X-ray FEL Lays the Groundwork for Scandium-45 Nuclear Clock

Yuri Shvyd'ko

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Warsaw Clock Tower

Brief Introduction to Scandium-45

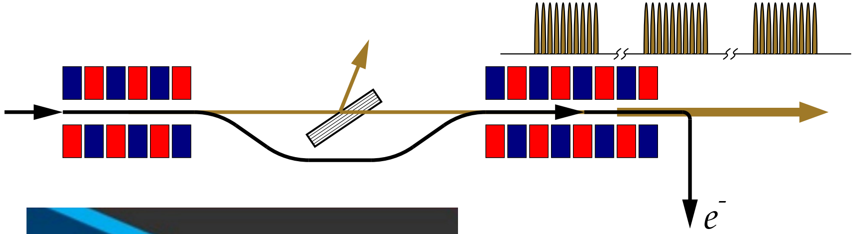
- ^{45}Sc nuclei exhibit an extraordinary narrowband
$$\Gamma_o^{(^{45}\mathrm{Sc})} \simeq 1.4\ \mathrm{feV} = 1.4 \times 10^{-15}\ \mathrm{eV}$$
x-ray resonance transition with transition energy
$$E \simeq 12.4\ \mathrm{keV}$$
and with exceptionally large quality factor
$$Q = E/\Gamma_o^{(^{45}\mathrm{Sc})} \simeq 10^{19}.$$

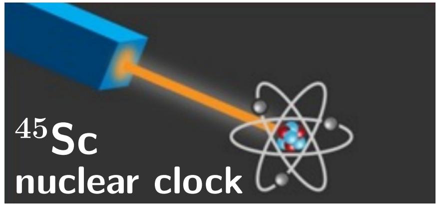
- It has succeeeded in driving this extremely sharp x-ray quantum transition with an x-ray source of highest average spectral brightness: a self-seeded high-repetition-rate XFEL.

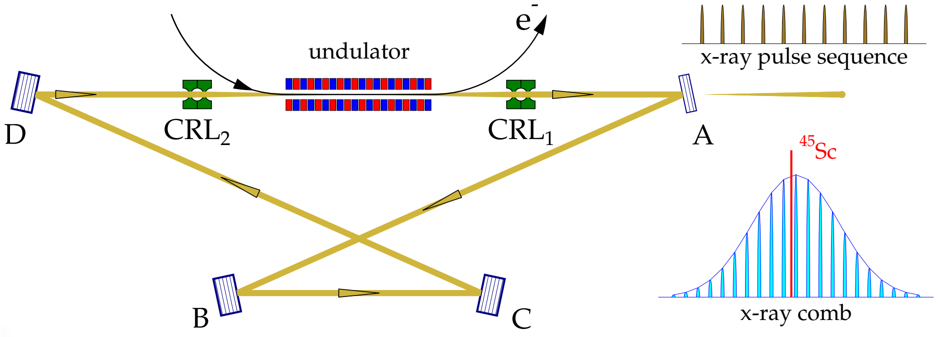
- This opens up new horizons for exquisite applications such as nuclear clocks, extreme metrology, ultra-high-resolution spectroscopy, etc.

- These applications call for further development of the XFEL technology towards XFEL oscillators (XFELO) and x-ray combs.

$$\frac{\Gamma_o^{(^{57}\mathrm{Fe})}}{\Gamma_o^{(^{45}\mathrm{Sc})}} = \frac{4.8\ \mathrm{neV}}{1.4\ \mathrm{feV}} \simeq 3 \times 10^{6}$$







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- ^{45}Sc as a nuclear frequency standard and XFELs.
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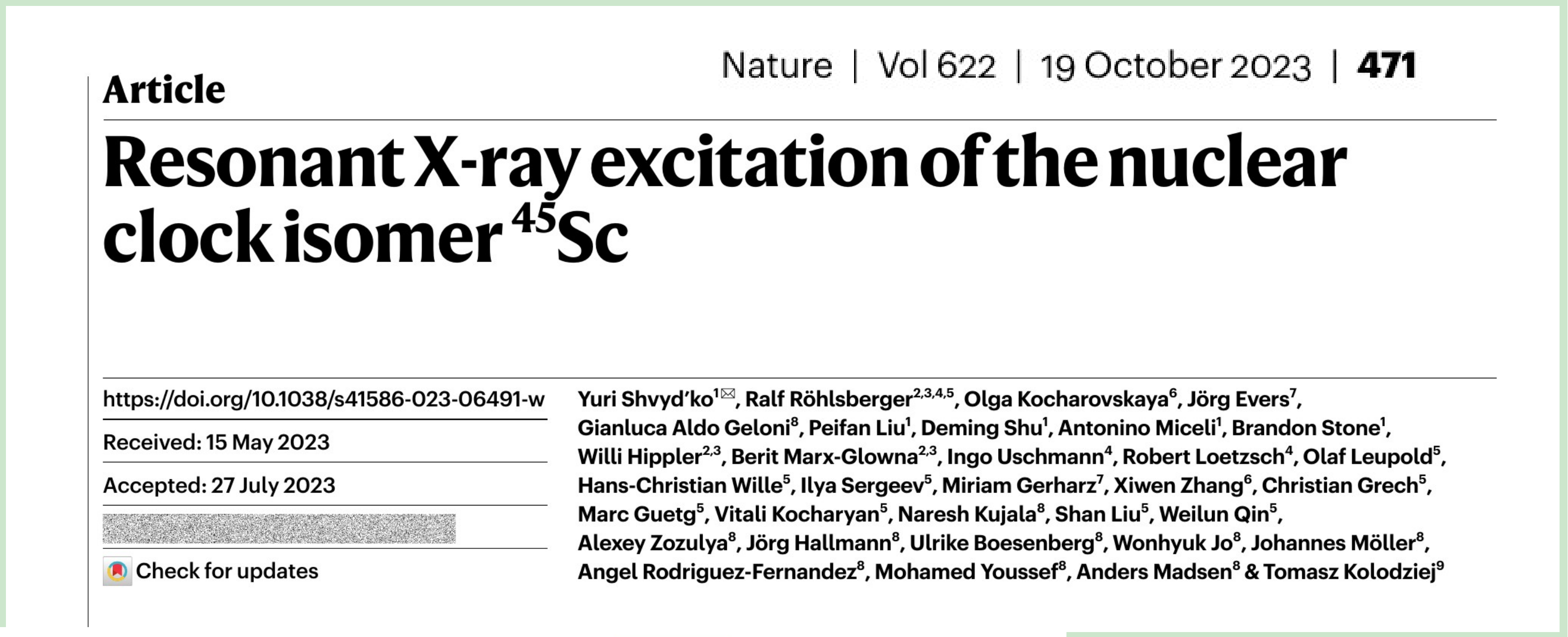

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Article

Resonant X-ray excitation of the nuclear clock isomer ^{45}Sc

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Check for updates

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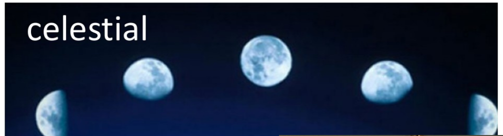
Frequency Standards Enable Time Measurements

Oscillators with stable frequencies and large quality factors – frequency standards – determine our ability to keep track of time. Atomic clocks are presently our most precise measurement devices.

They define the second; enable GPS; test fundamental principles of physics with highest precision ...



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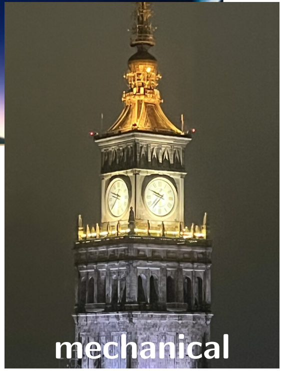

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solid state

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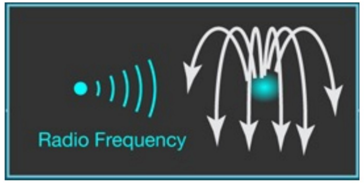
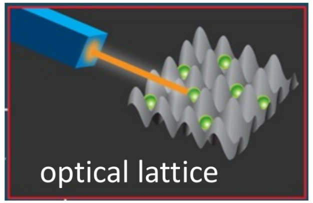
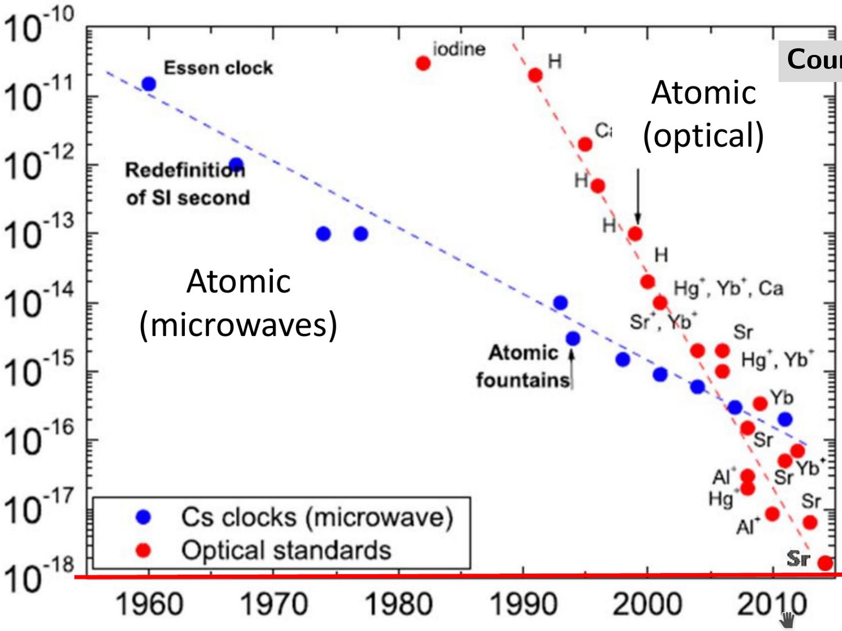
fractional uncertainty







Courtesy of Ralf Röhlsberger

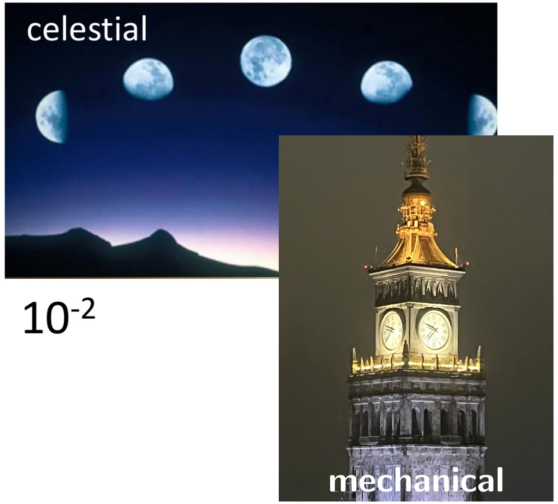
1s in the age of the universe

A. Ludlow, M. Boyd, J. Ye, E. Peik, and P.O. Schmidt "Optical atomic clocks" Rev. Mod. Phys 87 (2015) 637

Frequency Standards Enable Time Measurements

Oscillators with stable frequencies and large quality factors – frequency standards – determine our ability to keep track of time. Atomic clocks are presently our most precise measurement devices.

