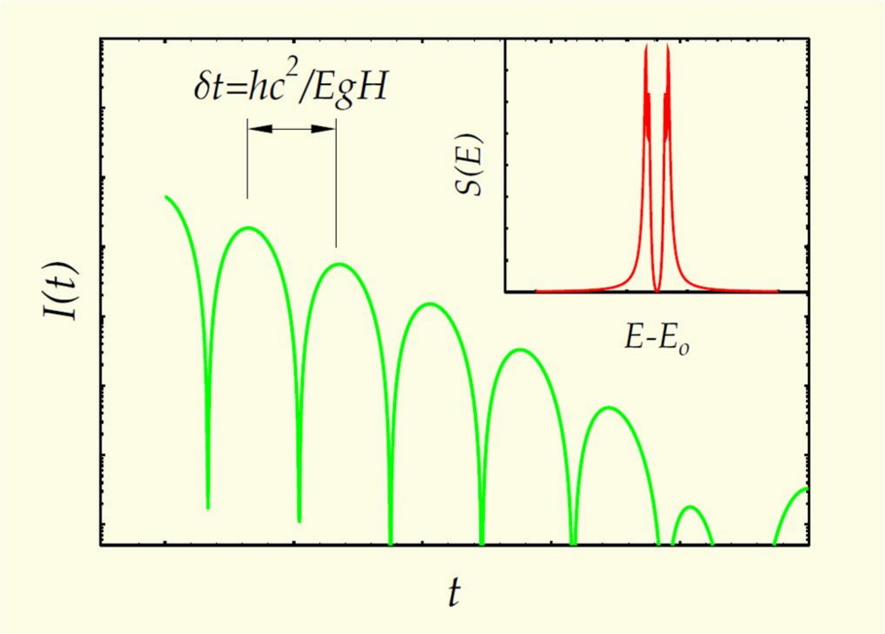
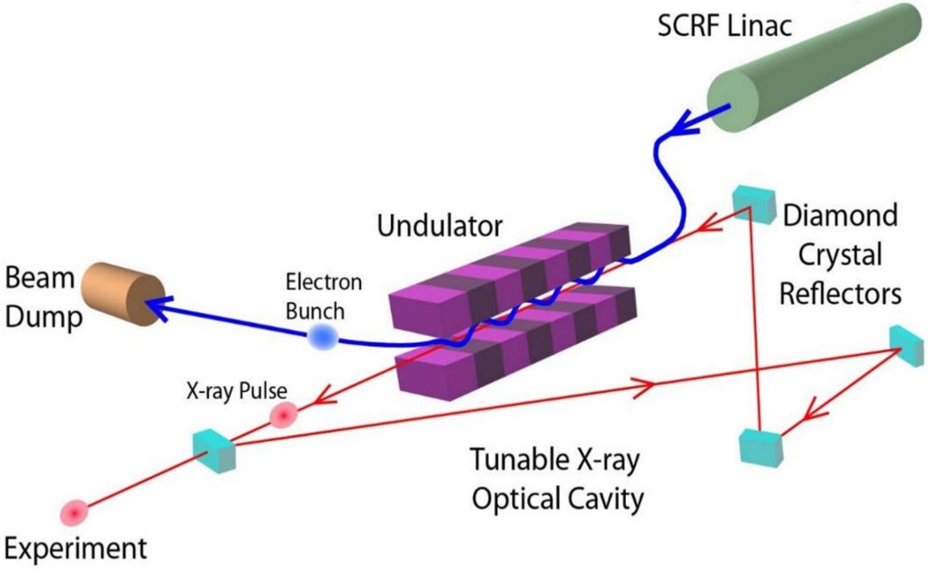
Exploring extremely narrow nuclear resonances using XFELO radiation.





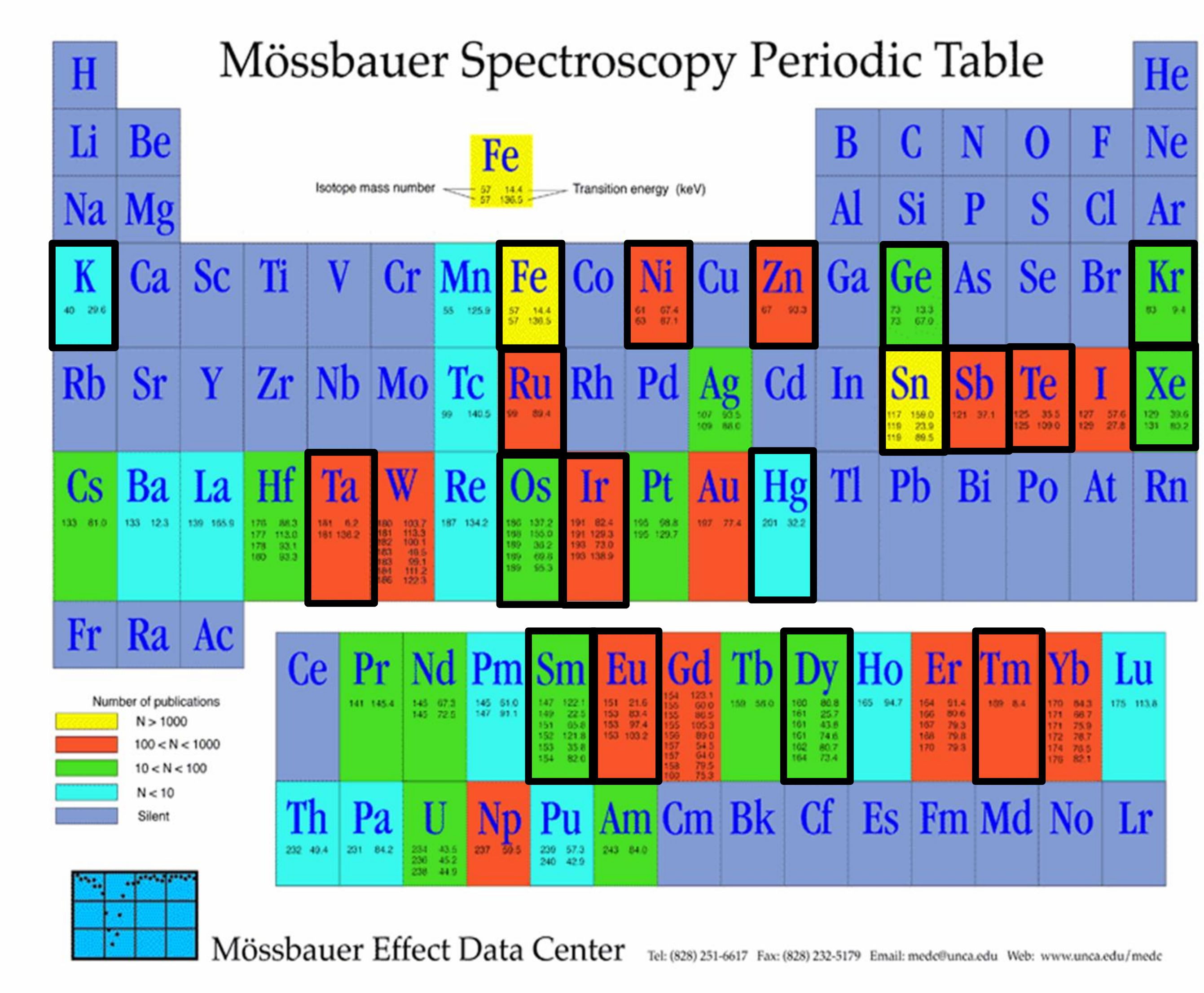
Hans-Christian Wille

XFELO workshop

HELMHOLTZ
GEMEINSCHAFT

DESY

Nuclear resonance scattering - Elements



▯ ⟺ NRS spectroscopy measurements done

18 isotopes

6 keV < E < 93 keV

What means extremely narrow nuclear transitions?

Isotope	E_0 [keV]	Γ_0 [eV]	$\Delta E/E$	τ [s]	a [%]	f [%] 300K / 0K		α $\sigma_0 \sim \alpha^{-1}$
^{57}Fe	14.4	$4.7*10^{-9}$	$3.2*10^{-13}$	$1.4*10^{-7}$	2.1	75	88	8.2

Transitions narrower than ^{57}Fe

Isotope	E_0 [keV]	Γ_0 [eV]	$\Delta E/E$	τ [s]	a [%]	f [%] 300K / 0K		α $\sigma_0 \sim \alpha^{-1}$
^{57}Fe	14.4	$4.7 \cdot 10^{-9}$	$3.2 \cdot 10^{-13}$	$1.4 \cdot 10^{-7}$	2.1	75	88	8.2
^{181}Ta	6.2	$7.5 \cdot 10^{-11}$	$1.2 \cdot 10^{-14}$	$8.7 \cdot 10^{-6}$	99.99			71.5
^{67}Zn	93.3	$4.9 \cdot 10^{-11}$	$5.1 \cdot 10^{-16}$	$1.3 \cdot 10^{-5}$	4.1			
^{45}Sc	12.4	$1.4 \cdot 10^{-15}$	$1.1 \cdot 10^{-19}$	0.45	100	77	93	427
^{107}Ag	93.1	$1.0 \cdot 10^{-17}$	$1.1 \cdot 10^{-22}$	63.9	51.4	10^{-5}	4	20
^{103}Rh	39.8	$1.4 \cdot 10^{-19}$	$3.4 \cdot 10^{-24}$	4856	100	45	74	1350
^{229m}Th	0.0078	$\approx 7.8 \cdot 10^{-20}$	$\approx 10^{-20}$	600 ?	0	no	IC	

Transitions within the XFELO energy range

Isotope	E_0 [keV]	Γ_0 [eV]	$\Delta E/E$	τ [s]	a [%]	f [%] 300K / 0K		α $\sigma_0 \sim \alpha^{-1}$
^{57}Fe	14.4	$4.7*10^{-9}$	$3.2*10^{-13}$	$1.4*10^{-7}$	2.1	75	88	8.2
^{181}Ta	6.2	$7.5*10^{-11}$	$1.2*10^{-14}$	$8.7*10^{-6}$	99.99	Fe	Fe	71.5
^{45}Sc	12.4	$1.4*10^{-15}$	$1.1*10^{-19}$	0.45	100	77	93	427
^{229m}Th	0.0078	$\approx 7.8*10^{-20}$	$\approx 10^{-20}$	600 ?	0	no	IC	

