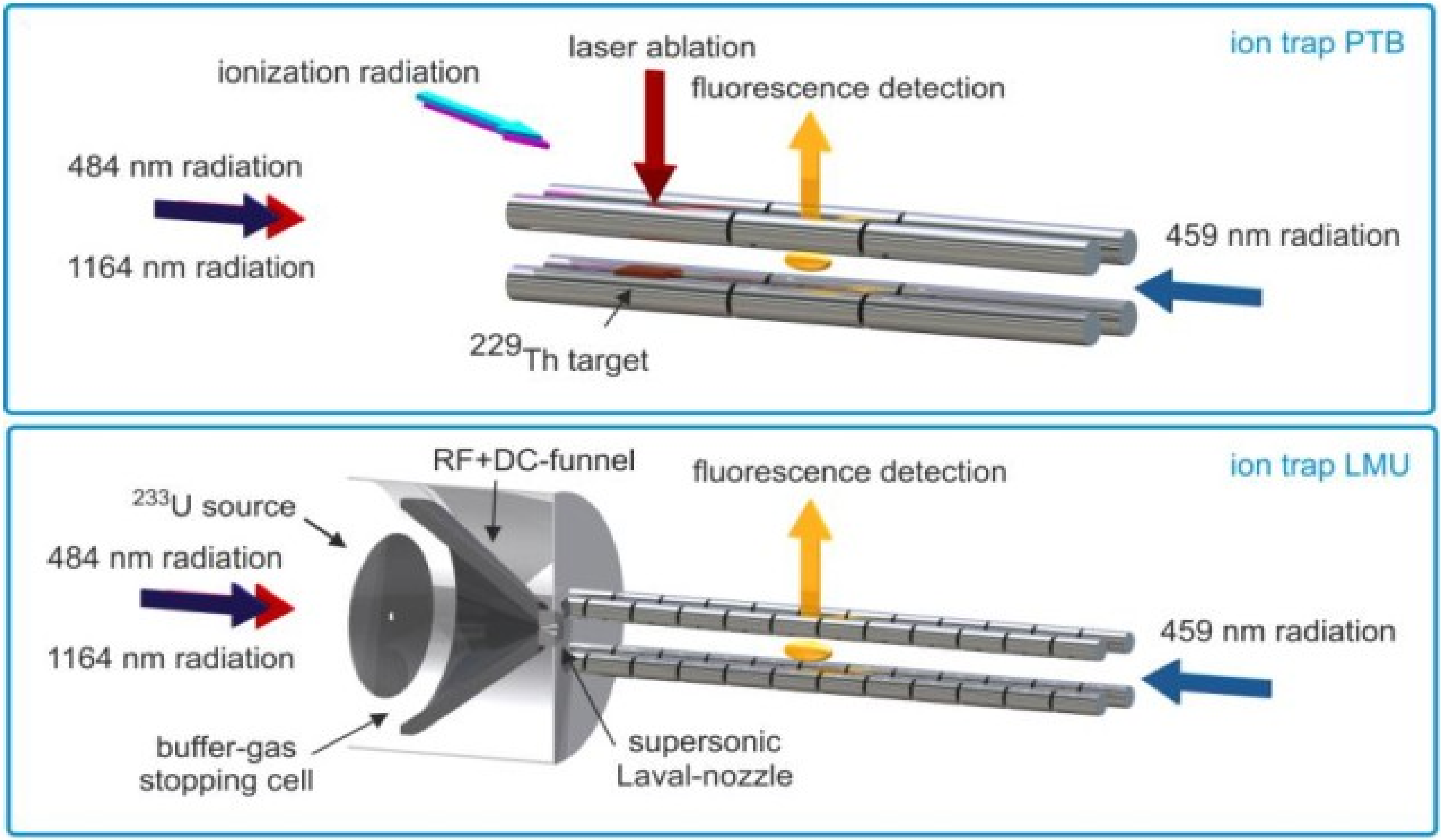

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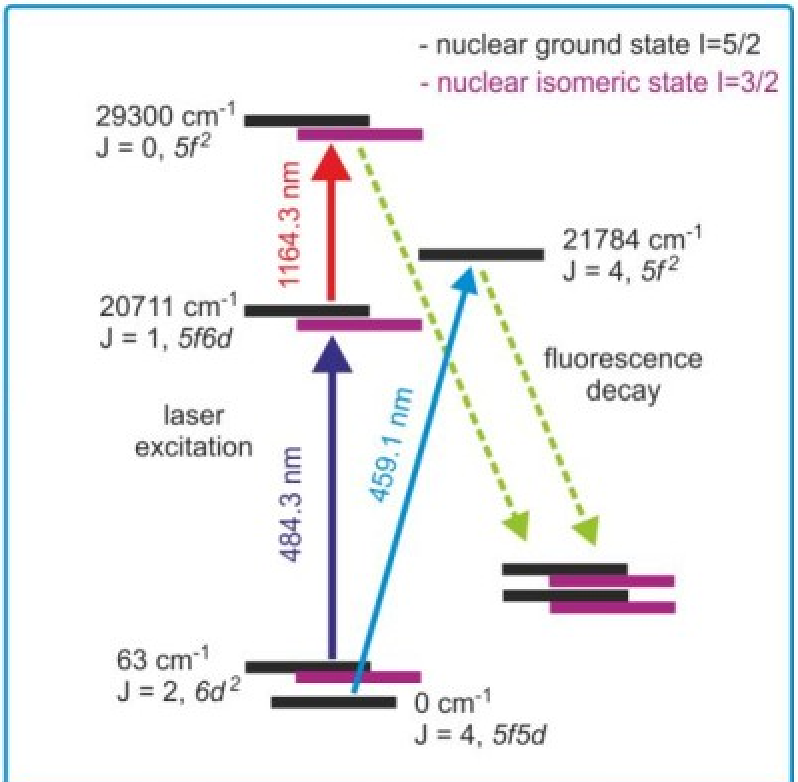