Search for more accurate, stable, and convenient reference oscillators is ongoing.



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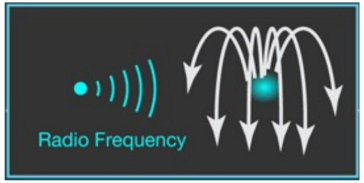

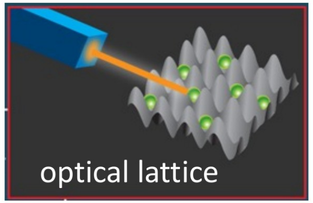

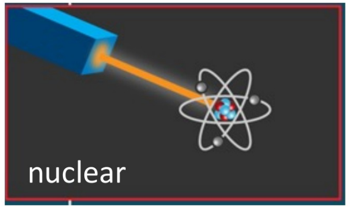

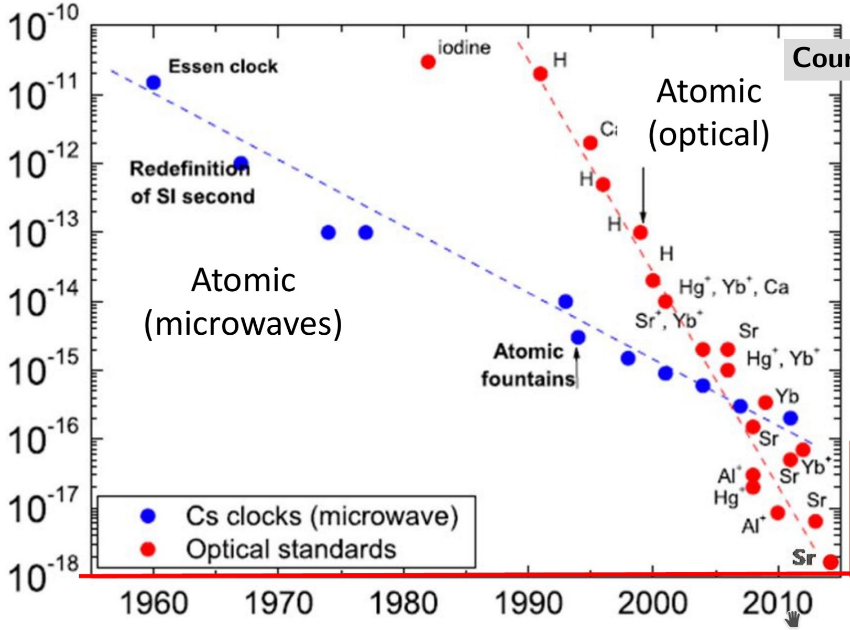

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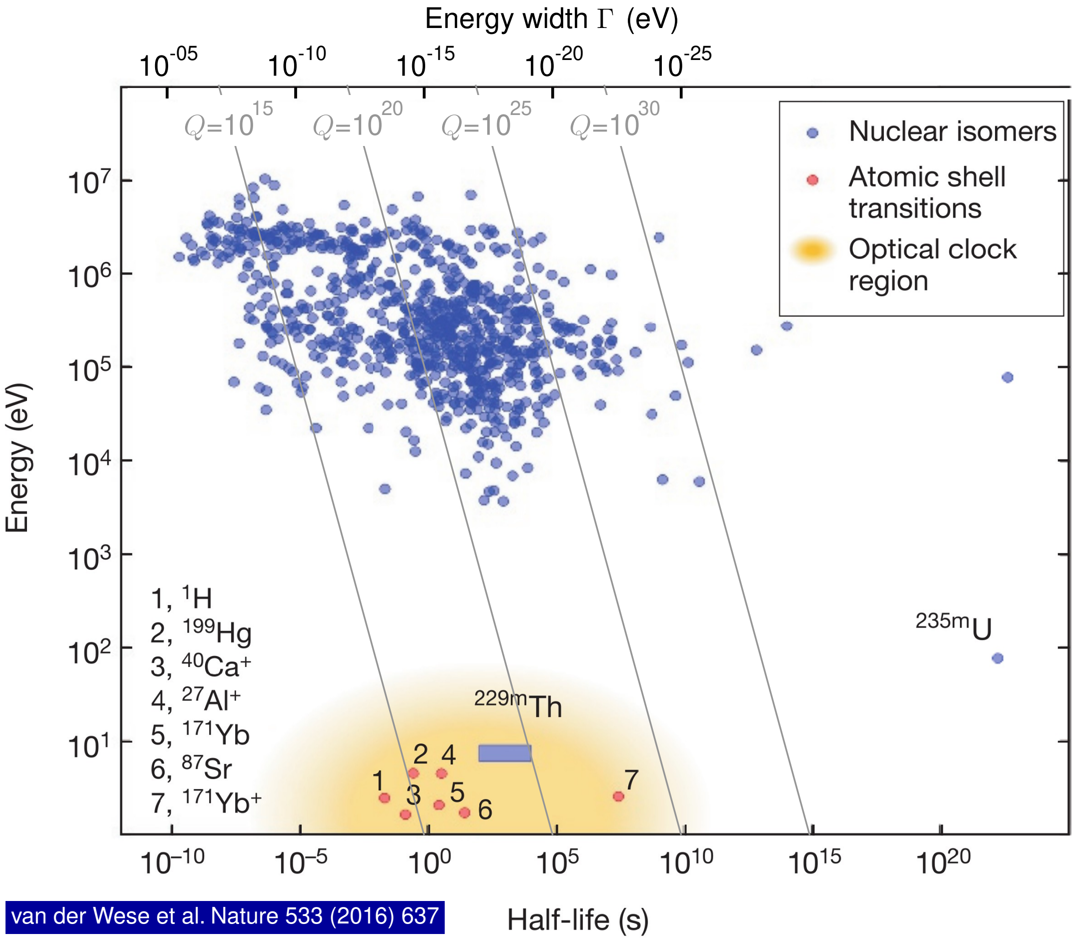
Nuclear vs. Atomic Resonances

1. **Higher Q-factors.** $Q = E/\Gamma$
2. **Higher frequency**: a higher-frequency transition offers greater stability for simple statistical reasons (fluctuations are averaged over more cycles).
3. **Insensitivity to environmental effects.** Due to its small size, small magnetic moments, and the shielding effect of the surrounding electrons, an atomic nucleus is much less sensitive to ambient electromagnetic fields than is an electron in an orbital.
4. **Macroscopic number of atoms can be used,** because of the insensitivity to ambient fields, it is not necessary to have the clock atoms well-separated in a dilute gas or in ion traps a very low temperatures.
5. **Mössbauer effect with nuclei in solids** would allow solid-state amount of nuclei to exhibit narrow spectral resonance line at moderately-low temperatures.

E Peik, et al."Nuclear clocks for testing fundamental physics"
Quantum Sci. Technol. 6 (2021) 034002



van der Wese et al. Nature 533 (2016) 637

Nuclear Clock Isomer ^{229m}Th

$\Gamma_o^{(^{229m}\mathrm{Th})} \sim 10^{-18}$ **eV**

A lot of effort was dedicated to studies of the ^{229m}Th isomer and to accurate measurements of the nuclear transition energy: 8.338(24) eV [*].

L. van der Wese et al. Nature 533 (2016) 637
“Direct detection of the ^{229m}Th nuclear clock transition”

Masuda, T. et al. Nature 573, 239 (2019)
X-ray pumping of the ^{229m}Th nuclear clock isomer.

Seiferle, B. et al. Nature 573, 243 (2019)
Energy of the ^{229m}Th nuclear clock transition.

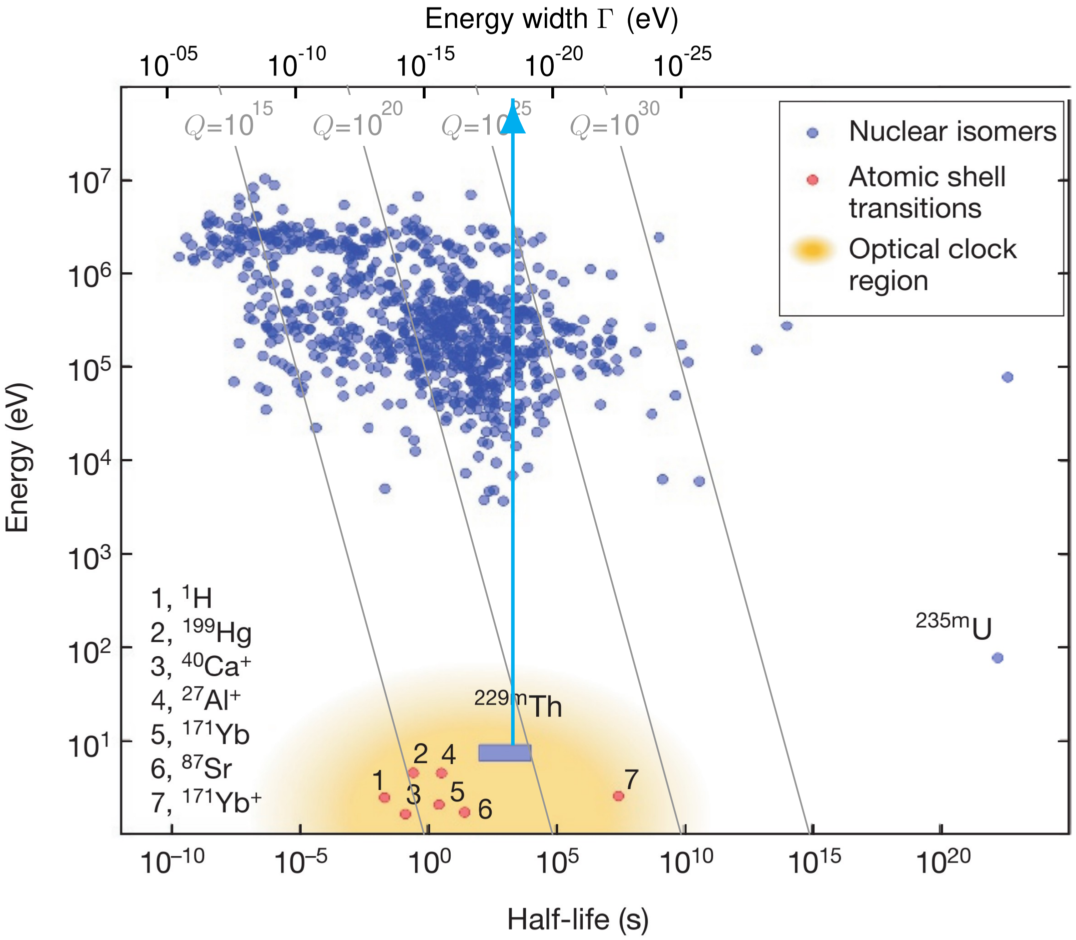
Sikorsky, T. et al. Phys. Rev. Lett. 125, 142503 (2020)
Measurement of the ^{229m}Th isomer energy with a magnetic microcalorimeter

[*] Kraemer, S. et al. Nature 617, 706 (2023)
Observation of the radiative decay of the ^{229m}Th nuclear clock isomer.