Transitions fitting to the XFELO energy range

Isotope	E_0 [keV]	Γ_0 [eV]	ΔE/E	τ [s]	a [%]	f [%] 300K / 0K		α $\sigma_0 \sim \alpha^{-1}$
^{45}Sc	12.4	$1.4*10^{-15}$	$1.1*10^{-19}$	0.45	100	77	93	427
^{229m}Th	0.0076	$\approx 7.6*10^{-20}$	$\approx 10^{-20}$	600 ?	0	no	IC	

HELMHOLTZ
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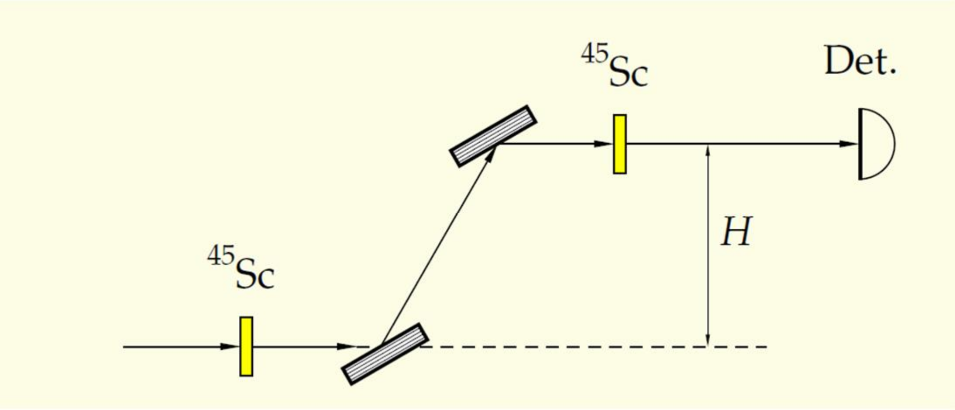
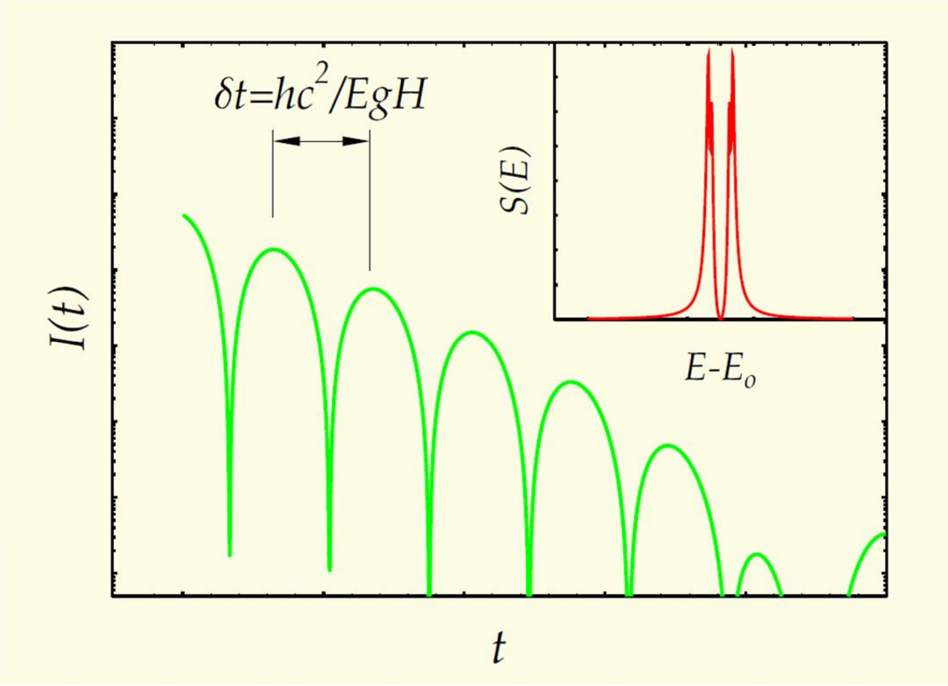
Extreme metrology using the ^{45}Sc transition



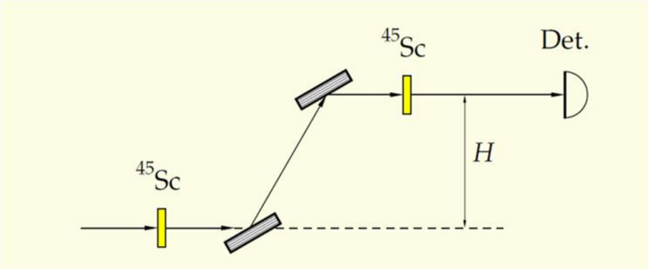


$\Delta E/E = 1.1 \cdot 10^{-19}$

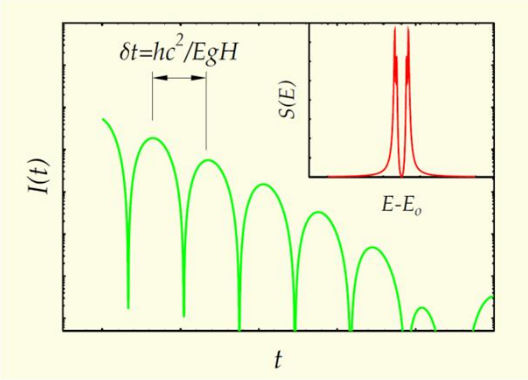
$g = 9.81\ \mathrm{m\,s^{-2}} = 1.1 \cdot 10^{-16}\ c^2\ \mathrm{m^{-1}}$

Red shift of a photon travelling 1mm up in the earth gravitational field corresponds to a linewidth

Extreme metrology using the ^{45}Sc transition



XFELO will provide 10^{14} photons/sec/meV
≈ 100 photons/sec/ Γ_0



Applications

Gravitational constant, Cosmology, Quantization of gravity

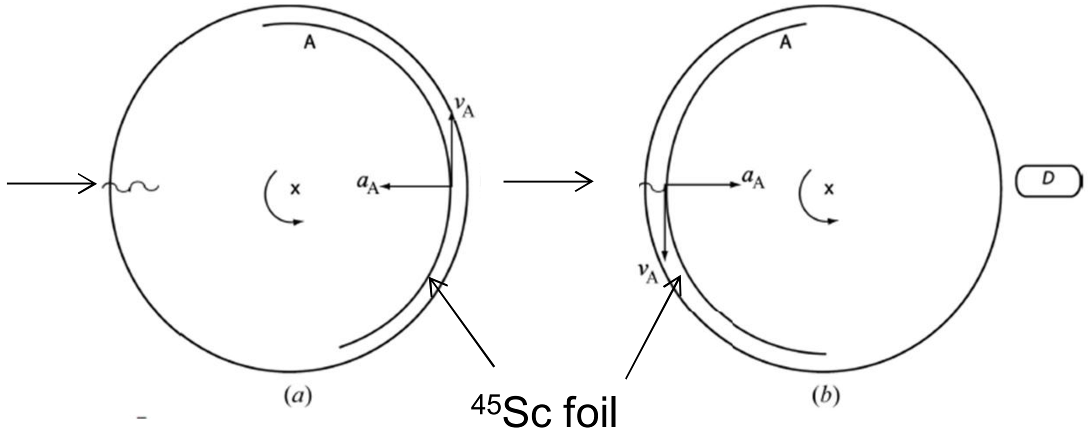
Table top red shift and nuclear quantum optics experiments

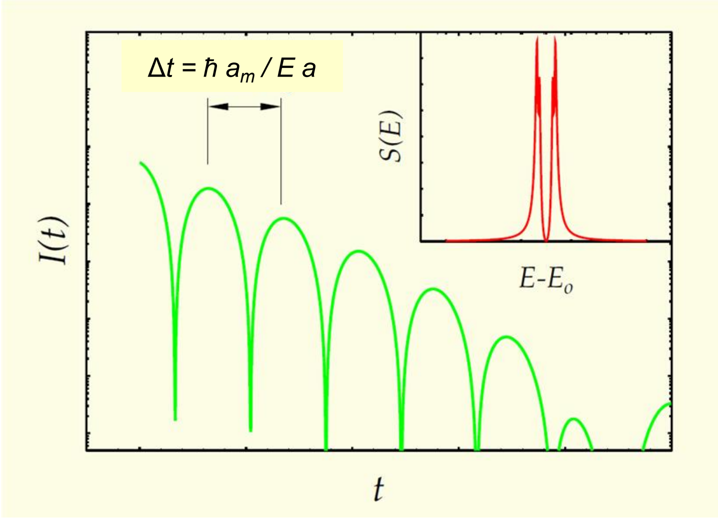
Validity of Einstein's Clock Hypothesis – Is there a maximal acceleration ?

The rate of an accelerated clock is the same as the rate of an unaccelerated co-moving clock.

Einstein, A. (1911). *Ann. Phys.* **35**, 898–908.