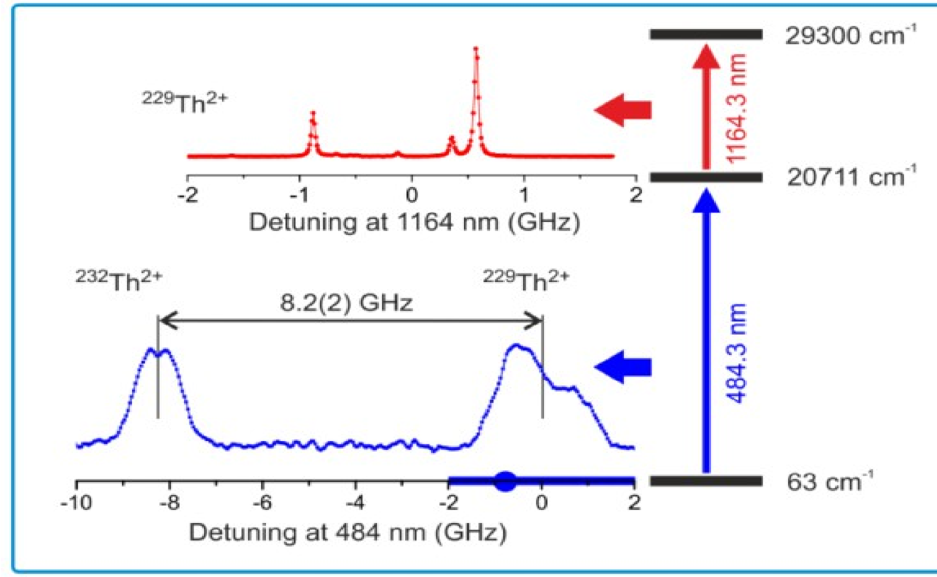
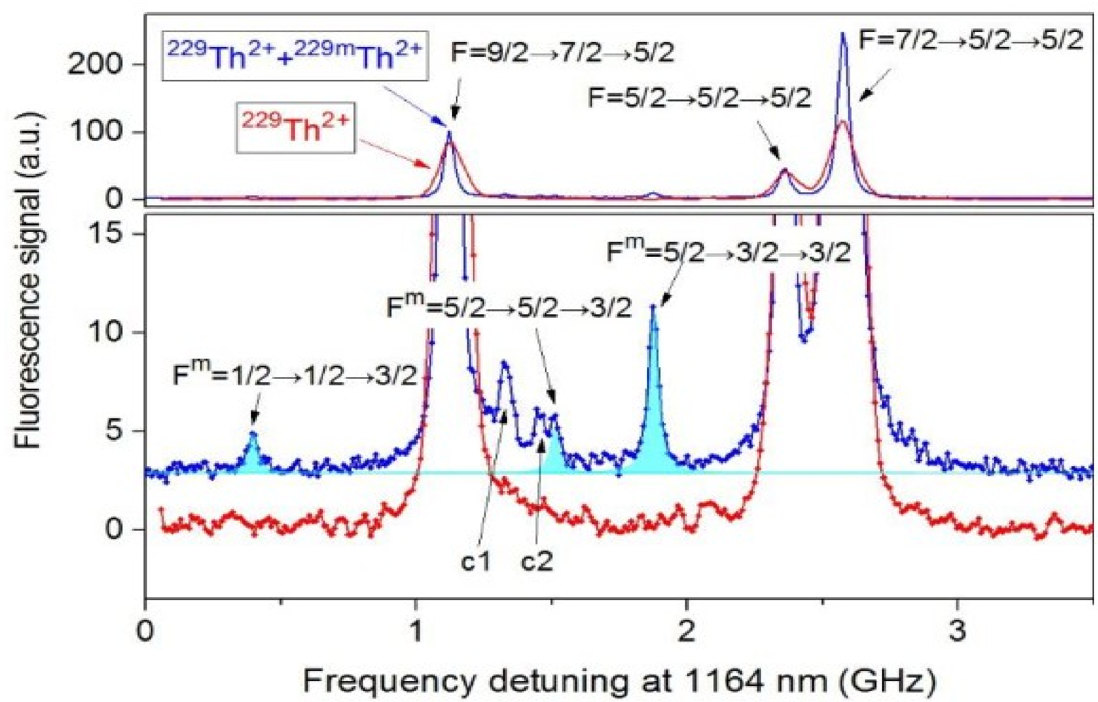
Спектр Th^{2+}