Excitation of the ^{229m}Th resonance with photons was achieved very recently: 8.355733(10) eV

[**] J. Tiedau, Peik E. et al. Phys. Rev. Lett. 132 (2024) 182501

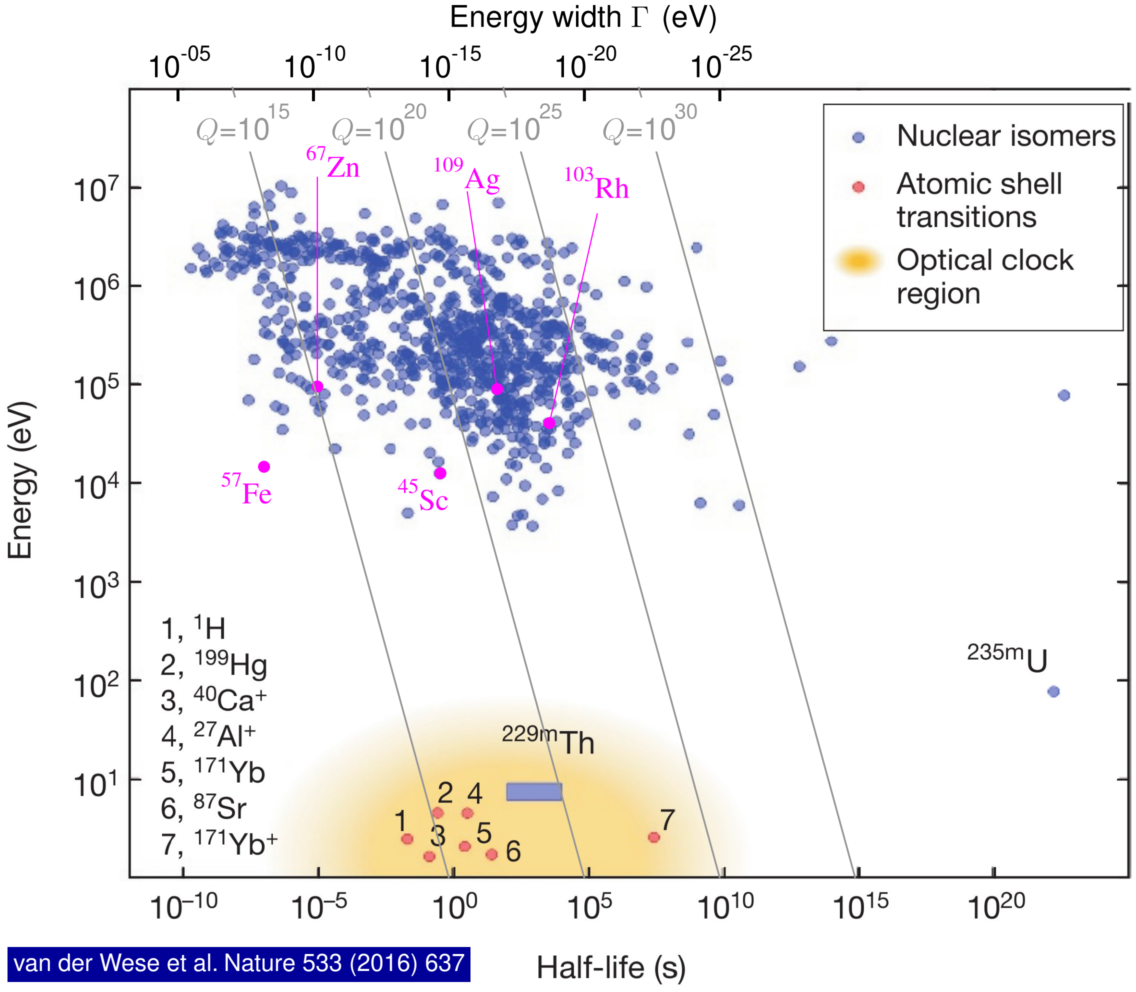
[**] R. Elwell, E. Hudson et al. Phys. Rev. Lett. 133 (2024) 013201



Other Candidates for Nuclear Clocks

Most of the nuclear isomers (with stable ground states) have the excitation energy above 30 keV (^{67}Zn, ^{109}Ag, ^{119}Rh) and therefore cannot be driven by the modern coherent sources of electromagnetic radiation.

Fortunately, along with ^{229m}Th there is another notable exception – ^{45}Sc.

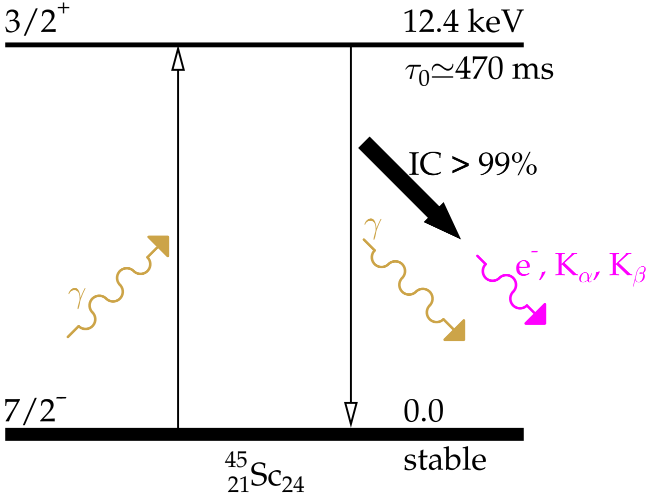


van der Wese et al. Nature 533 (2016) 637

12.4-keV Nuclear Resonance of ^{45}Sc
Basic Features

Excitation energy: $E = 12.40 \pm 0.05$ keV, [1,2,3,6]
excited state lifetime: $\tau = 0.47$ s, [1,5,6]
natural energy width: $\Gamma_0 = \hbar/\tau = 1.4\times10^{-15}$ eV=1.4 feV,
resonance quality: $Q = E/\Gamma_0 \simeq 10^{19}$,
internal conversion coefficient: $\alpha \simeq 630$, [4,5,6]
^{45}Sc natural abundance: 100%,
gravitational red shift: 1 mm/Γ_0,

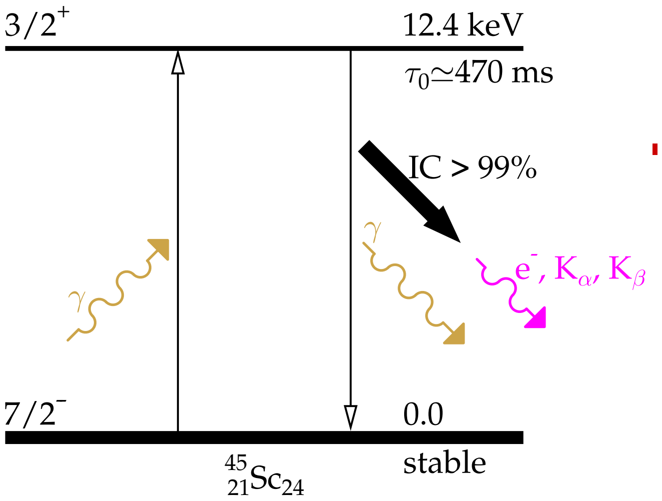
room temperature Lamb-Mössbauer factor: $f_{\mathrm{LM}} \simeq 0.8$.



[1] Holland R.E., Lynch F.J., Nystén K.E., PRL 13 (1964) 241-243.
[2] Freedman, M. S., Porter, F. T. & Wagner F.Jr, Phys. Rev. 140, B563-B565 (1965).
[3] Porter, F. T., Freedman, M. S., Wagner F., & Orlandini, K. A., Phys. Rev. 146, 774-780 (1966).
[4] Jones, K. W. and Schwarzschild, Phys. Rev. 148, 1148–1150 (1966).
[5] Blaugrund, A. E., Holland, R. E. & Lynch, F. J., Phys. Rev. 159, 926–930 (1967).

[6] Burrows, T. W., Nuclear Data Sheets 109, 171-296 (2008).

12.4-keV Nuclear Resonance of ^{45}Sc History in Brief



Excitation energy: $E = 12.40 \pm 0.05$ **keV,**
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- **A 13-keV gamma-emitting state of 0.44-sec mean lifetime was found in ^{45}Sc by (p, p') reaction on ^{45}Sc at Argonne National Laboratory in 1964.** **R.E. Holland, F.J. Lynch, K.E. Nystén, PRL 13 (1964) 241-243**

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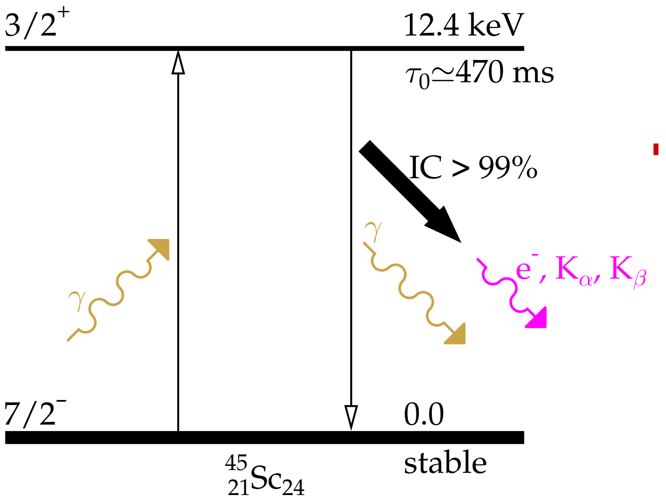

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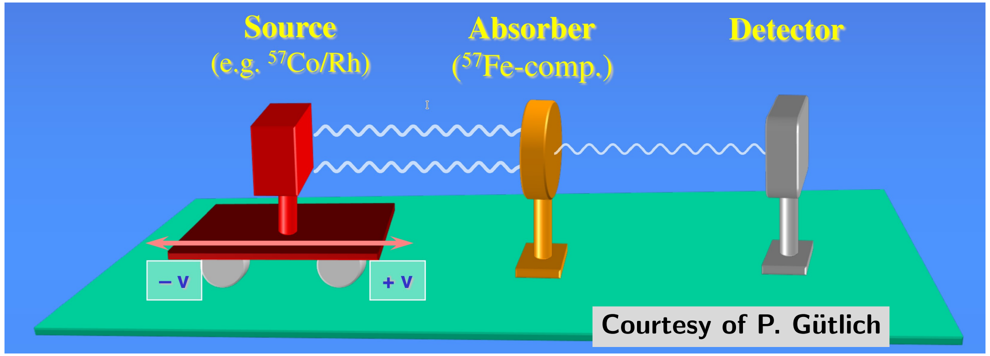
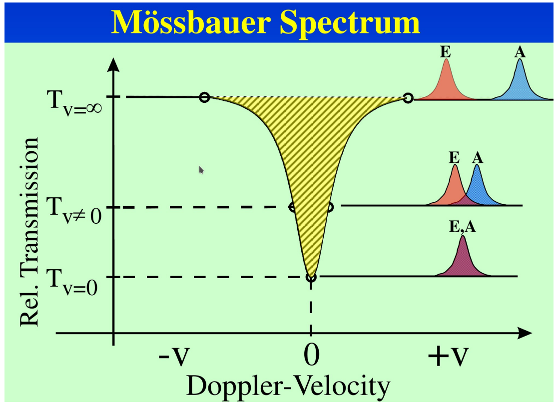
- Unfortunately, ^{45}Sc does not have any convenient parent radioactive source.