Testing the clock hypothesis using the ^{45}Sc transition





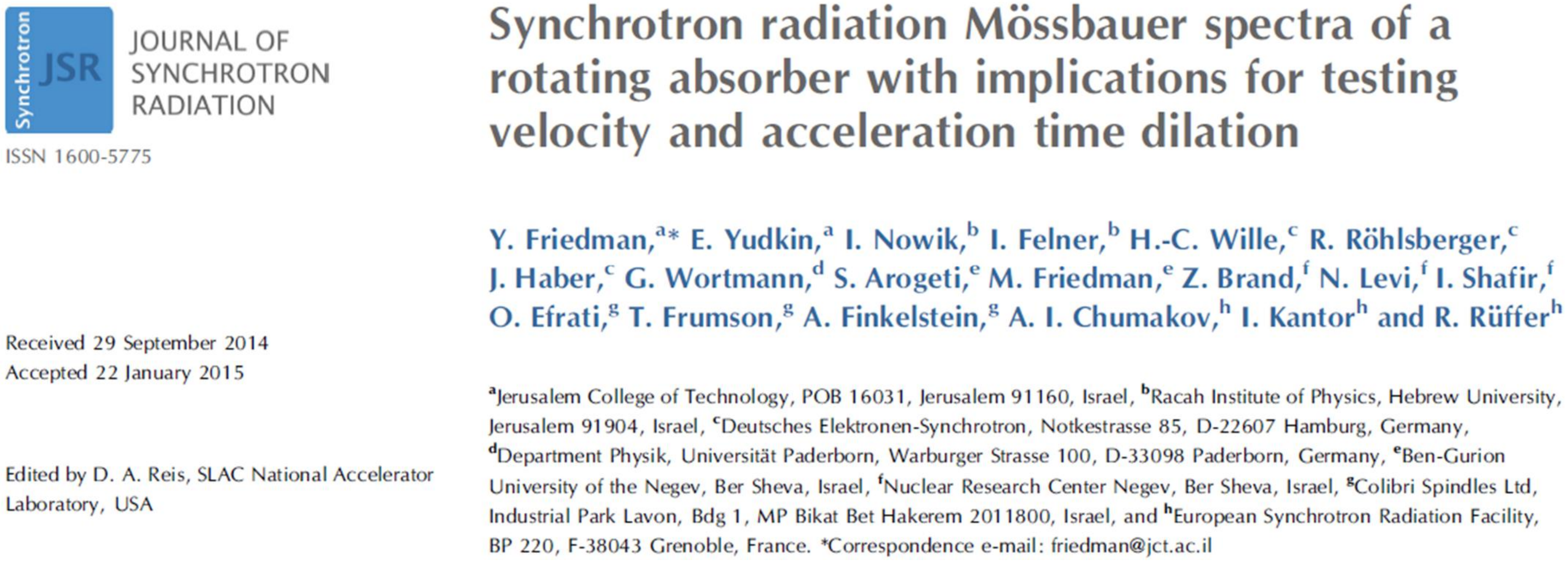
$$E_\gamma = E_0\,(1+\frac{v}{c}) \rightarrow E_\gamma = E_0\,(1+\frac{a}{a_m})$$

If clock hypothesis is wrong and a_m exists

Friedman, Y. (2011). *Ann. Phys. (Berlin)*, **523**, 408–416.

Current limit $a_m \geq 1.5 \times 10^{21}$ m/s^2 W. Potzel (^{67}Zn)

^{45}Sc applications – relativity – clock hypothesis



JOURNAL OF SYNCHROTRON RADIATION

ISSN 1600-5775

Synchrotron radiation Mössbauer spectra of a rotating absorber with implications for testing velocity and acceleration time dilation

Y. Friedman,[a]* E. Yudkin,[a] I. Nowik,[b] I. Felner,[b] H.-C. Wille,[c] R. Röhlsberger,[c] J. Haber,[c] G. Wortmann,[d] S. Arogeti,[e] M. Friedman,[e] Z. Brand,[f] N. Levi,[f] I. Shafir,[f] O. Efrati,[g] T. Frumson,[g] A. Finkelstein,[g] A. I. Chumakov,[h] I. Kantor[h] and R. Rüffer[h]

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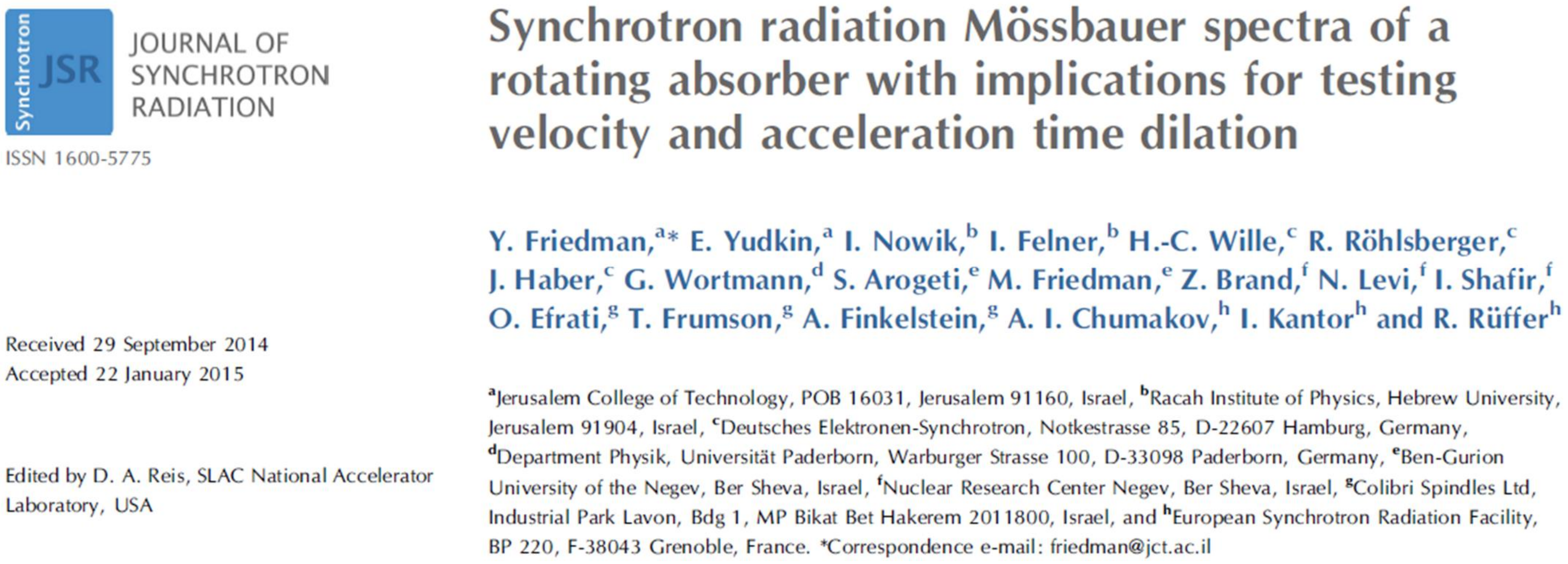
Accepted 22 January 2015

Edited by D. A. Reis, SLAC National Accelerator Laboratory, USA

$$s_{\mathrm{a}} = r\omega_{\mathrm{r}}^{2}/a_{\mathrm{m}}$$

^{45}Sc applications – relativity – clock hypothesis



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Impact of non-random vibrations in Mössbauer rotor experiments testing time dilation

Y. FRIEDMAN[1], I. NOWIK[2], I. FELNER[2], J. M. STEINER[1], E. YUDKIN[1], S. LIVSHITZ[1], H.-C. WILLE[3], G. WORTMANN[4], S. AROGETI[5], R. LEVY[5], A. I. CHUMAKOV[6] and R. RÜFFER[6]

^{45}Sc applications – relativity – clock hypothesis

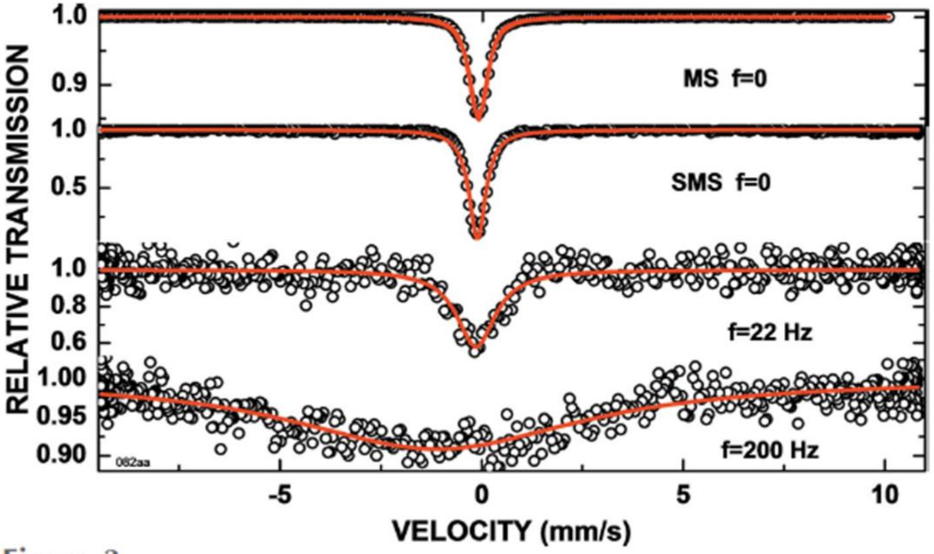
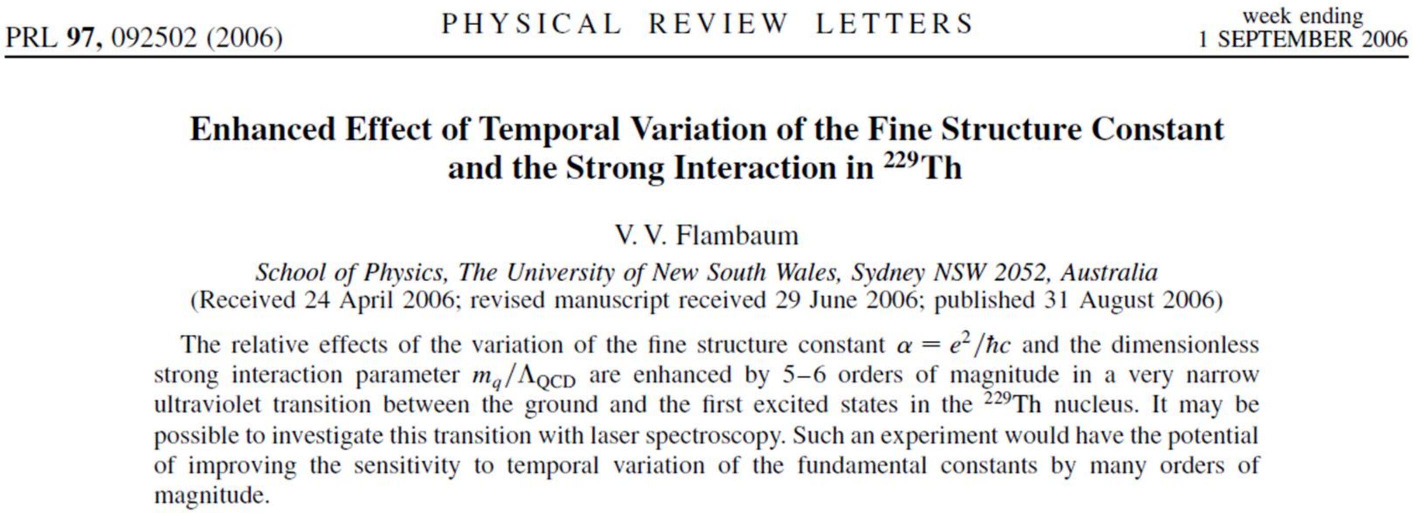


Figure 3
Mössbauer transmission spectra measured in relative transmission by conventional MS at rest and by SMS at rest and at 22 Hz and 200 Hz.