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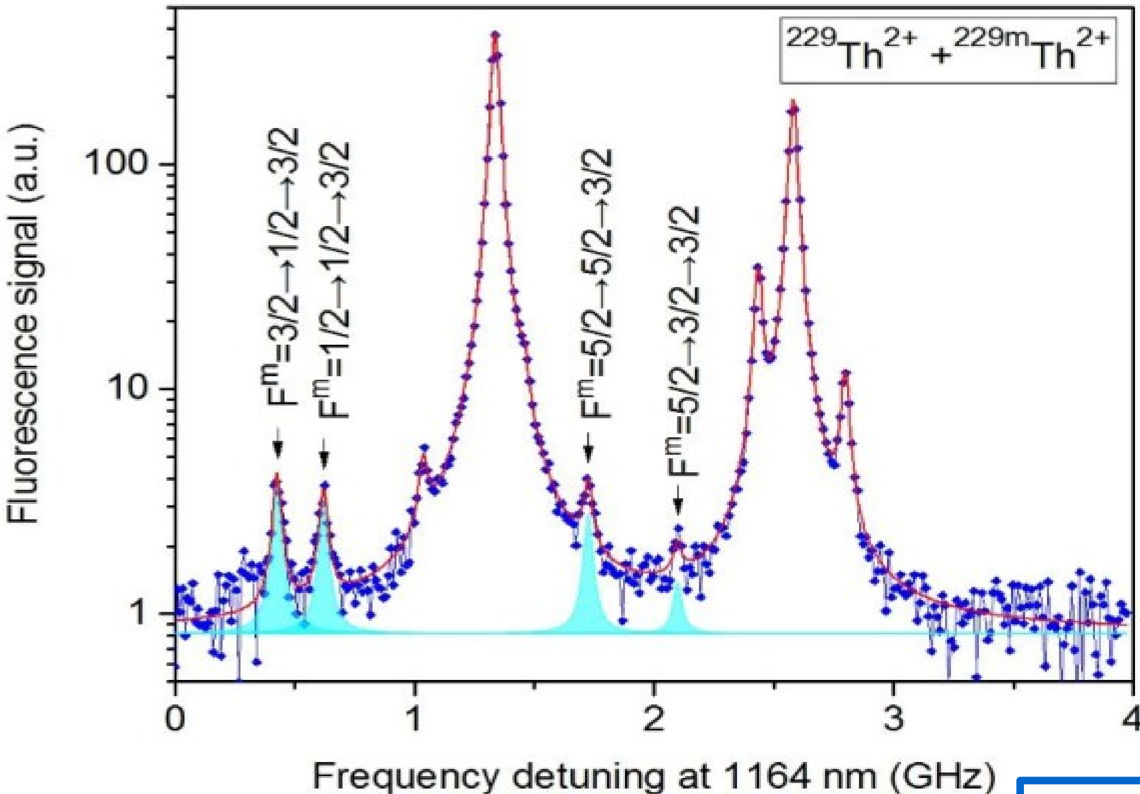

Level [cm^{-1}]	Nuclear ground state		Nuclear isomeric state	
	A [MHz]	B [MHz]	A^m [MHz]	B^m [MHz]
63	151(8)	73(27)	-263(29)	53(65)
20711	88(4)	897(14)	-151(22)	498(15)

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Свойства изомерного состояния

A^m/A = -1.73(25) ==> $\mu^m = \mu\,(A^m I^m)/(AI)$

μ^m/μ = -1.04(15)