This prevented performing classical Mössbauer-type nuclear-resonance measurements.



Courtesy of P. Gütlich



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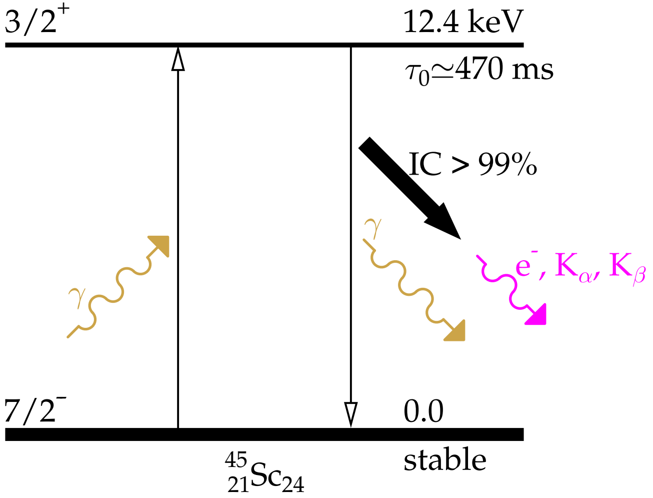

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(1) resonant excitation of ^{45}Sc is feasible using 12.4-keV x-rays from accelerator-based x-ray sources of high spectral brightness and flux, which started to emerge in 1990s (ESRF, APS, SPring-8);
(2) spectral width of the long-lived state can be accessed by measuring time dependence of coherent nuclear-resonant forward scattering (NFS) Yu. Shvyd'ko and G.V. Smirnov NIM 51 (1990) 452-457.

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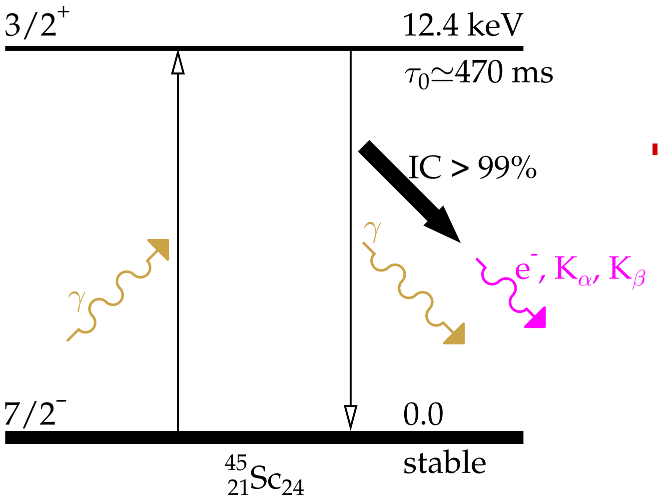

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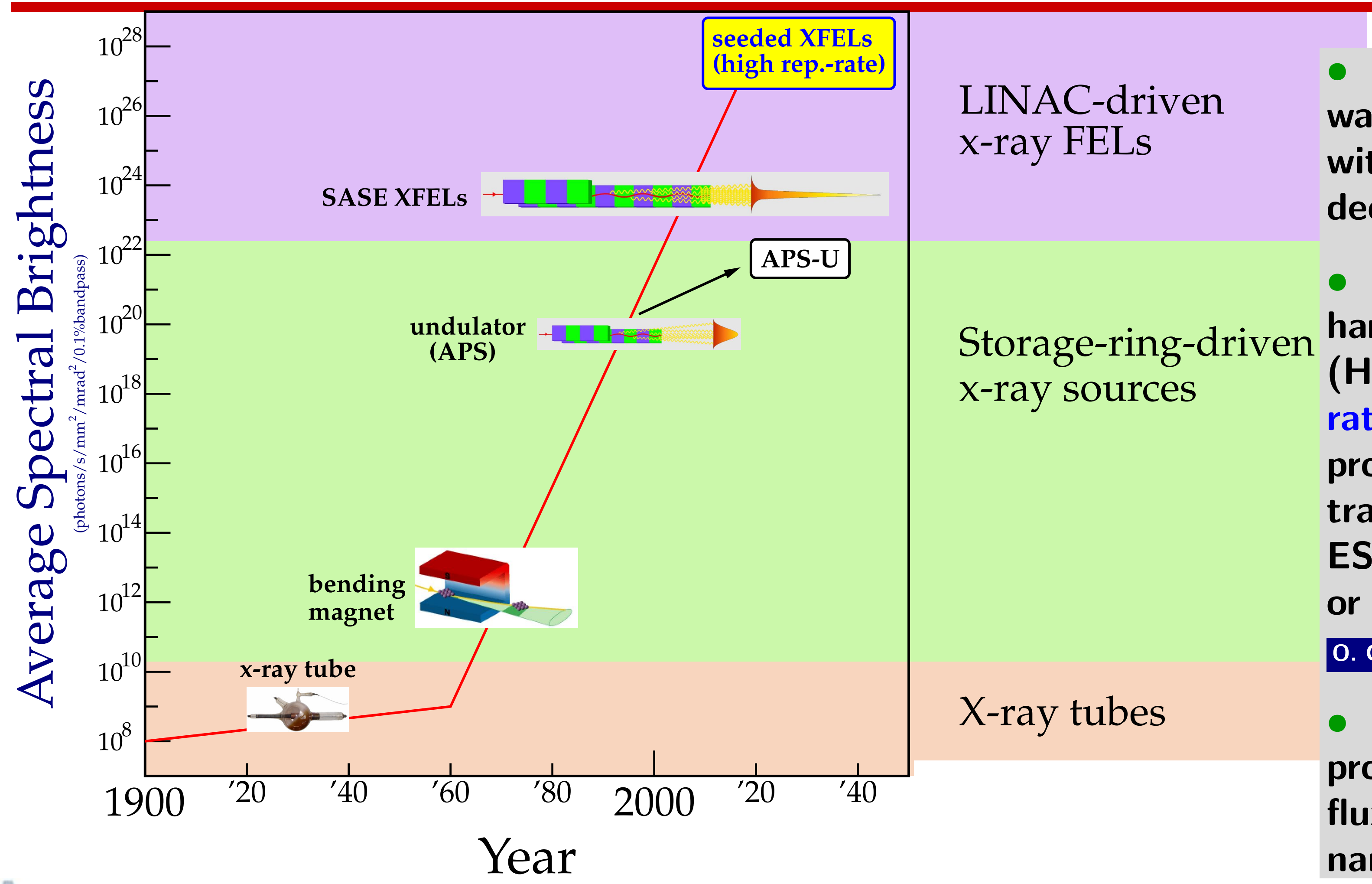
- Attempts to detect the ^{45}Sc resonance at 3rd-generation synchrotron radiation sources (ESRF, APS, SPring-8) were so far unsuccessful. Spectral flux was still low.

History of Hard X-ray Spectral Brightness



- Simultaneously, there was a remarkable progress with XFELs in the past two decades.

- The most advanced hard XFELs – self-seeded (HXRSS) high-repetition-rate (HRR) XFELs – may provide average spectral flux >1000 than ESRF, APS, SPring-8, or PETRA-III undulators.

O. Chubar et al., JSR 23 (2016) 410

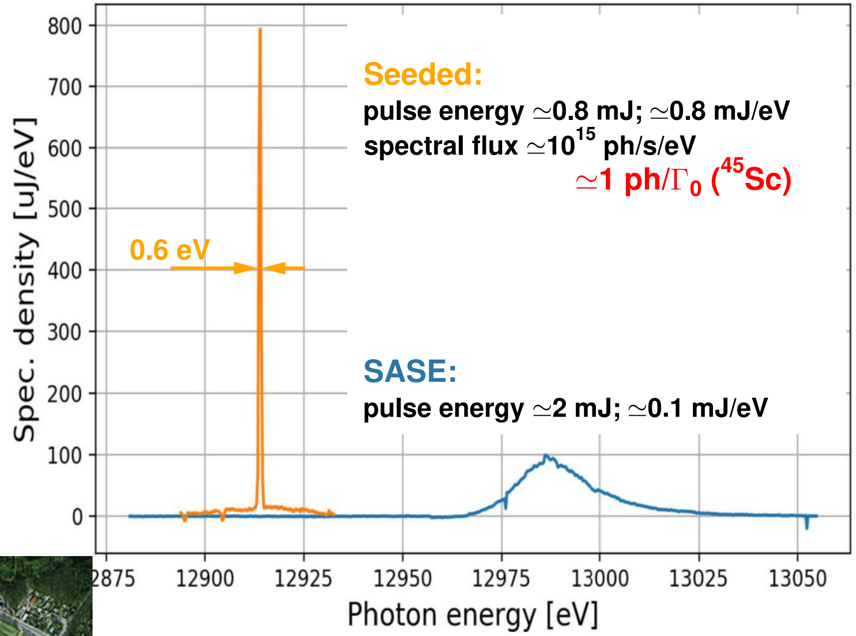
- HXRSS HRR XFELs may provide sufficient spectral flux to drive ^{45}Sc resonance.

^{45}Sc Experiment at European XFEL (Hamburg, Germany)

- European XFEL is the 1st high rep.-rate XFEL W. Decking, et al. Nat. Photonics, 14 (2020) 391.

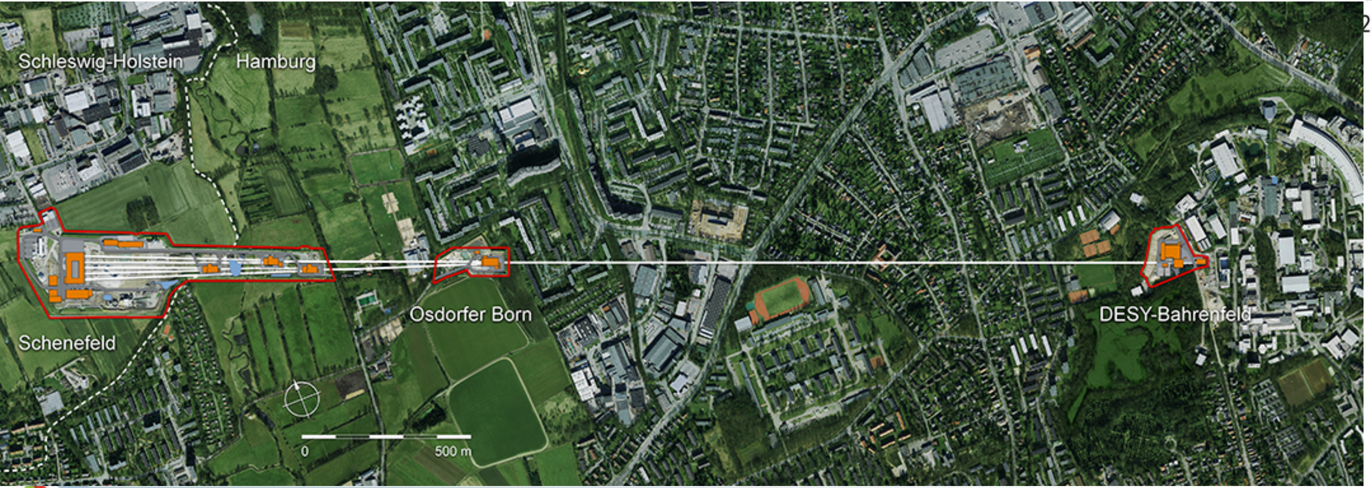
- An average spectral flux at 13 keV of up to $\simeq 10^{15}$ ph/s/eV $\simeq 1$ ph/Γ_0(^{45}Sc) was demonstrated in self-seeded mode S. Liu et al. Nature Photonics 17 (2023) 984.