Broadening and shifts both increase with ω
-> keep ω small using the ^{45}Sc transition

^{229}Th applications – fine structure ‘constant’



PRL **97,** 092502 (2006) PHYSICAL REVIEW LETTERS week ending 1 SEPTEMBER 2006

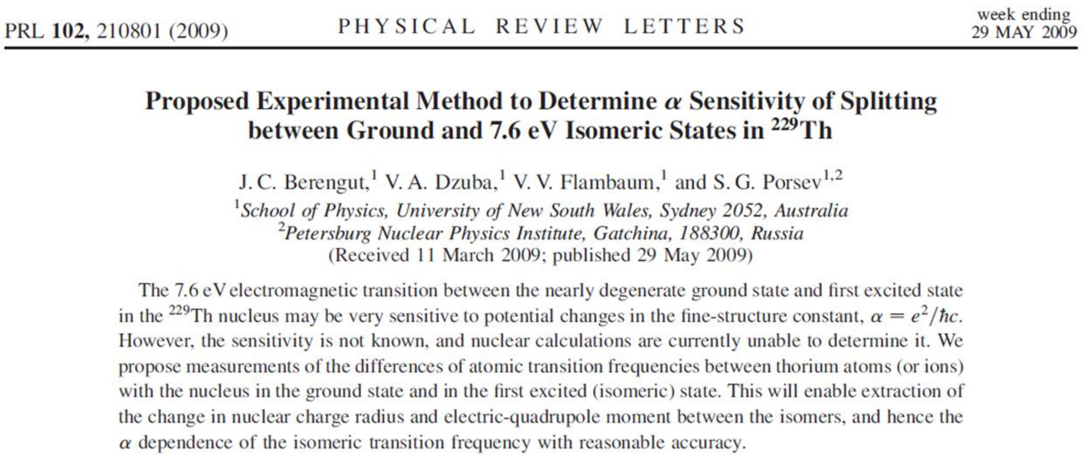
Enhanced Effect of Temporal Variation of the Fine Structure Constant and the Strong Interaction in ^{229}Th

V. V. Flambaum

School of Physics, The University of New South Wales, Sydney NSW 2052, Australia

(Received 24 April 2006; revised manuscript received 29 June 2006; published 31 August 2006)

The relative effects of the variation of the fine structure constant $\alpha = e^2/\hbar c$ and the dimensionless strong interaction parameter $m_q/\Lambda_{\mathrm{QCD}}$ are enhanced by 5–6 orders of magnitude in a very narrow ultraviolet transition between the ground and the first excited states in the ^{229}Th nucleus. It may be possible to investigate this transition with laser spectroscopy. Such an experiment would have the potential of improving the sensitivity to temporal variation of the fundamental constants by many orders of magnitude.



PRL **102,** 210801 (2009) PHYSICAL REVIEW LETTERS week ending 29 MAY 2009

Proposed Experimental Method to Determine α Sensitivity of Splitting between Ground and 7.6 eV Isomeric States in ^{229}Th

J. C. Berengut,[1] V. A. Dzuba,[1] V. V. Flambaum,[1] and S. G. Porsev[1,2]

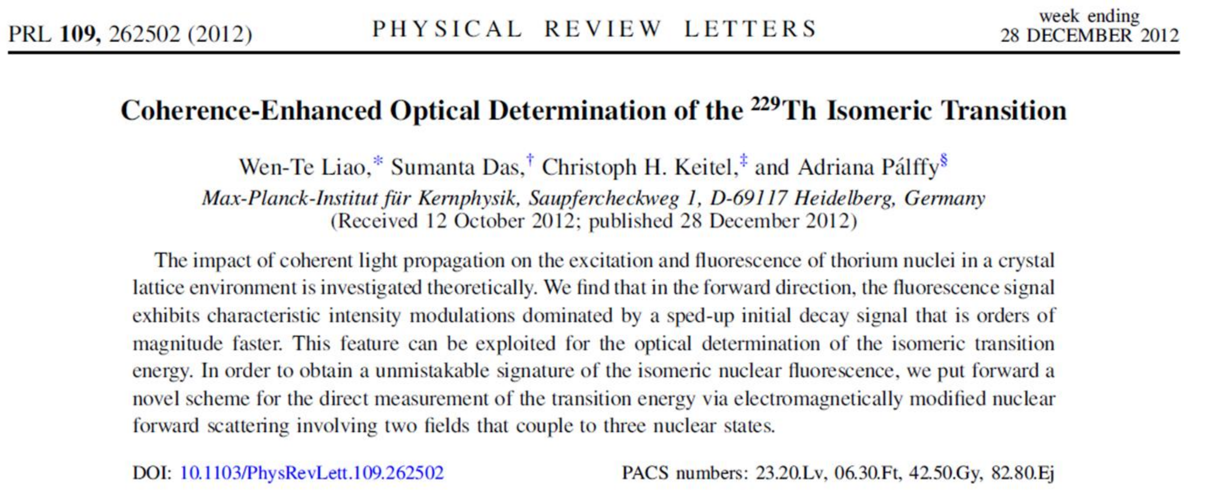
[1]*School of Physics, University of New South Wales, Sydney 2052, Australia*

[2]*Petersburg Nuclear Physics Institute, Gatchina, 188300, Russia*

(Received 11 March 2009; published 29 May 2009)

The 7.6 eV electromagnetic transition between the nearly degenerate ground state and first excited state in the ^{229}Th nucleus may be very sensitive to potential changes in the fine-structure constant, $\alpha = e^2/\hbar c$. However, the sensitivity is not known, and nuclear calculations are currently unable to determine it. We propose measurements of the differences of atomic transition frequencies between thorium atoms (or ions) with the nucleus in the ground state and in the first excited (isomeric) state. This will enable extraction of the change in nuclear charge radius and electric-quadrupole moment between the isomers, and hence the α dependence of the isomeric transition frequency with reasonable accuracy.

^{229}Th applications



PRL **109,** 262502 (2012) PHYSICAL REVIEW LETTERS week ending 28 DECEMBER 2012

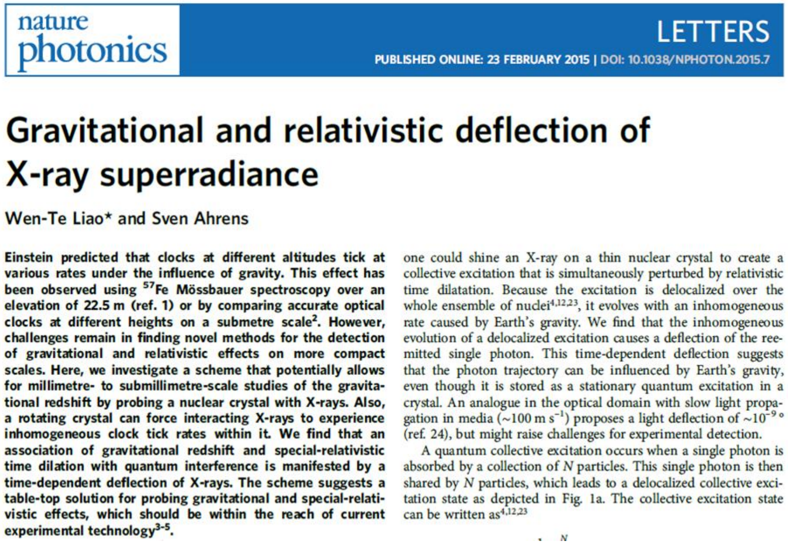
Coherence-Enhanced Optical Determination of the ^{229}Th Isomeric Transition

Wen-Te Liao,[*] Sumanta Das,[†] Christoph H. Keitel,[‡] and Adriana Pálffy[§]
Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany

(Received 12 October 2012; published 28 December 2012)

The impact of coherent light propagation on the excitation and fluorescence of thorium nuclei in a crystal lattice environment is investigated theoretically. We find that in the forward direction, the fluorescence signal exhibits characteristic intensity modulations dominated by a sped-up initial decay signal that is orders of magnitude faster. This feature can be exploited for the optical determination of the isomeric transition energy. In order to obtain a unmistakable signature of the isomeric nuclear fluorescence, we put forward a novel scheme for the direct measurement of the transition energy via electromagnetically modified nuclear forward scattering involving two fields that couple to three nuclear states.