μ = 0.360(7) μ_N [СТС $^{229}Th^{3+}$]

μ^m = -0.37(6) μ_N

$B^m/B = Q^m/Q$; $Q = Q_0\,(3K^2-I(I+1))/((I+1)(2I+3))$

Q^m/Q = 0.555(19)

Q = 3.15(3) eb [Q_0 = 8.82(8) eb]

Q^m = 1.74(6) eb [Q_0^m = 8.7(3) eb]

Зарядовый радиус:

Изотоп. сдвиг между изотопами 229 и 232: 8.2(2) ГГц
Изотоп. сдвиг между изомерами 229m и 229: 0.29(3) ГГц

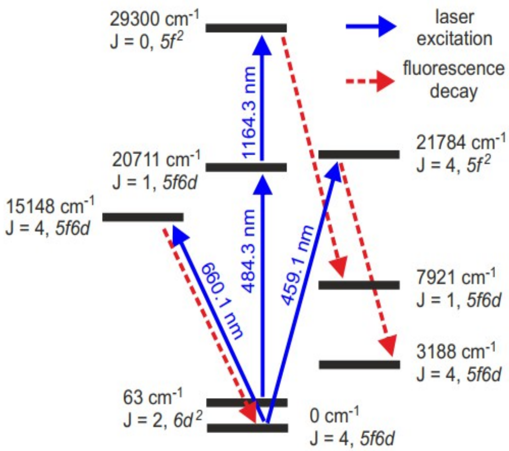
$$\langle r^2\rangle^{232} - \langle r^2\rangle^{229} = 0.33(5)\ \text{fm}^2\ \text{(ref. 29), with}\ \langle r^2\rangle^{229} \approx (5.7\ \text{fm})^2$$

$$\langle r^2\rangle^{229\text{m}} - \langle r^2\rangle^{229} = 0.012(2)\ \text{fm}^2.$$

Hyperfine interaction with the ^{229}Th nucleus and its low lying isomeric state

Robert A. Müller,[1,2,*] Anna V. Maiorova,[3] Stephan Fritzsche,[4,5] Andrey V. Volotka,[4] Randolf Beerwerth,[4,5] Przemyslaw Glowacki,[1,†] Johannes Thielking,[1] David-Marcel Meier,[1] Maksim Okhapkin,[1] Ekkehard Peik,[1] and Andrey Surzhykov[1,2]

[arXiv:1801.10470]



energy level			A[MHz]			B[MHz]		
configuration	J^Π	energy [cm]$^{-1}$	CI+MBPT	MCDF	exp.	CI+MBPT	MCDF	exp.
$[\mathrm{Rn}] + 5f6d$	4^-	0	64(17)	81(4)	–	3287(630)	3008(260)	–
$[\mathrm{Rn}] + 6d^2$	2^+	63	143(47)	162(8)	151(8)	68(23)	71(7)	73(27)
$[\mathrm{Rn}] + 5f^2$	4^+	15148	38(3)	72(3)	–	1221(390)	1910(200)	–
$[\mathrm{Rn}] + 5f6d$	1^-	20711	109(36)	90(4)	88(5)	839(220)	689(110)	901(18)
$[\mathrm{Rn}] + 5f^2$	4^+	21784	8(36)	26(2)	–	65(21)	39(45)	–

energy level			A/μ_{iso} [MHz/μ_N]		A [MHz]	μ_{iso} [μ_N]		B/Q_{iso} [MHz/eb]		B [MHz]	Q_{iso} [eb]	
configuration	J^Π	energy [cm^{-1}]	(a)	(b)	exp.	(a)	(b)	(a)	(b)	exp.	(a)	(b)
$[\mathrm{Rn}] + 6d^2$	2^+	63	660	750	−263(29)	−0.38	−0.35	22	23	53(65)	–	–
$[\mathrm{Rn}] + 5f6d$	1^-	20711	506	419	−151(22)	−0.30	−0.36	270	229	498(15)	1.84	2.25

Nuclear charge radii of ^{229}Th from isotope and isomer shifts

M. S. Safronova[1,2], S. G. Porsev[1,3], M. G. Kozlov[3,4], J. Thielking[5], M. V. Okhapkin[5], P. Głowacki[6], D. M. Meier[5], E. Peik[5]

[arXiv:1806.03525]