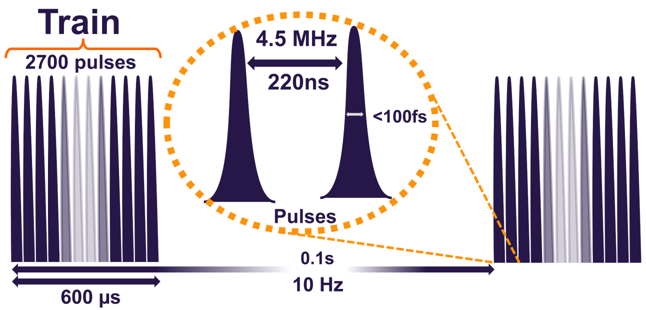
- European XFEL has a unique time structure suitable perfectly for the detection of the ^{45}Sc resonance: sub-ms pulse trains with a 100-ms dark time.



Seeded:
pulse energy $\simeq$0.8 mJ; $\simeq$0.8 mJ/eV
spectral flux $\simeq 10^{15}$ ph/s/eV
$\simeq$1 ph/Γ_0 (^{45}Sc)

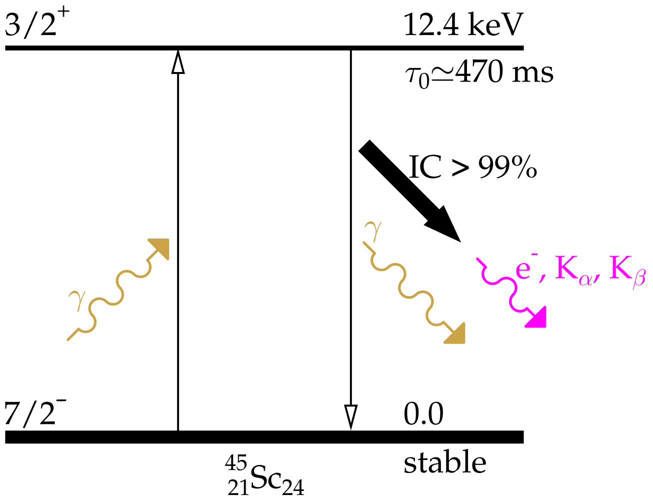
SASE:
pulse energy $\simeq$2 mJ; $\simeq$0.1 mJ/eV

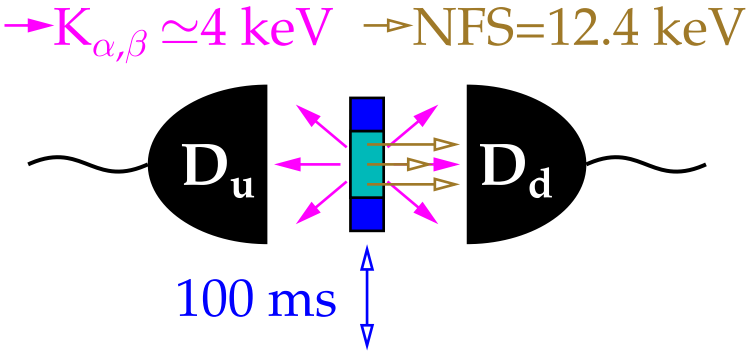


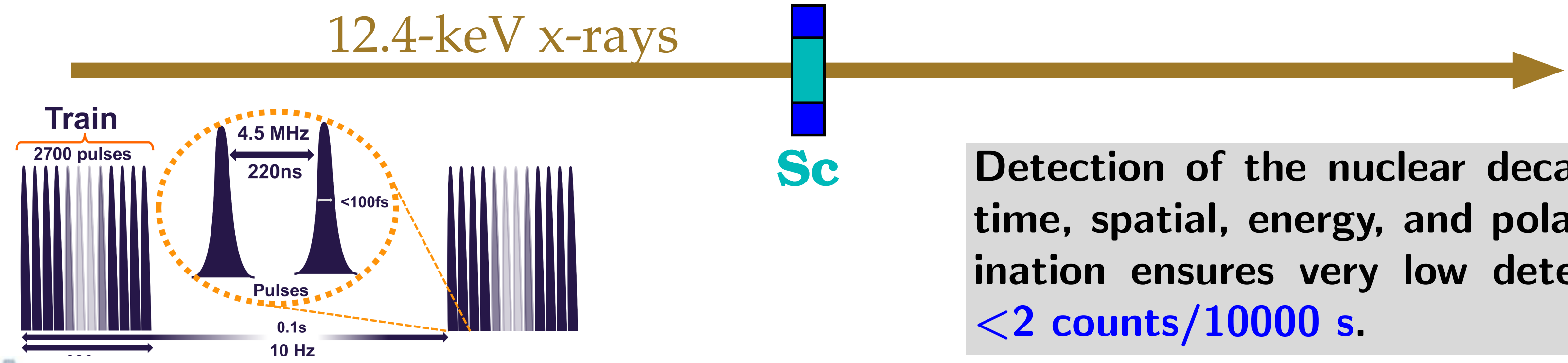


^{45}Sc Experiment in a Nutshell: Highest Spectral Flux – Lowest Detector Background

With a 25-μm thick Sc metal target exposed to an x-ray beam with $\simeq 1$ ph/s/$\Gamma_0 \simeq 10^{15}$ ph/s/eV, the expected count-rate in D$_1$ or D$_2$ of 4-keV K$_{\alpha,\beta}$-fluorescence is 1-5 ph/100 s.

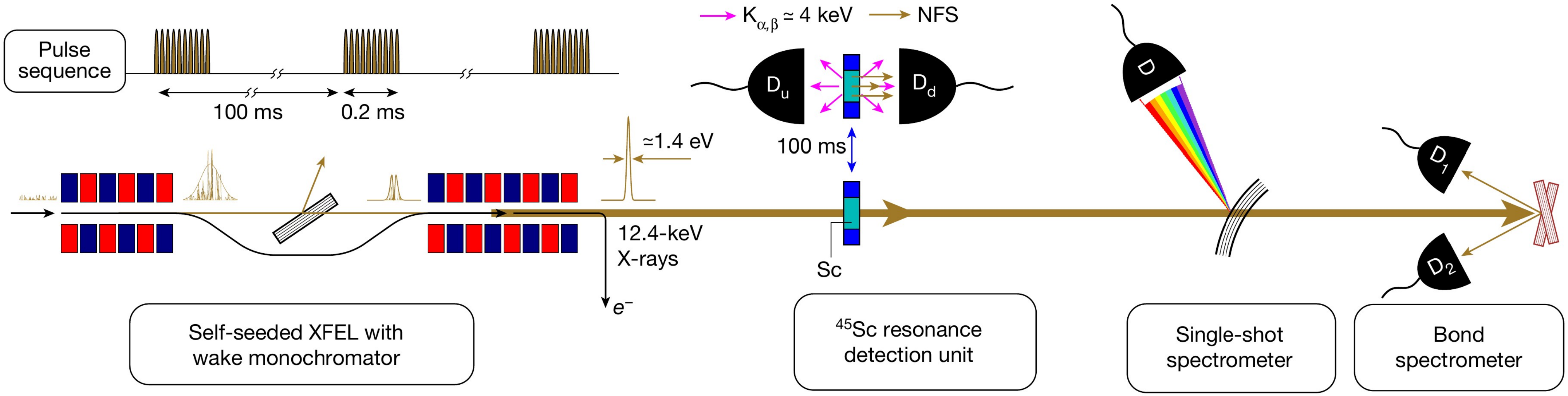




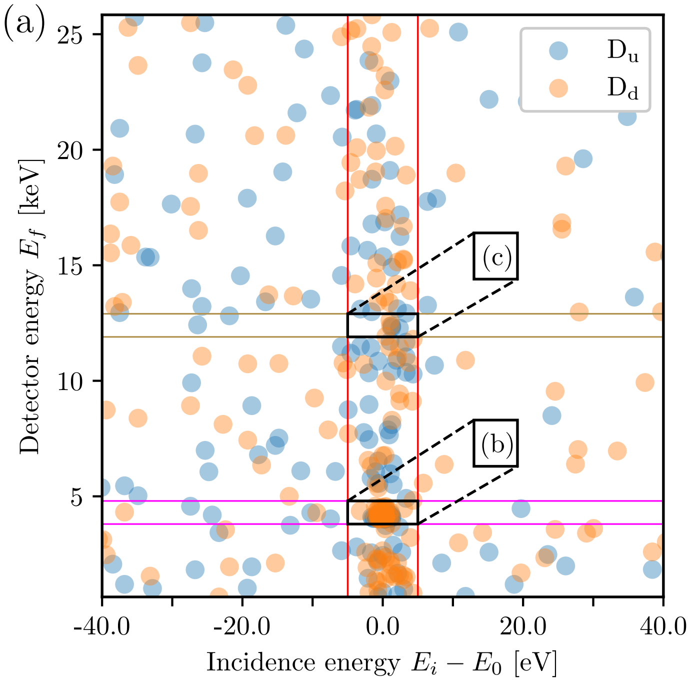


Detection of the nuclear decay products with time, spatial, energy, and polarization discrimination ensures very low detector noise floor <2 counts/10000 s.