DOI: 10.1103/PhysRevLett.109.262502 PACS numbers: 23.20.Lv, 06.30.Ft, 42.50.Gy, 82.80.Ej



nature photonics LETTERS
PUBLISHED ONLINE: 23 FEBRUARY 2015 | DOI: 10.1038/NPHOTON.2015.7

Gravitational and relativistic deflection of X-ray superradiance

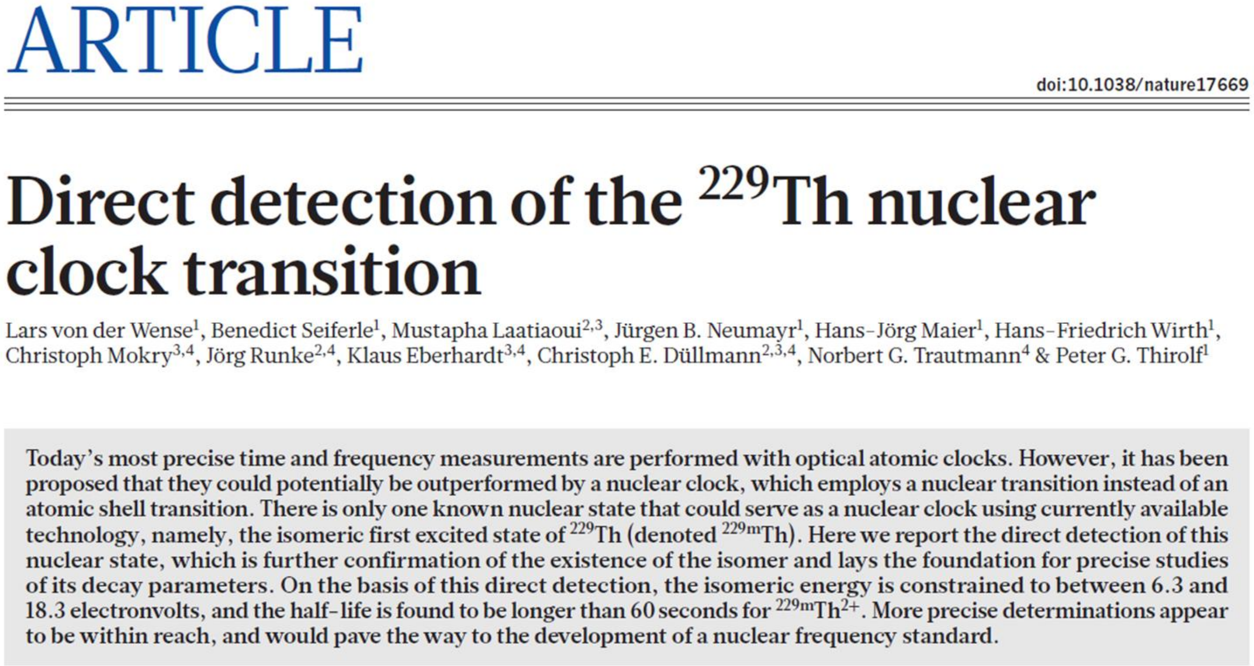
Wen-Te Liao* and Sven Ahrens

Einstein predicted that clocks at different altitudes tick at various rates under the influence of gravity. This effect has been observed using ^{57}Fe Mössbauer spectroscopy over an elevation of 22.5 m (ref. 1) or by comparing accurate optical clocks at different heights on a submetre scale[2]. However, challenges remain in finding novel methods for the detection of gravitational and relativistic effects on more compact scales. Here, we investigate a scheme that potentially allows for millimetre- to submillimetre-scale studies of the gravitational redshift by probing a nuclear crystal with X-rays. Also, a rotating crystal can force interacting X-rays to experience inhomogeneous clock tick rates within it. We find that an association of gravitational redshift and special-relativistic time dilation with quantum interference is manifested by a time-dependent deflection of X-rays. The scheme suggests a table-top solution for probing gravitational and special-relativistic effects, which should be within the reach of current experimental technology[3-5].

one could shine an X-ray on a thin nuclear crystal to create a collective excitation that is simultaneously perturbed by relativistic time dilatation. Because the excitation is delocalized over the whole ensemble of nuclei[4,12,23], it evolves with an inhomogeneous rate caused by Earth's gravity. We find that the inhomogeneous evolution of a delocalized excitation causes a deflection of the reemitted single photon. This time-dependent deflection suggests that the photon trajectory can be influenced by Earth's gravity, even though it is stored as a stationary quantum excitation in a crystal. An analogue in the optical domain with slow light propagation in media ($\sim 100\,\mathrm{m\,s^{-1}}$) proposes a light deflection of $\sim 10^{-9}$ ° (ref. 24), but might raise challenges for experimental detection.

A quantum collective excitation occurs when a single photon is absorbed by a collection of N particles. This single photon is then shared by N particles, which leads to a delocalized collective excitation state as depicted in Fig. 1a. The collective excitation state can be written as[4,12,23]

^{229}Th applications



ARTICLE

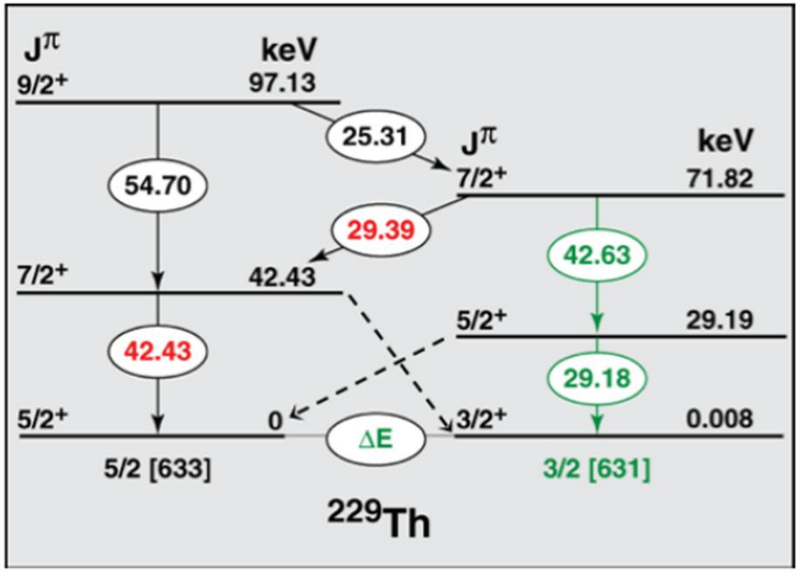
doi:10.1038/nature17669

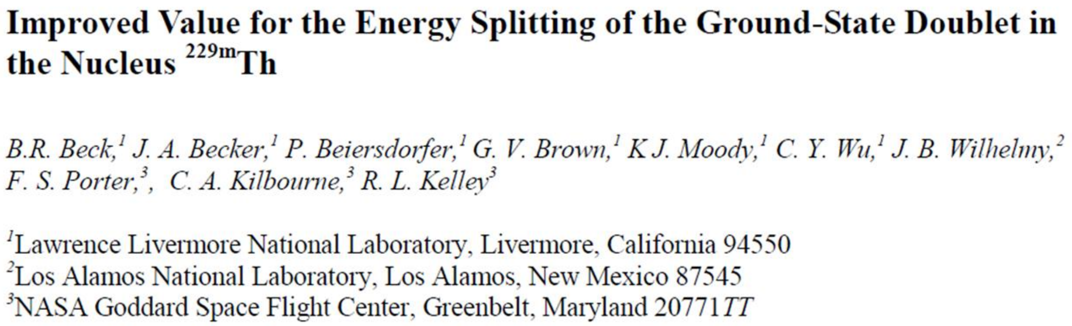
Direct detection of the ^{229}Th nuclear clock transition

Lars von der Wense[1], Benedict Seiferle[1], Mustapha Laatiaoui[2,3], Jürgen B. Neumayr[1], Hans-Jörg Maier[1], Hans-Friedrich Wirth[1], Christoph Mokry[3,4], Jörg Runke[2,4], Klaus Eberhardt[3,4], Christoph E. Düllmann[2,3,4], Norbert G. Trautmann[4] & Peter G. Thirolf[1]

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 an atomic shell transition. There is only one known nuclear state that could serve as a nuclear clock using currently available technology, namely, the isomeric first excited state of ^{229}Th (denoted ^{229m}Th). Here we report the direct detection of this nuclear state, which is further confirmation of the existence of the isomer and lays the foundation for precise studies of its decay parameters. On the basis of this direct detection, the isomeric energy is constrained to between 6.3 and 18.3 electronvolts, and the half-life is found to be longer than 60 seconds for ^{229m}Th^{2+}. More precise determinations appear to be within reach, and would pave the way to the development of a nuclear frequency standard.

^{229}Th applications





Improved Value for the Energy Splitting of the Ground-State Doublet in the Nucleus ^{229m}Th

B.R. Beck,[1] J. A. Becker,[1] P. Beiersdorfer,[1] G. V. Brown,[1] K J. Moody,[1] C. Y. Wu,[1] J. B. Wilhelmy,[2] F. S. Porter,[3], C. A. Kilbourne,[3] R. L. Kelley[3]

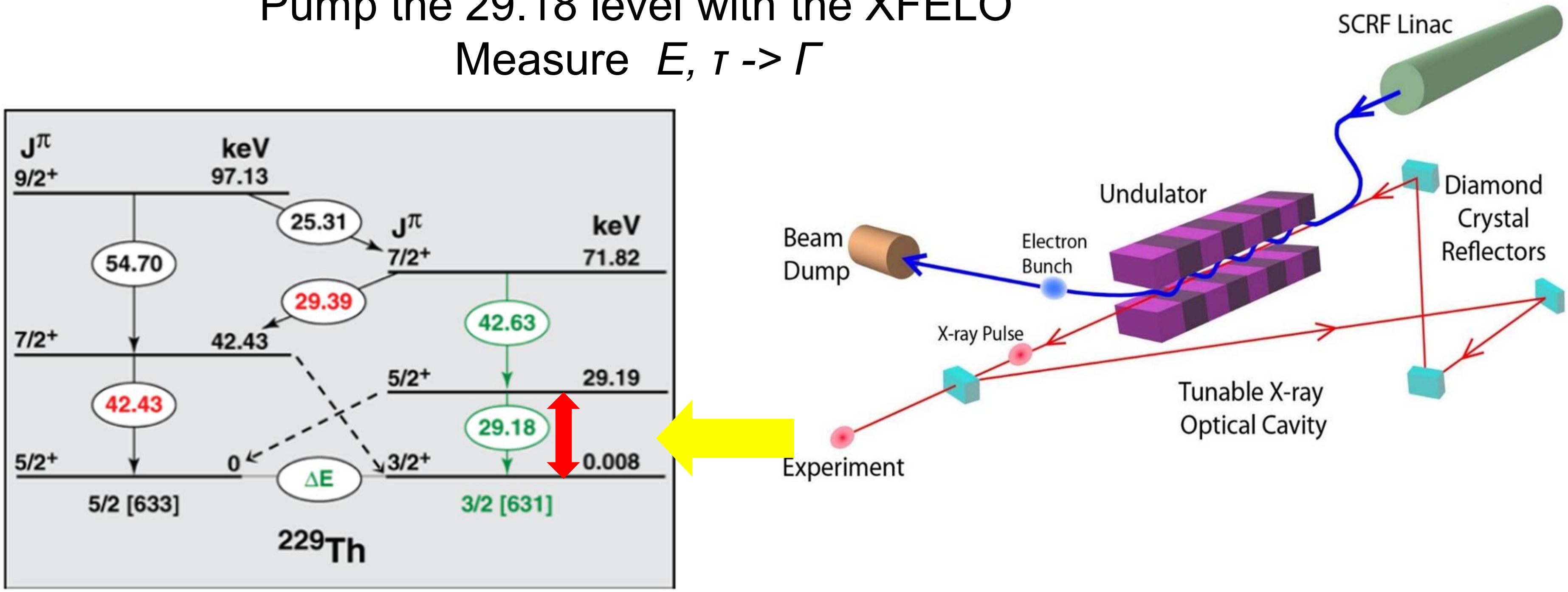
[1]Lawrence Livermore National Laboratory, Livermore, California 94550
[2]Los Alamos National Laboratory, Los Alamos, New Mexico 87545
[3]NASA Goddard Space Flight Center, Greenbelt, Maryland 20771*TT*