Ion	Energy Ref. [26].	Electronic configuration	Field shift				Specific mass shift			IS Expt.	$\delta\langle r^2\rangle^{232,229}$
			$\partial E/\partial\lambda$ CI+MBPT	$\partial E/\partial\lambda$ CI+All	Diff.	$K_{\rm FS}$ CI+All	$\partial E/\partial\lambda$ CI+All	$K_{\rm SMS}$ CI+All	$\delta\nu_{\rm SMS}$ CI+All		
	cm^{-1}		a.u.	a.u.	%	GHz/fm^2	a.u.	GHz/amu	GHz	GHz	fm^2
Th^{2+}	63	$6d^2\ ^3F_2$	-0.000421	-0.000372	13%	-36.6	-1.79	-6440	0.364		
	20711	$5f6d\ ^1P_1$	-0.000667	-0.000647	3%	-63.6	-3.30	-11900	0.672		
	29300	$5f^2\ J=0$	-0.000805	-0.000854	6%	-84.1	-4.19	-15100	0.853		
Transitions		$6d^2-5f6d$	0.000247	0.000274	10%	27.0	1.52	5480	-0.309	8.2(2)	0.315(32)
		$5f6d-5f^2$	0.000138	0.000208	34%	20.4	0.88	3180	-0.180	6.2(3)	0.312(42)
Th^{2+}	0	$5f6d\ ^3H_4$	-0.0007129	-0.0006981	2%	-68.7	-3.34	-12000	0.680		
	15149	$5f^2\ ^3H_4$		-0.0009096		-89.5	-4.47	-16100	0.912		
	21784	$5f^2\ ^3F_4$	-0.0008133	-0.0008683	6%	-85.5	-4.31	-15550	0.878		
Transitions		$5f6d-5f^2\ ^3H_4$		0.0002115		20.8	1.14	4100	-0.232	6.8(2)	0.335(43)
		$5f6d-5f^2\ ^3F_4$	0.0001004	0.0001703	41%	16.8	0.97	3510	-0.198	5.2(2)	0.332(54)
Th^+	0	$6d7s^2\ ^2D_{3/2}$	0.000572	0.000555	3%	54.6	-2.24	-8090	0.457		
	17122	$5f6d^2\ J=3/2$	-0.000360	-0.000322	12%	-31.6	-3.69	-13300	0.751		
Transition		$6d7s^2-5f6d^2$	0.000932	0.000876	6%	86.2	1.45	5240	-0.296	25.01(9)	0.294(17)
Final											0.299(15)

$$\delta\langle r^2\rangle^{229m,229} = 0.0105(13)\ \text{fm}^2$$

Excitation of ^{229}Th nuclei in laser plasma: the energy and half-life of the low-lying isomeric state

P. V. Borisyuk,[1,*] E. V. Chubunova,[1] N. N. Kolachevsky,[2,1]
Yu. Yu. Lebedinskii,[1] O. S. Vasiliev,[1] and E. V. Tkalya[3,1,4,†]

[arXiv:1804.00299]

The results of experimental studies of the low-energy isomeric state in the ^{229}Th nucleus are presented. The work is consisted of several stages. During the first stage ^{229}Th nuclei were excited with the inverse internal conversion to the low-lying isomeric level in plasma that was formed by laser pulse at the ^{229}Th-containing target surface. Then thorium ions having excited nuclei were extracted from the plasma by an external electrical field and implanted into thin SiO_2 film grown on a silicon

obtained that allowed determining the energy of photons. In order to prove that the detected signal is caused by isomeric ^{229}Th nuclei decay a series of experiments was carried. The analysis of electron spectra gives the following results: the energy of the nuclear transition is $E_{\text{is}} = 7.1(^{+0.1}_{-0.2})$ eV, the half-life of the isomeric level in bare nucleus in vacuum is $T_{1/2} = 1880 \pm 170$ s, the reduced probability of the isomeric nuclear transition is $B_{\text{W.u.}}(M1; 3/2^+ \to 5/2^+) = (3.3 \pm 0.3) \times 10^{-2}$.

[Borisyuk et al, arXiv:1804.00299]