Experimental Setup and Experiment Execution



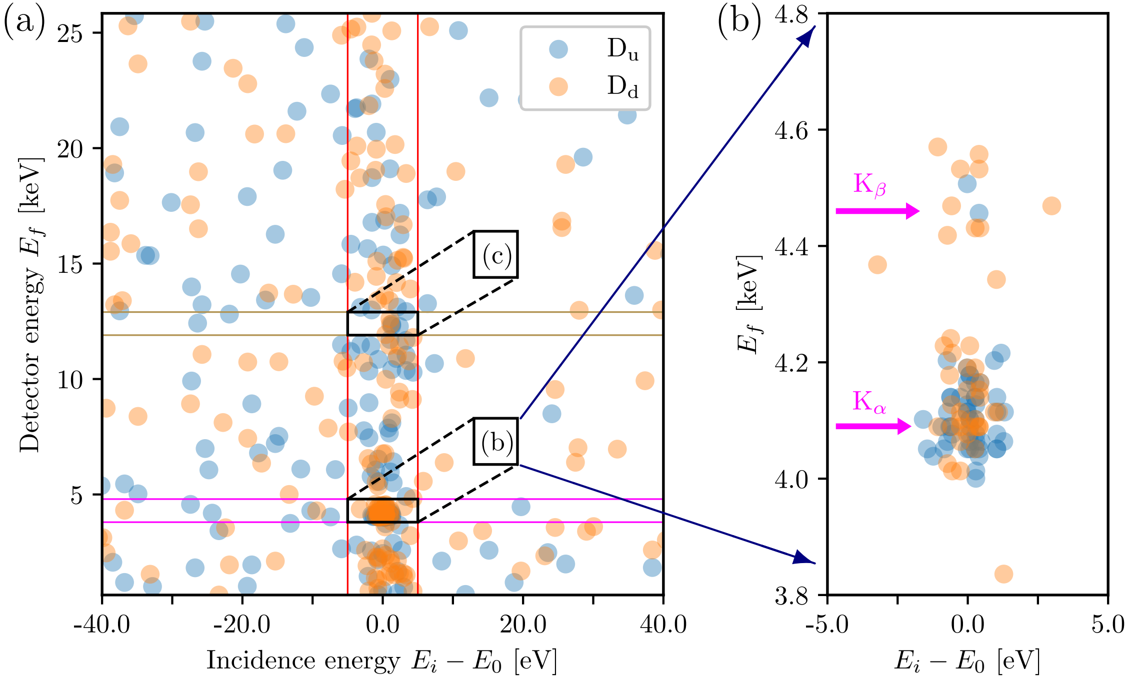
^{45}Sc Resonance Detected - 2D Picture



(a) Counts from the D_u and D_d x-ray detectors plotted as the energy E_f of the detected X-ray photons versus incident X-ray photon energy $E_i - E_0$. The photons were recorded in a time window of ≃20-80 ms after every pulse-train excitation.

- **XFEL photon energy E_i was scanned in a ± 50 eV range around 12.4 keV.**
- **$\simeq 10^{20}$ of 12.4-keV photons were directed to Sc targets.**

^{45}Sc Resonance Detected - 2D Picture



- XFEL photon energy E_i was scanned in a ± 50 eV range around 12.4 keV.
- $\simeq 10^{20}$ of 12.4-keV photons were directed to Sc targets.

- $\simeq$93 of 4-keV $K_{\alpha,\beta}$-fluorescence photons were detected with a $>$20-ms delay.
- Signal to noise ratio $\simeq 70$.

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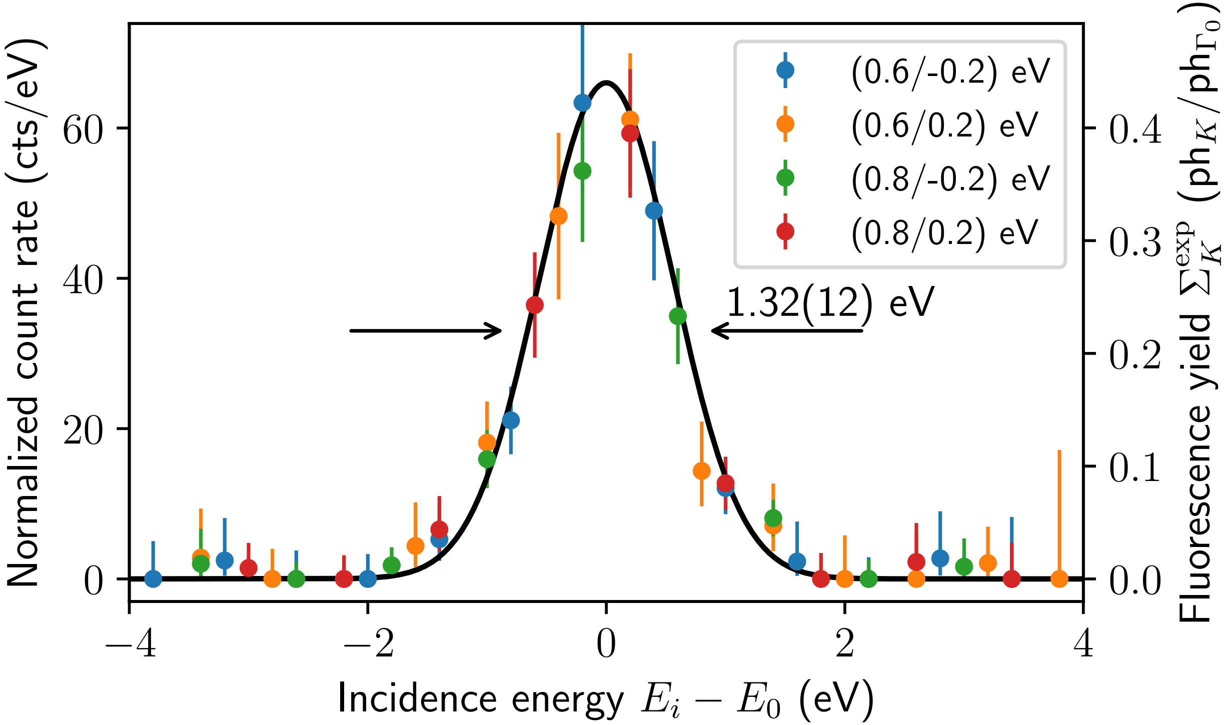
(b) Close-up of the 4.3-keV ROI, showing two clusters of counts centered at the energies of Sc K_α (4.09 keV) and K_β (4.46 keV) fluorescence as a direct confirmation of detection of the ^{45}Sc resonance.

^{45}Sc Resonance Detected & Resonance Energy Determined



Time-delayed ^{45}Sc K-shell fluorescence as a function of incoming X-ray photon energy E_i relative to resonance energy E_0.

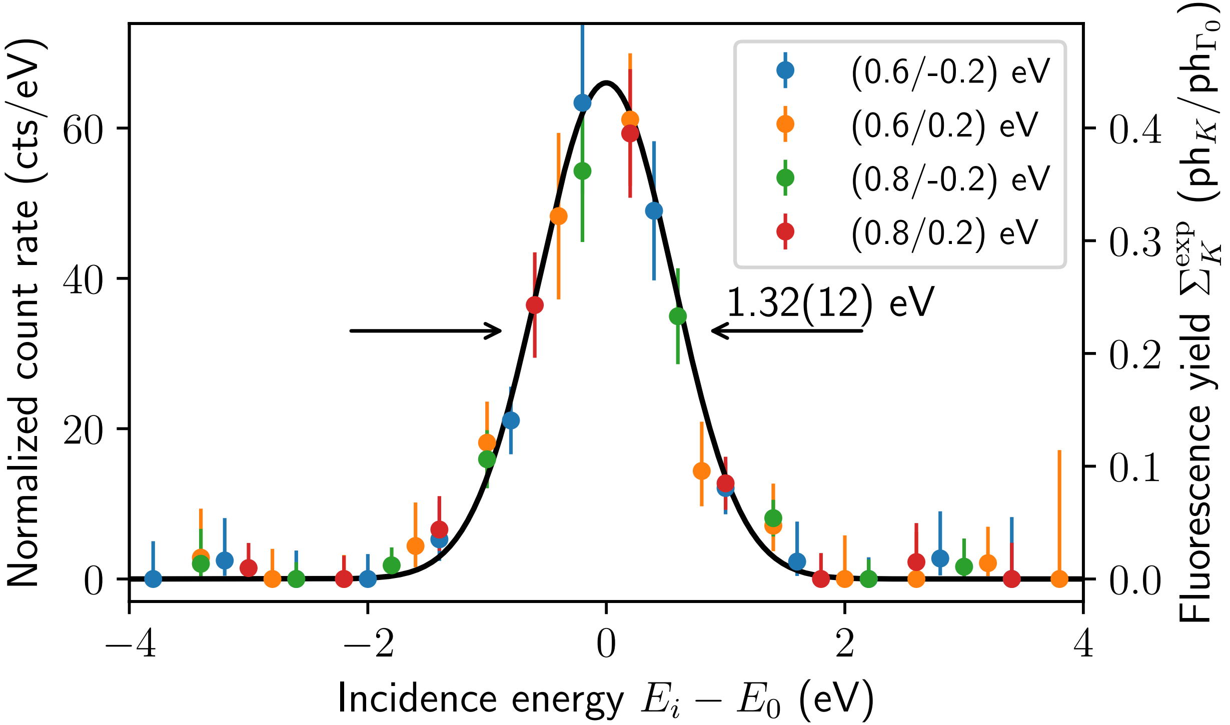
The spectral width of 1.32(12) eV reflects the spectral width of the incoming XFEL radiation. The colored dots are exemplary binned data.

The ^{45}Sc nuclear resonance transition energy E_0 previously known to an uncertainty of $\simeq \pm 50$ eV, was determined with more than a hundred times higher accuracy as

$$E_0 = 12{,}389.59^{\pm 0.15(\mathrm{stat})}_{+0.12(\mathrm{syst})}\ \mathrm{eV}$$

using Bond technique.

^{45}Sc Internal Conversion Coefficients α & α_K and Nuclear Resonance Cross-section σ_0 Refined



The measured nuclear-resonance-assisted K-shell fluorescence yield $\Sigma_K^{\text{exp}} = 0.44(10)$ ph$_K$/ph$_\Gamma$ for one incident resonant photon within Γ_0 is in a 100% disagreement with the value calculated with a theory, which uses published IC coefficients [3-5].

Parameter		Magnitude
Energy	E_0	12,400(50) eV [1,2,5] $12{,}389.59^{\pm 0.15(\text{stat})}_{+0.12(\text{syst})}$ eV
Internal conversion (IC) coefficients	α, α_K	632(71), 474 [3,4,5] 424, 363 [6]
Cross section	σ_0	$1.26(15)\times 10^{-20}$ cm^2 $1.9(5)\times 10^{-20}$ cm^2

A good agreement with the experiment is achieved with IC coefficients predicted by the state-of- the-art internal conversion theory [6]. The resonant cross-section σ_0 can be refined appropriately.

[1] Freedman, M. S., et al., Phys. Rev. 140, B563-B565 (1965).
[2] Porter, F. T., et al., Phys. Rev. 146, 774-780 (1966).
[3] Jones, K. W. and Schwarzschild, Phys. Rev. 148, 1148–1150 (1966).
[4] Blaugrund, A. E., et al., Phys. Rev. 159, 926–930 (1967).
[5] Burrows, T. W., Nuclear Data Sheets 109, 171-296 (2008).

[6] Kibedi, T., et al., NIM A 589, 202-229 (2008).

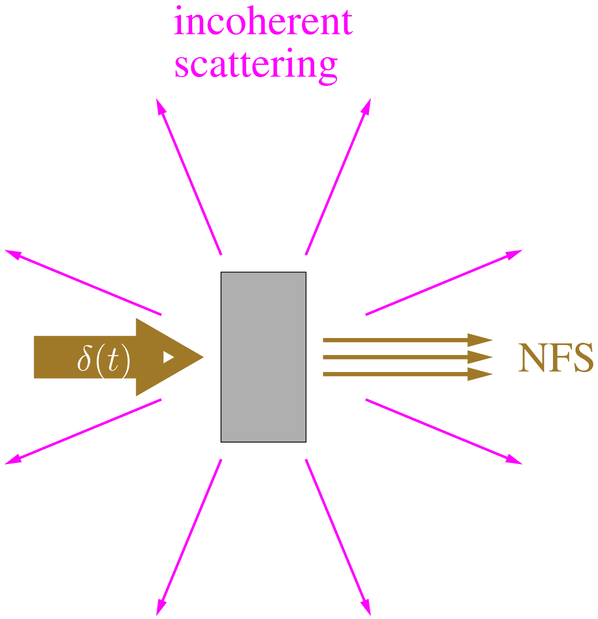
What are the Next Steps with ^{45}Sc?