LLNL-PROC-415170

^{229}Th applications

Pump the 29.18 level with the XFELO

Measure *E, τ -> Γ*



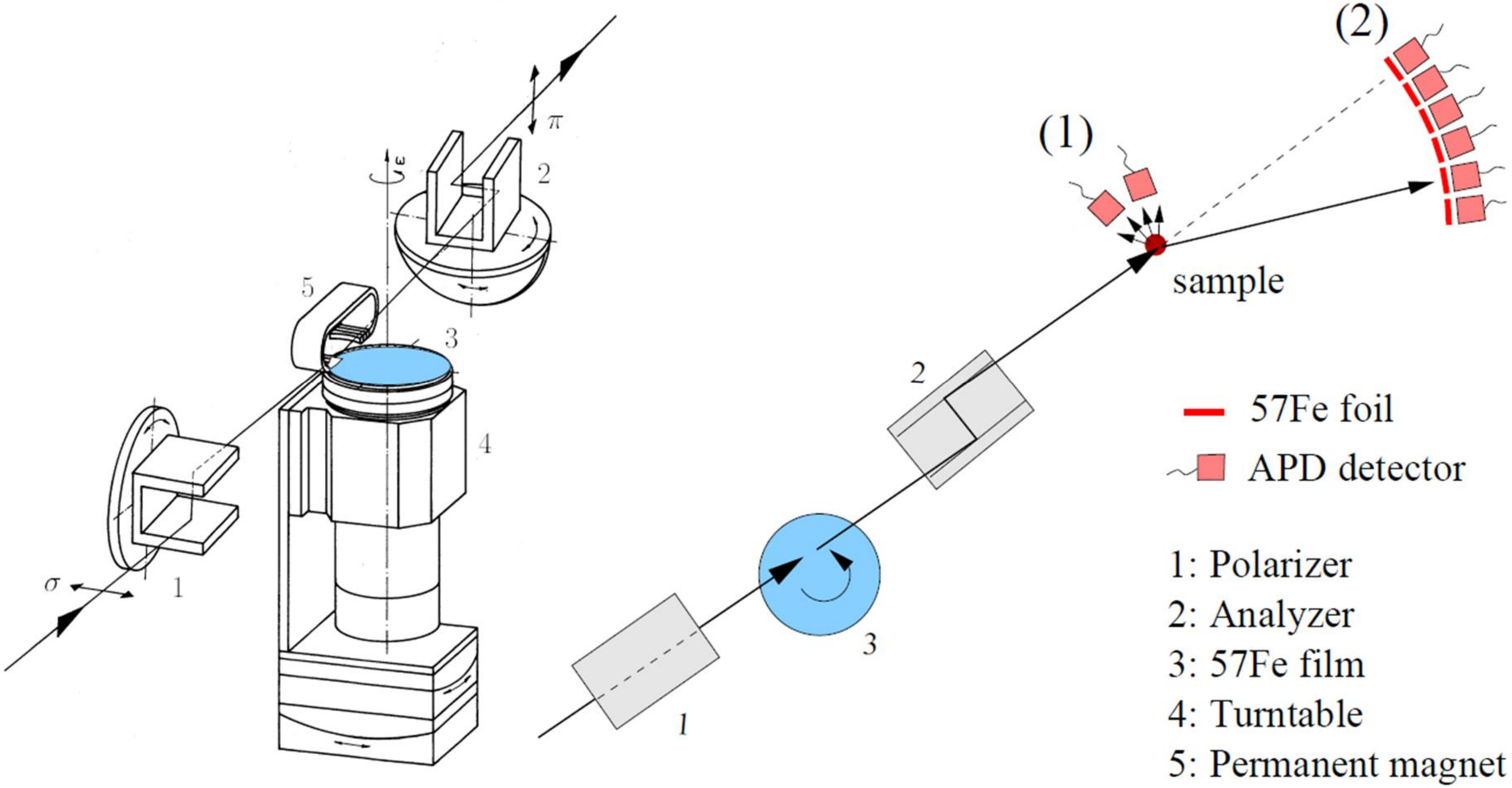
XFELO will allow for spectroscopy with yet unreachable energy resolution

$$\Delta E / E \leq \mathbf{10^{-19}}$$

!! THANK YOU FOR YOUR ATTENTION !!

HELMHOLTZ
GEMEINSCHAFT

Outlook – The dynamics of friction on the nano-metre level



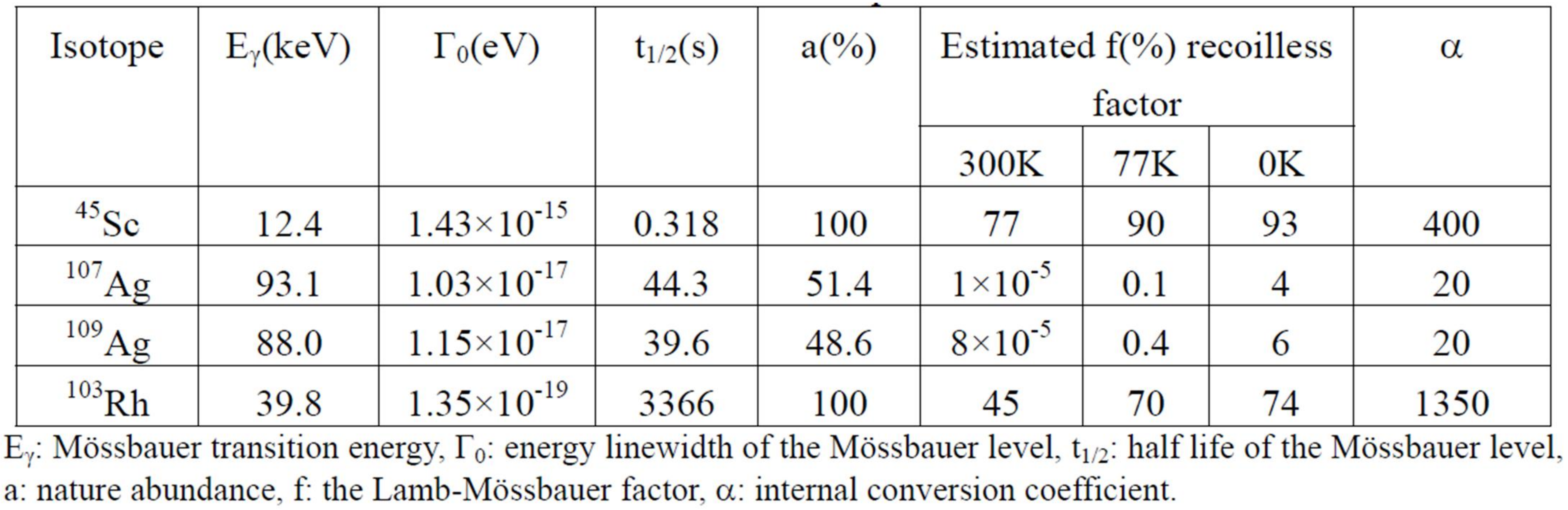
🟥 57Fe foil

🟥 APD detector

1: Polarizer
2: Analyzer
3: 57Fe film
4: Turntable
5: Permanent magnet

μeV – IXS spectrometer

Outlook – Extreme metrology using the ^{45}Sc transition



Isotope	E_γ(keV)	Γ_0(eV)	$t_{1/2}$(s)	a(%)	Estimated f(%) recoilless factor			α
					300K	77K	0K	
^{45}Sc	12.4	1.43×10^{-15}	0.318	100	77	90	93	400
^{107}Ag	93.1	1.03×10^{-17}	44.3	51.4	1×10^{-5}	0.1	4	20
^{109}Ag	88.0	1.15×10^{-17}	39.6	48.6	8×10^{-5}	0.4	6	20
^{103}Rh	39.8	1.35×10^{-19}	3366	100	45	70	74	1350