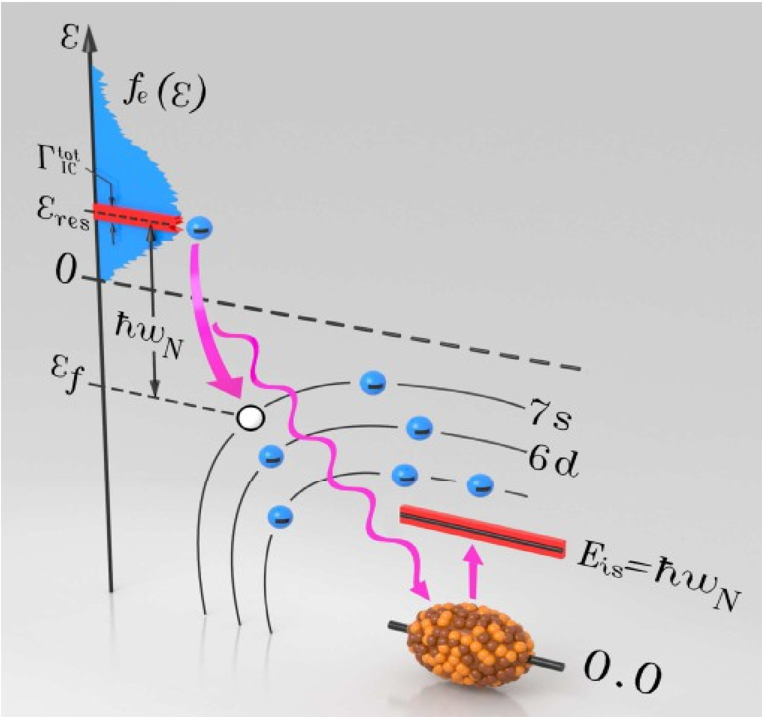
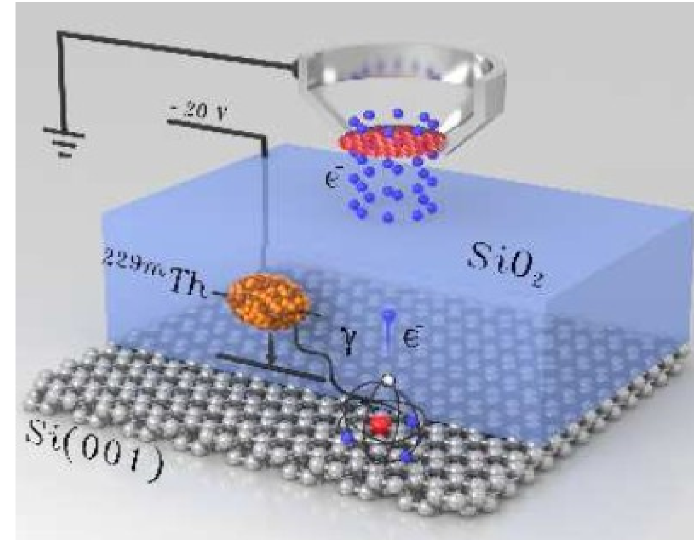
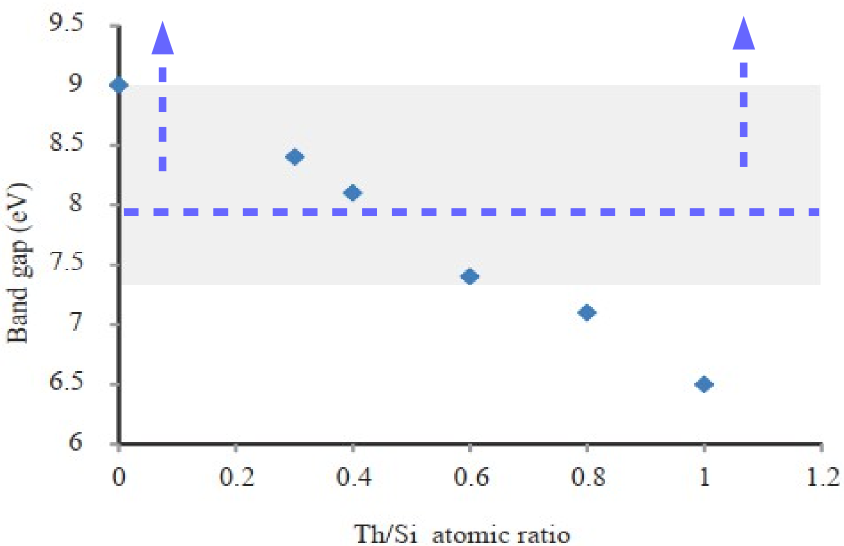
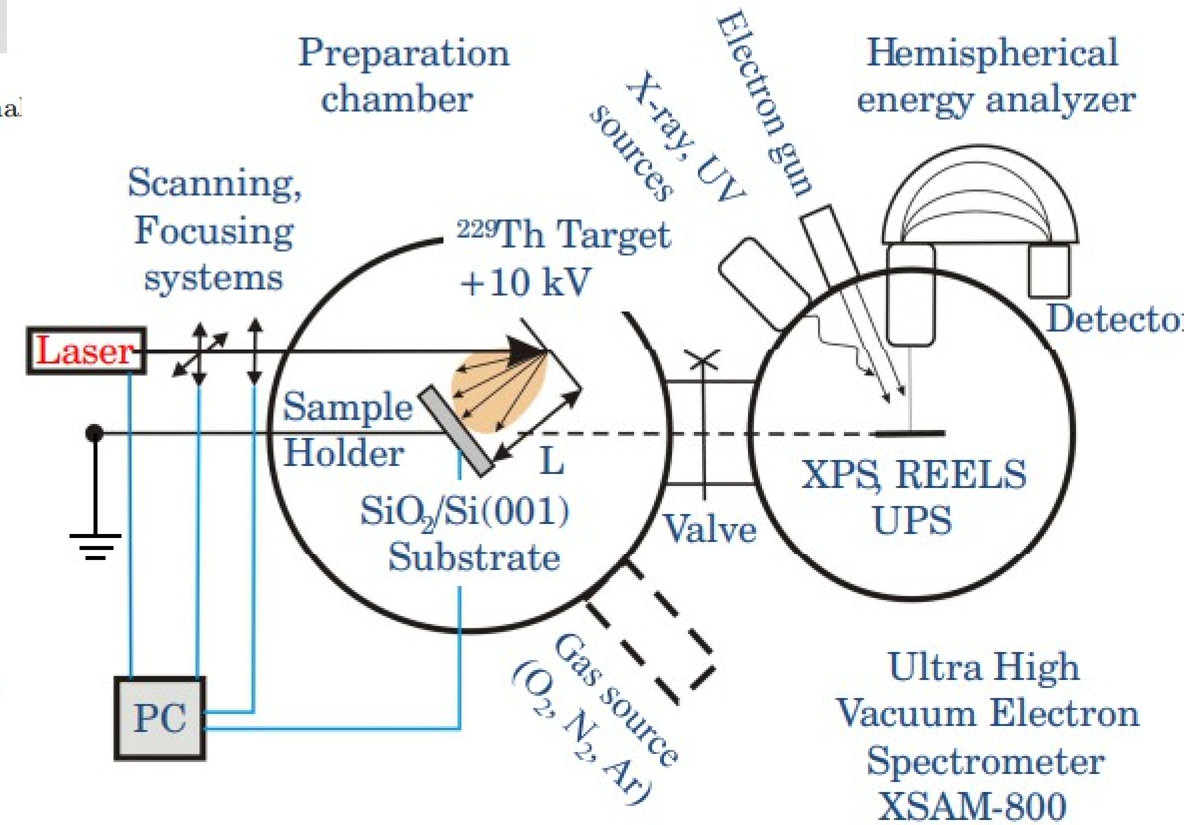