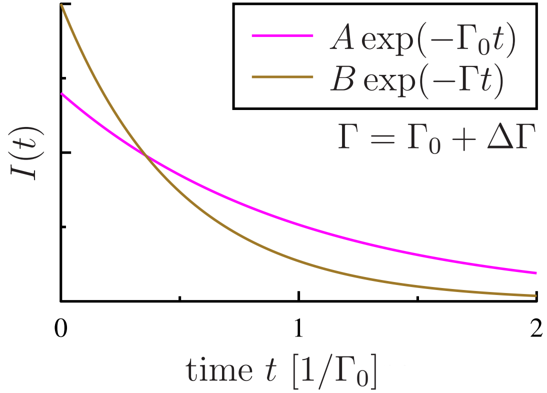
^{45}Sc Nuclear Forward Scattering to Determine the Actual Resonance Width

- We do not know the actual width $\Gamma = \Gamma_0 + \Delta\Gamma$ of the ^{45}Sc resonance in a solid state target, and how much is it broadened – $\Delta\Gamma$ – compared to the natural linewidth Γ_0=1.4 feV?
- Measuring $\Gamma \simeq$ feV directly is a formidable challenge.

- Measuring complementary time dependences on the millisecond-scale instead of energy dependences on the feV-scale is a more straightforward approach.
- It requires measuring time dependence of coherent nuclear forward scattering (NFS) to access Γ.

Yu. Shvyd'ko and G.V. Smirnov NIM 51 (1990) 452-457





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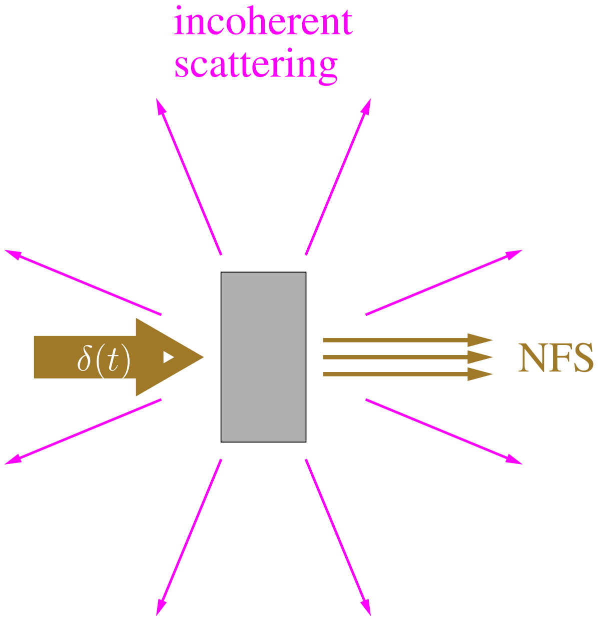
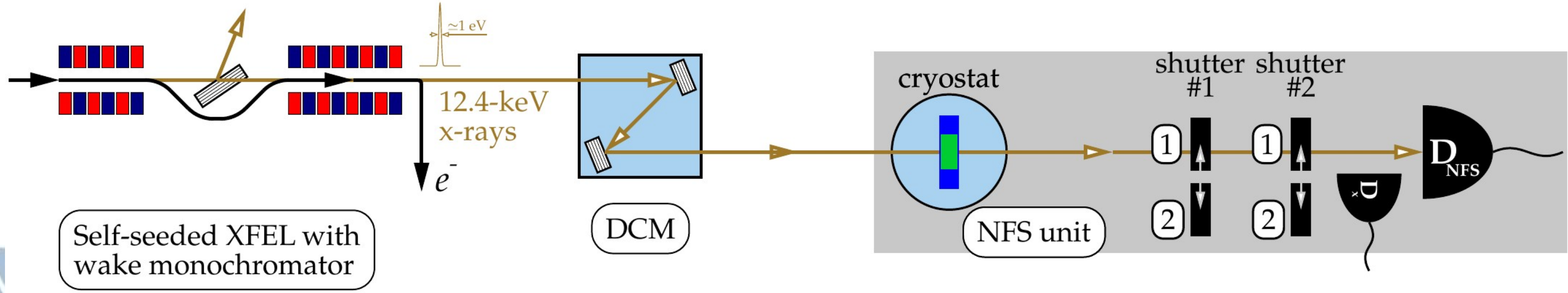
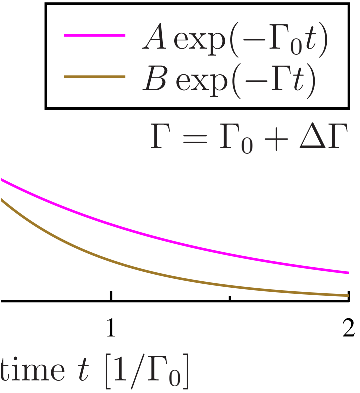


The first ^{45}Sc NFS experiment is planned for 2024 at EuXFEL.





^{45}Sc Nuclear Forward Scattering to Determine the Actual Resonance Width

- We do not know the actual width $\Gamma = \Gamma_0 + \Delta\Gamma$ of the ^{45}Sc resonance in a solid state target, and how much is it broadened – $\Delta\Gamma$ – compared to the natural linewidth Γ_0=1.4 feV?
- Measuring $\Gamma \simeq$ feV directly is a formidable challenge.

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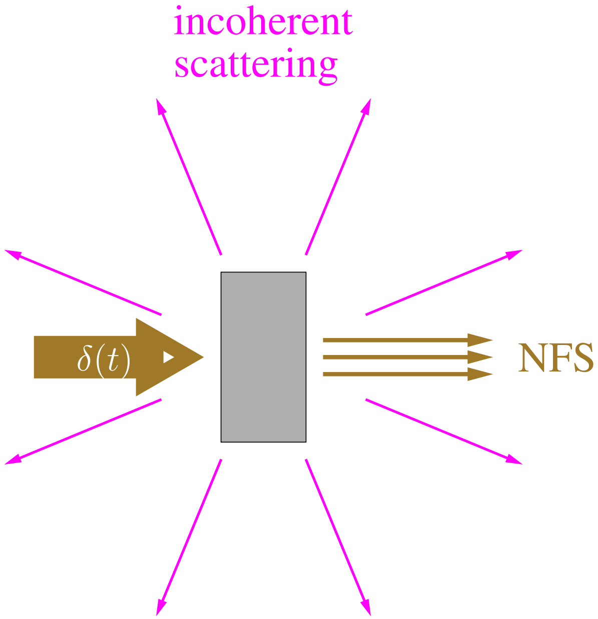
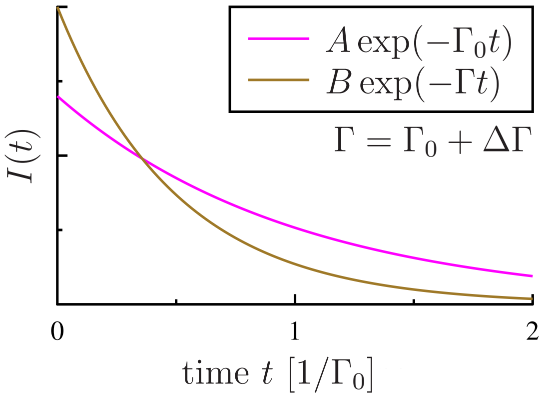
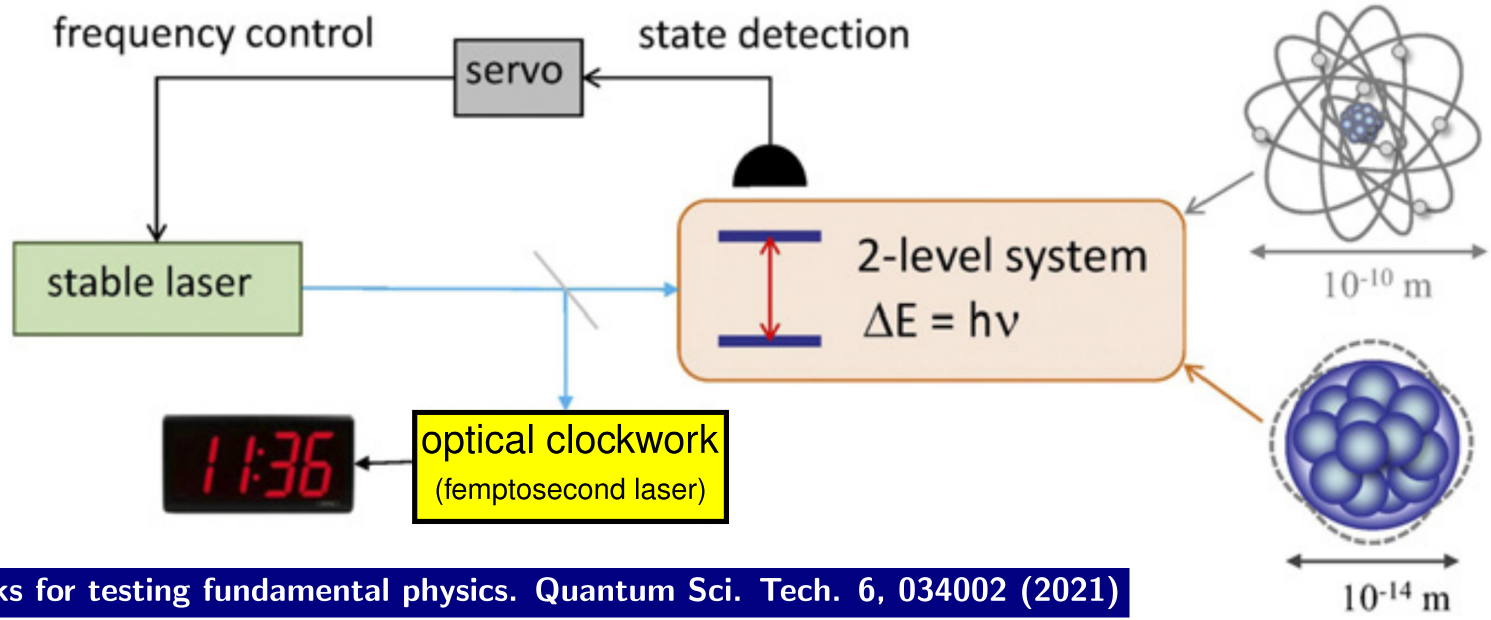
Yu. Shvyd'ko and G.V. Smirnov NIM 51 (1990) 452-457

- Observation of ^{45}Sc NFS will not only allow us to determine Γ, but also enable important applications in ultra-high-precision coherent NFS spectroscopy, extreme metrology, etc. since the narrowness of the ^{45}Sc resonance is expected to surpass all currently accessible Mössbauer resonances by orders of magnitude.