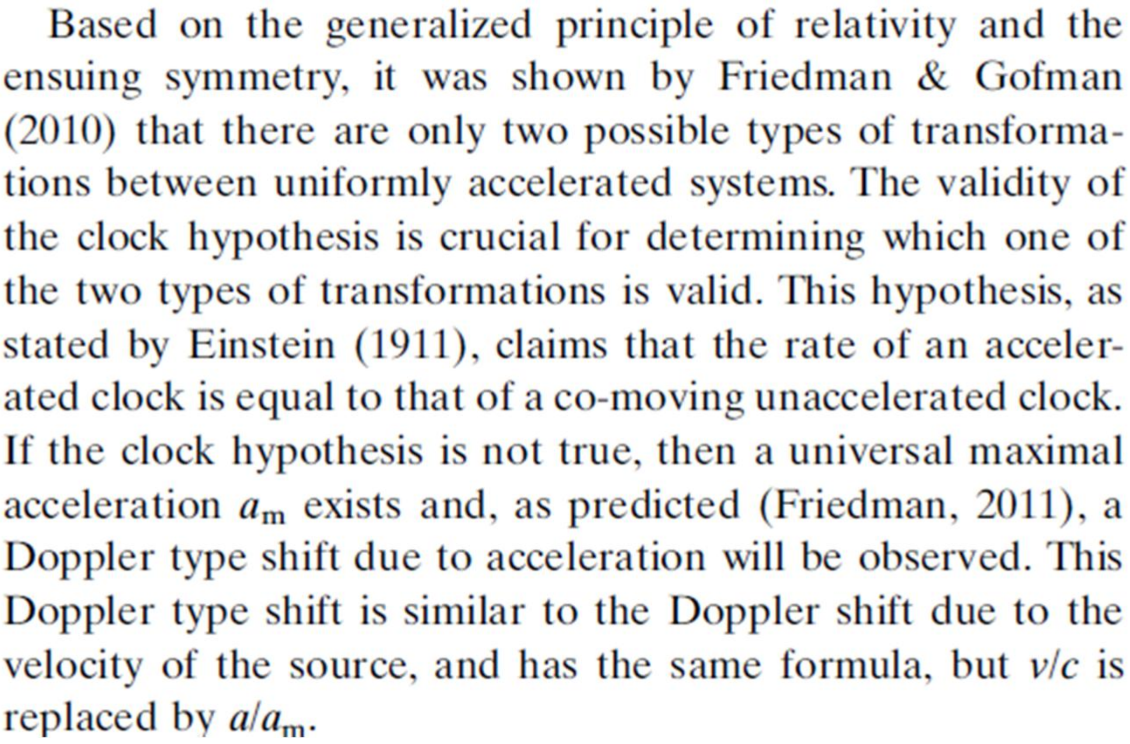
E_γ: Mössbauer transition energy, Γ_0: energy linewidth of the Mössbauer level, $t_{1/2}$: half life of the Mössbauer level, a: nature abundance, f: the Lamb-Mössbauer factor, α: internal conversion coefficient.

$$\Delta E/E = 1.1*10^{-19}$$

$$g = 9.81\ \mathrm{m\ s^{-2}} = 1.1*10^{-16}\ c^2\ \mathrm{m^{-1}}$$

Red shift of a photon travelling 1mm up in the earth gravitational field corresponds to a linewidth

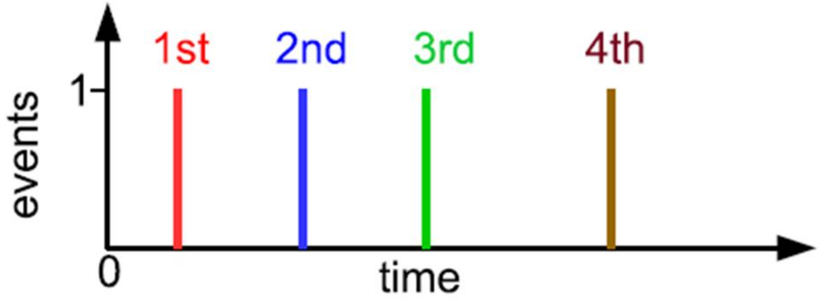
Clock hypothesis

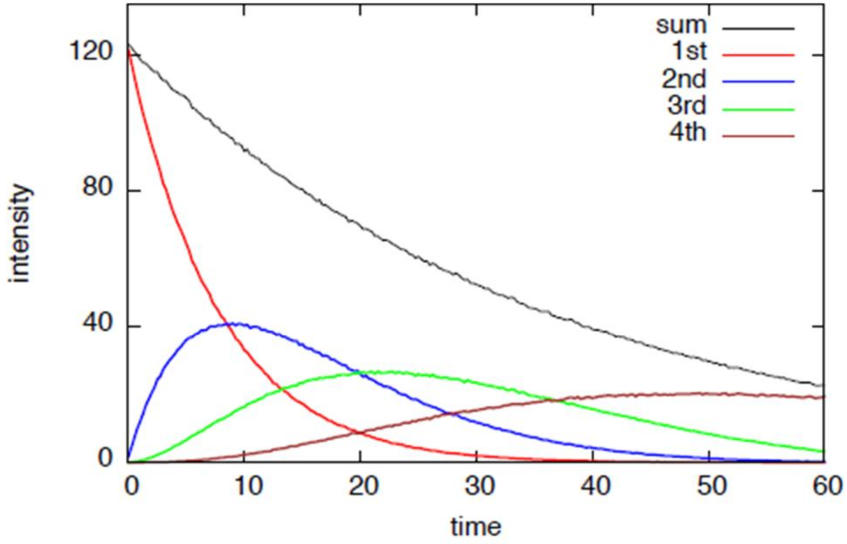


Based on the generalized principle of relativity and the ensuing symmetry, it was shown by Friedman & Gofman (2010) that there are only two possible types of transformations between uniformly accelerated systems. The validity of the clock hypothesis is crucial for determining which one of the two types of transformations is valid. This hypothesis, as stated by Einstein (1911), claims that the rate of an accelerated clock is equal to that of a co-moving unaccelerated clock. If the clock hypothesis is not true, then a universal maximal acceleration a_{m} exists and, as predicted (Friedman, 2011), a Doppler type shift due to acceleration will be observed. This Doppler type shift is similar to the Doppler shift due to the velocity of the source, and has the same formula, but v/c is replaced by a/a_{m}.

Outlook – multi photon events

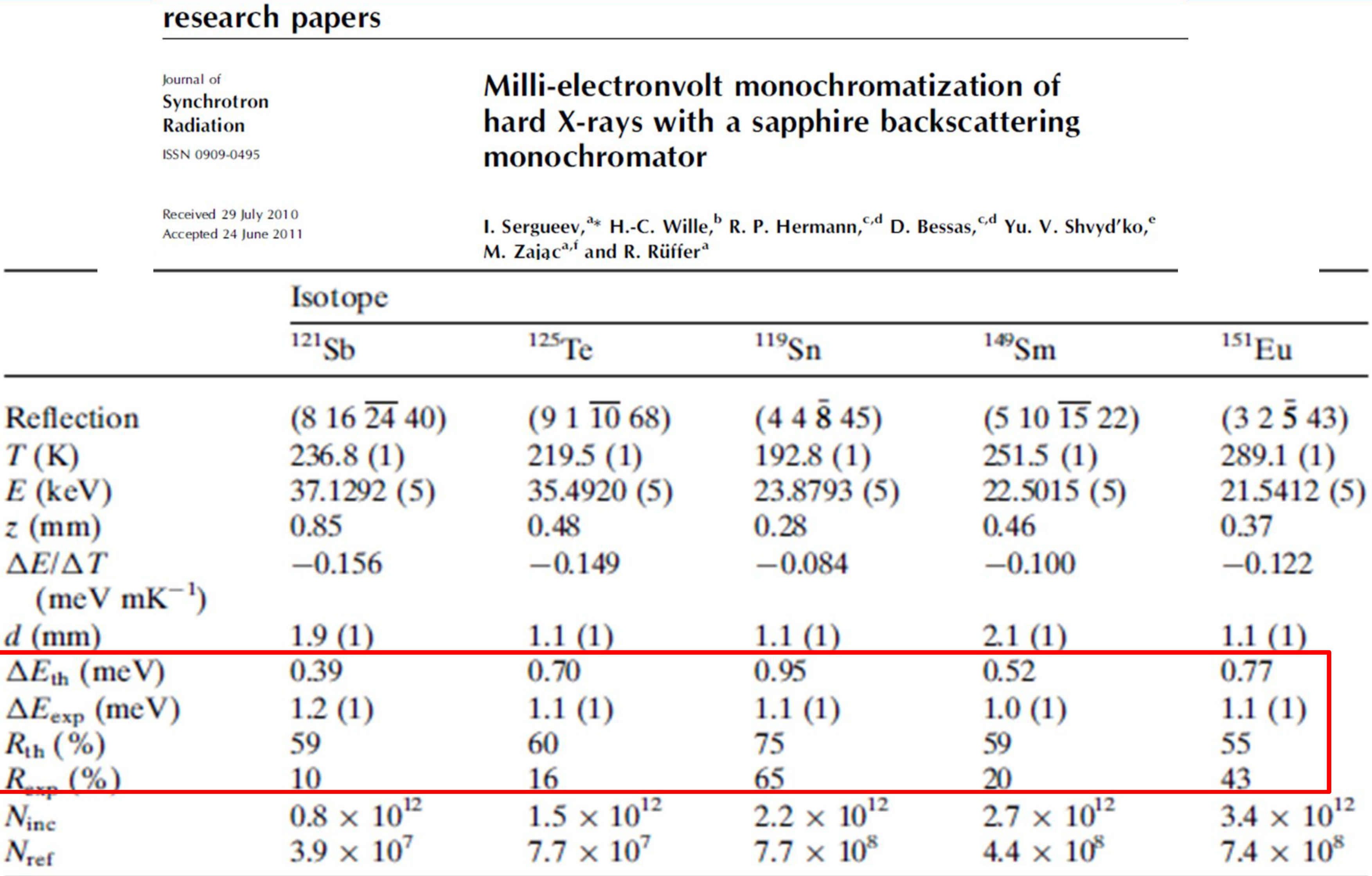
decay of the n-photon state
importance of detecting all photons
example n=4





(by courtesy of Cornelius Strohm)

It works …but good sapphire is hard to find…



research papers

Journal of
Synchrotron
Radiation
ISSN 0909-0495

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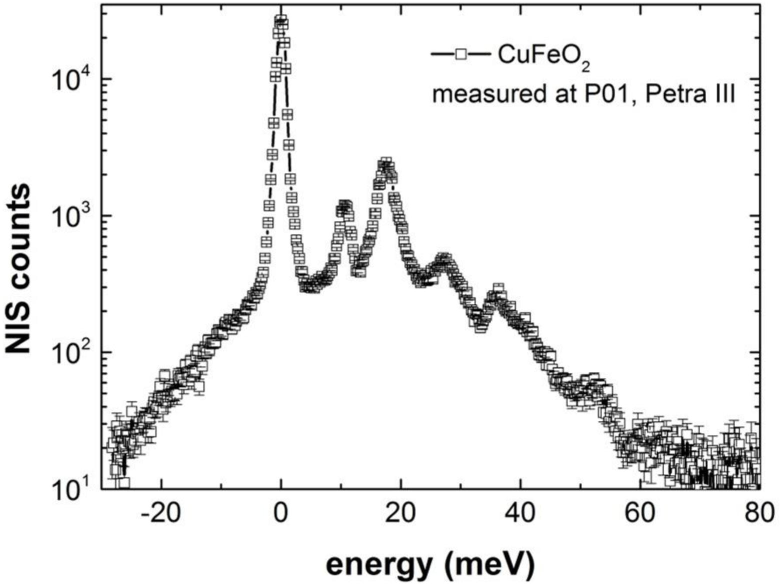
Milli-electronvolt monochromatization of hard X-rays with a sapphire backscattering monochromator