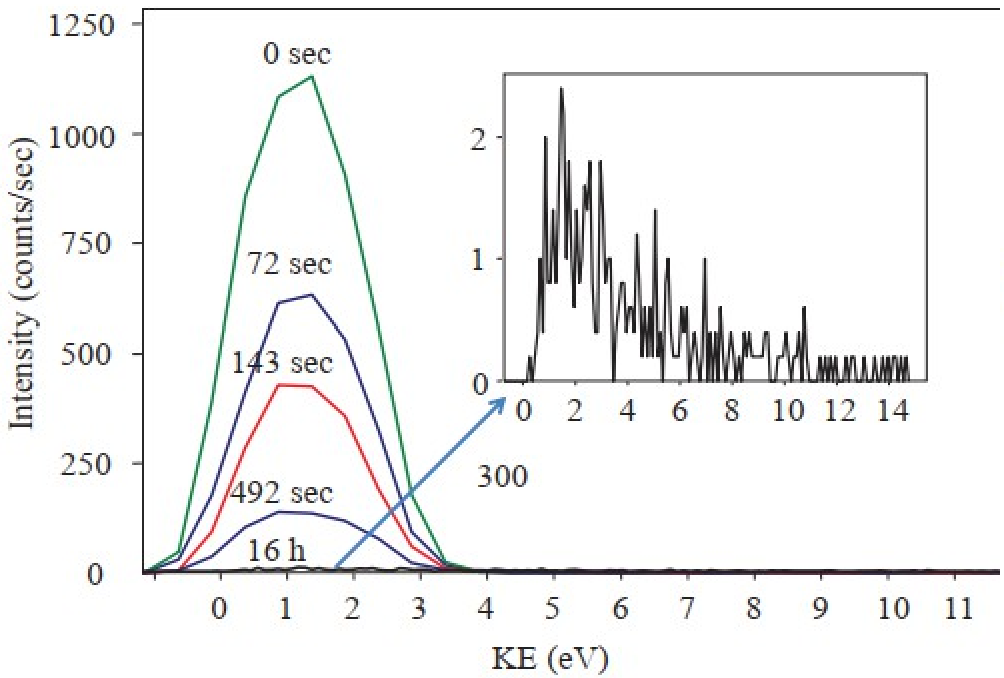
Figure 1: Excitation of ^{229}Th nucleus via inverse internal conversion to the 7s electron shell.

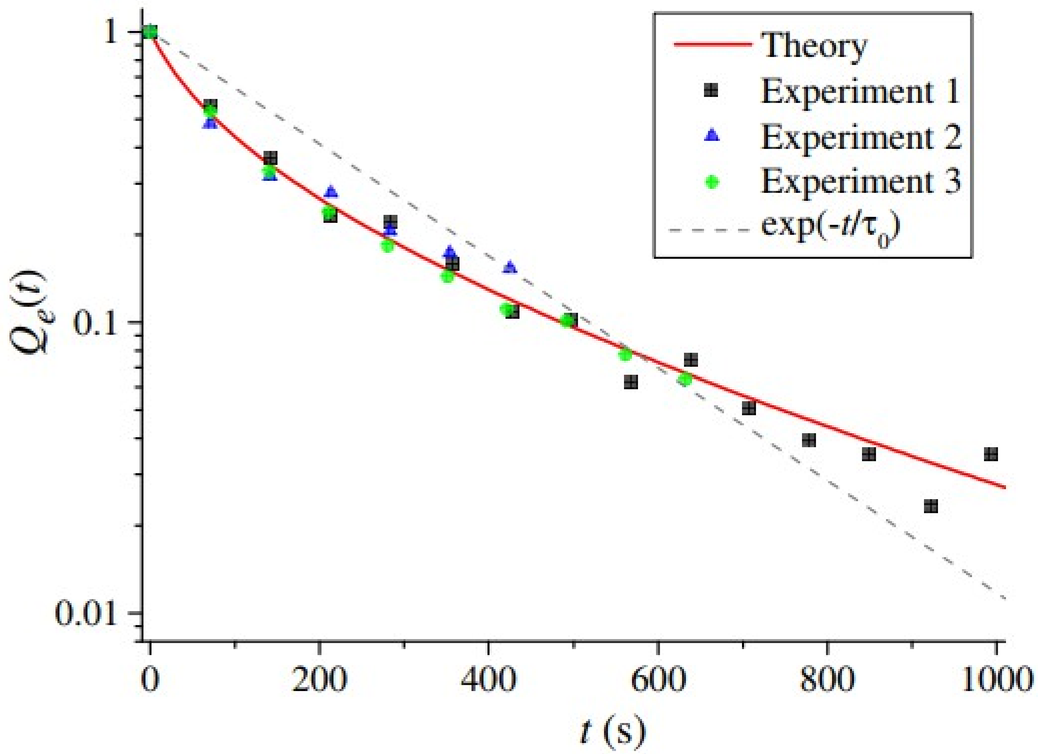






[Borisyuk et al, arXiv:1804.00299]





$$KE = \hbar\omega_N - BE - eU.$$

Table I: Spectral lines of xenon discharge lamp and corresponding $KE_{\max}$ energies for the photoelectron spectra presented in Fig. 10. The last raw shows deduced $KE_{\max}$ energy for ^{229}Th:SiO_2/Si sample with decaying isomeric ^{229}Th nuclei.

UV Source	λ (nm)	$\hbar\omega$ (eV)	$KE_{\max} = \hbar\omega - WF_{\mathrm{Si}}$ (eV)
Xe	147	8.4	$3.3(^{+0.1}_{-0.2})$
Th:SiO_2/Si		$7.1(^{+0.1}_{-0.2})$	$2.0(^{+0.1}_{-0.2})$

Чувствительность к вариации фундаментальных постоянных

[Berengut, Dzuba, Flambaum, and Porsev, *Phys. Rev. Lett.* **102**, 210801 (2009)]

$\omega = \Delta E_N + \Delta V_C \approx 7$ eV

$$\delta\omega = \Delta V_C \, \frac{\delta\alpha}{\alpha}, \quad \frac{\delta\omega}{\omega} = K \frac{\delta\alpha}{\alpha} \qquad K = \Delta V_C / \omega$$

$$\frac{\Delta V_C}{(\mathrm{MeV})} = -506 \, \frac{\Delta \langle r^2 \rangle}{\langle r^2 \rangle} + 23 \, \frac{\Delta Q_0}{Q_0} + 17 \, \frac{\Delta z}{z}$$

Чувствительность к вариации фундаментальных постоянных

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-0.16(2) **-0.2(7)** **<<1**

Спасибо!