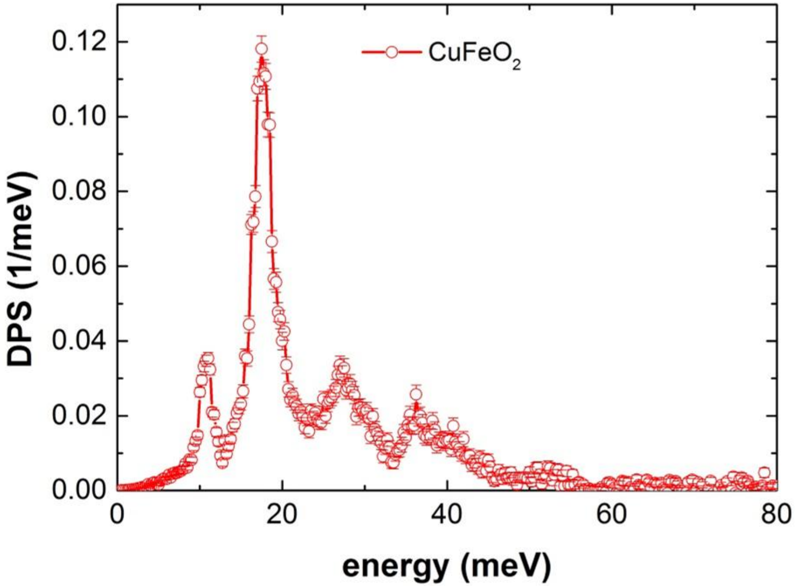
I. Sergueev,[a*] H.-C. Wille,[b] R. P. Hermann,[c,d] D. Bessas,[c,d] Yu. V. Shvyd'ko,[e] M. Zajac[a,f] and R. Rüffer[a]

	Isotope				
	^{121}Sb	^{125}Te	^{119}Sn	^{149}Sm	^{151}Eu
Reflection	$(8\ 16\ \overline{24}\ 40)$	$(9\ 1\ \overline{10}\ 68)$	$(4\ 4\ \bar{8}\ 45)$	$(5\ 10\ \overline{15}\ 22)$	$(3\ 2\ \bar{5}\ 43)$
T (K)	236.8 (1)	219.5 (1)	192.8 (1)	251.5 (1)	289.1 (1)
E (keV)	37.1292 (5)	35.4920 (5)	23.8793 (5)	22.5015 (5)	21.5412 (5)
z (mm)	0.85	0.48	0.28	0.46	0.37
$\Delta E/\Delta T$ (meV mK^{-1})	−0.156	−0.149	−0.084	−0.100	−0.122
d (mm)	1.9 (1)	1.1 (1)	1.1 (1)	2.1 (1)	1.1 (1)
$\Delta E_{\rm th}$ (meV)	0.39	0.70	0.95	0.52	0.77
$\Delta E_{\rm exp}$ (meV)	1.2 (1)	1.1 (1)	1.1 (1)	1.0 (1)	1.1 (1)
$R_{\rm th}$ (%)	59	60	75	59	55
$R_{\rm exp}$ (%)	10	16	65	20	43
$N_{\rm inc}$	0.8×10^{12}	1.5×10^{12}	2.2×10^{12}	2.7×10^{12}	3.4×10^{12}
$N_{\rm ref}$	3.9×10^{7}	7.7×10^{7}	7.7×10^{8}	4.4×10^{8}	7.4×10^{8}

Applications of the ΔE/E=10^{-8} monochromatization

Ultimate Goal of NIS → Density of Phonon States

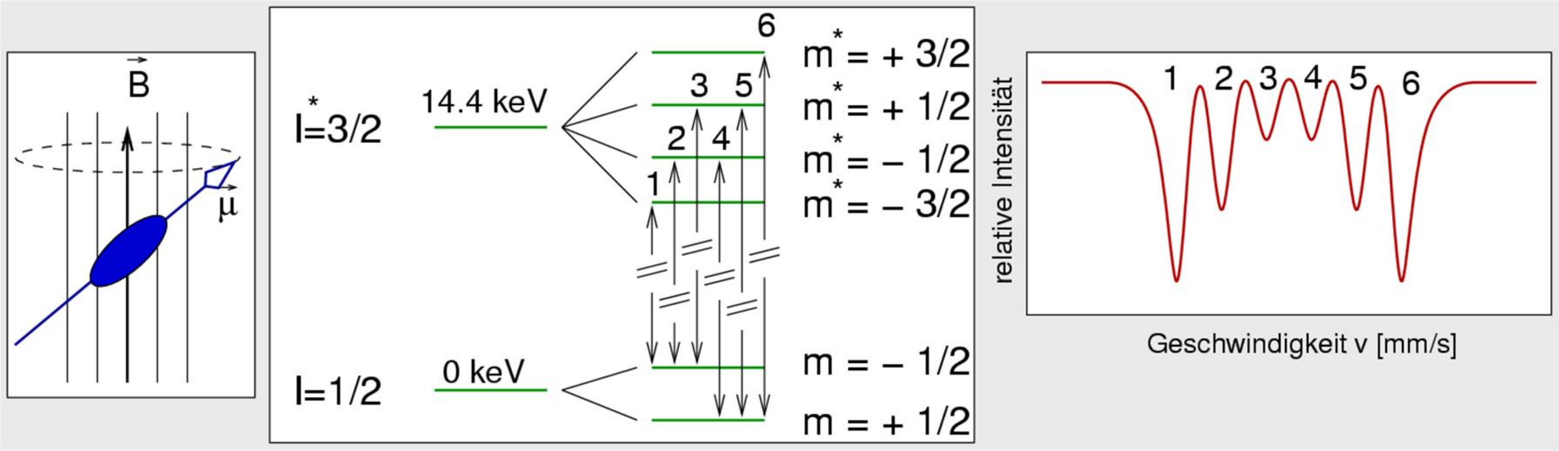




DPS

- speed of sound
- vibr. entropy
- phonons
- internal energy
- force constant
- Grüneisen parameter

Mössbauer Spectroscopy – Magnetic hyperfine splitting



$E_m = \mathbf{B} * \boldsymbol{\mu} = -g_N \mu_N m B$, $\mathbf{B} = \mathbf{B}_{hf} + \mathbf{B}_{ext}$, $\mu_N = e\hbar/(2m_p)$

$\Delta m = 0, \pm 1, \pm L$, degeneration of $2I$+1 states lost

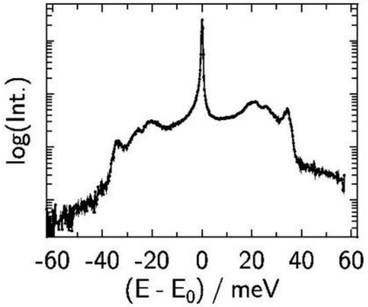
Six lines (multi polarity L=2 quasi not observed in Fe, dipole *M1* only)

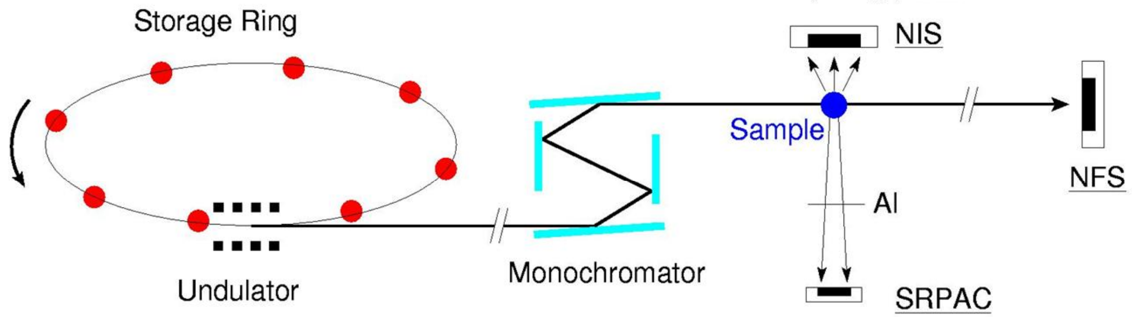
$|I_e - I_g| \leq L \leq I_e + I_g$

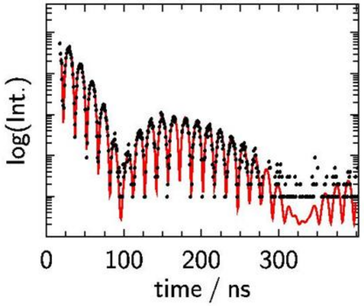
With a known direction of ***μ***, ***B*** can be measured very precisely and vice versa

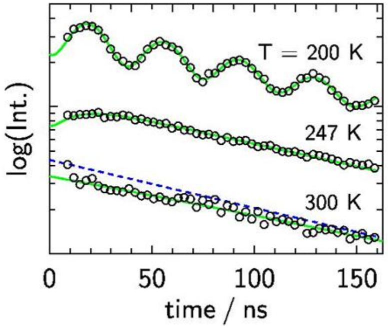
Nuclear Resonant Scattering Techniques

time integral
energy differential
measurement









energy integral
time differential
measurements

Only nuclear resonant photons are counted. These are delayed in time with respect to the prompt electronic scattering due to the lifetime of the nuclear level

-> fast detectors / electronics, timing mode

$$\Gamma = \hbar / \tau$$

Time energy Fourier transformation