Schematic of an Optical Atomic or Nuclear Clock



Peik, E. et al. Nuclear clocks for testing fundamental physics. Quantum Sci. Tech. 6, 034002 (2021)

The laser oscillator frequency is stabilized to the atomic or nuclear resonance frequency and an optical clockwork is employed to produce a time signal.

Realization of the ^{45}Sc Mössbauer nuclear clock will require (1) a further increase of the resonant spectral flux using improved narrow-band 12.4-keV X-ray sources and (2) frequency combs stretching up to this energy.

Path #1 to ^{45}Sc Mössbauer Nuclear Clock – HHG

- **HHG inside a femtosecond enhancement cavity enables phase-coherent frequency combs in the XUV range:**

  R.J. Jones et al. Phys. Rev. Lett. 94, 193201 (2005).

  A. Cingoz et al. Nature 482, 68–71 (2012).

- **The intracavity HHG was extended into the XUV range with a spectral width of each harmonic of the order of 0.1 Hz:**

  C. Benko, et al. Nature Photonics, 8, 530–537 (2014).

  This would perfectly match the spectral width of the ^{45}Sc resonance.

- **The cut-off photon energy in HHG has been pushed recently into the X-ray range (to 5.2 keV) from laser-induced multivalent ions of noble gas:**

  J. Gao et al. Optica 9, 1003–1008 (2022).

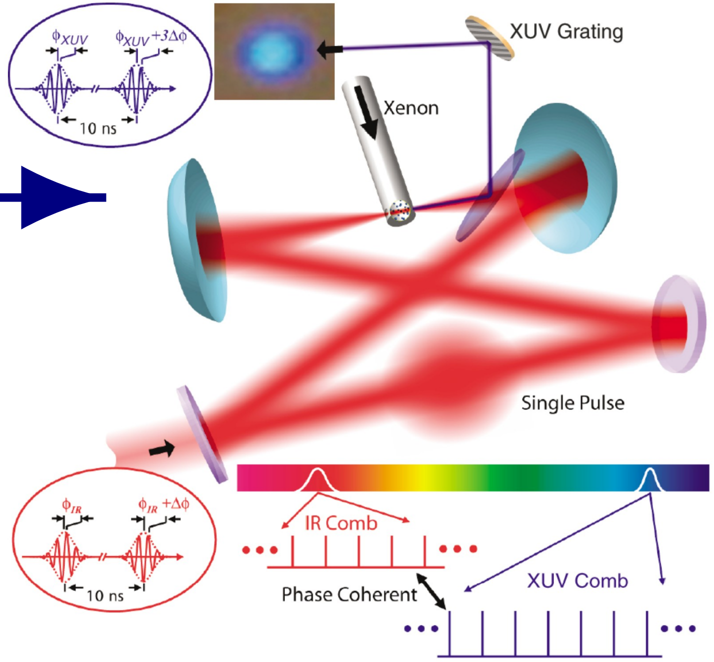


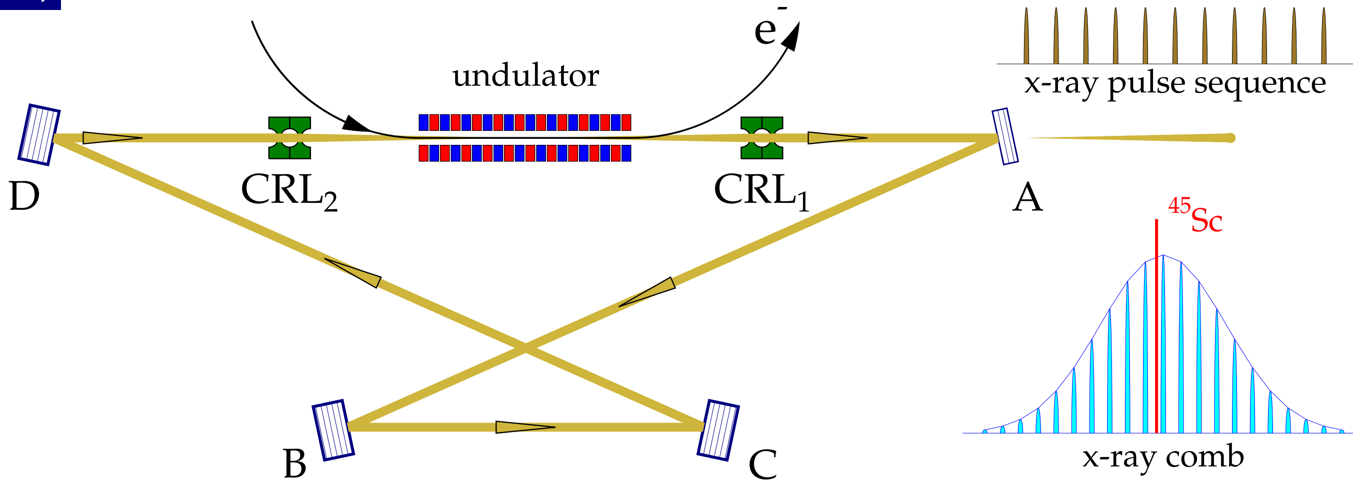
FIG. 1 (color). Schematic setup of intracavity high-harmonic generation. The incident pulse train is stabilized to a high finesse cavity, enhancing pulse energy nearly 3 orders of magnitude while maintaining a high repetition frequency. A gas target at the cavity focus enables phase-coherent HHG, resulting in a phase-stable frequency comb in the vacuum utraviolet (VUV) spectral

Path #2 to ^{45}Sc Mössbauer Nuclear Clock – XFELO

- X-ray free-electron-laser oscillator (XFELO) [1] and hard X-ray comb generated by a nuclear-resonance-stabilized XFELO [2].

[1] K.-J. Kim, Yu. Shvyd'ko, S. Reiche PRL 100, 244802 (2008)

[2] B. Adams and K.-J. Kim PRAB 18, 030711 (2015)



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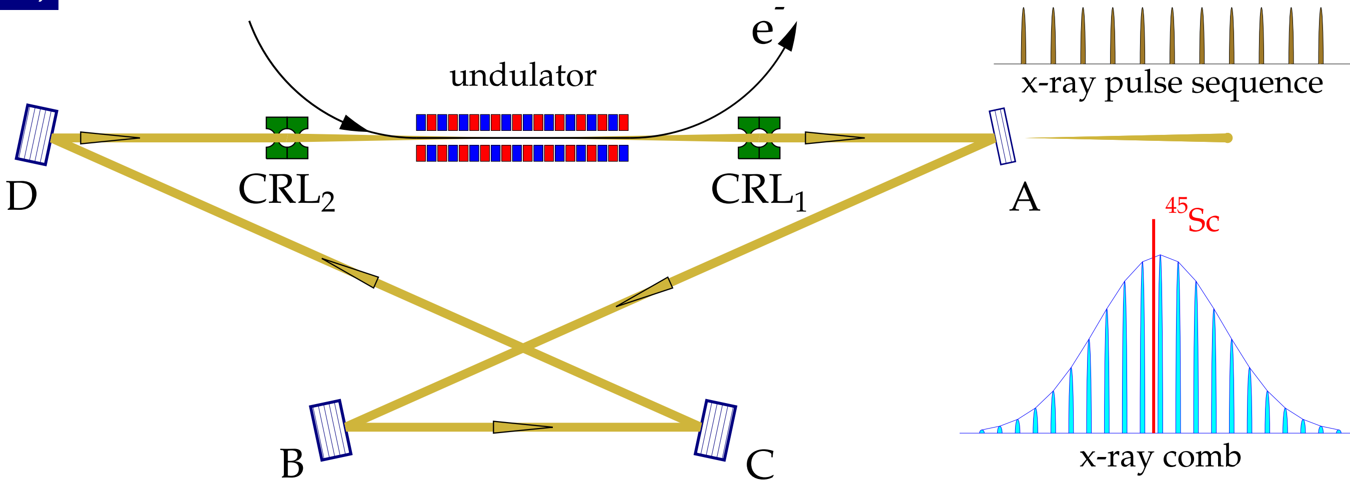


- R&D on the realization of such devices is presently in progress at ANL/SLAC (USA) [3], at EuXFEL (Germany) [4], and is considered at SHINE (China) [5].

[3] G. Marcus et al., (2019) https://doi.org/10.18429/JACoW- FEL2019-TUD04

[4] P. Rauer et al., PRAB 26, 020701 (2023)

[5] N.-S. Huang et al., Nuclear Science and Techniques (2023) 34:6

ANL-SLAC CBXFEL R&D Project (started 2019)

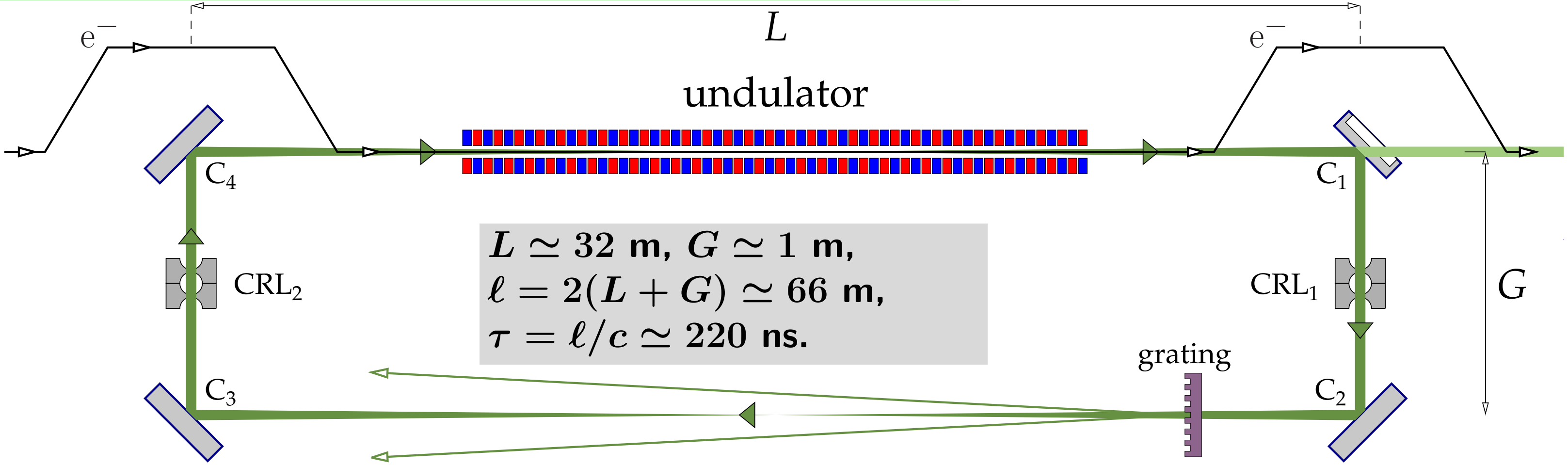
CBXFEL = Cavity-based XFEL

XFELO = low-gain CBXFEL

XRAFEL = high-gain CBXFEL

ANL-SLAC CBXFEL R&D Project (started 2019)

1. Design, construct, and align a rectangular 4-crystal x-ray cavity (32-m long & 220-ns roundtrip-time) in the LCLS-II undulator hall at SLAC enclosing 7 undulator modules.



$$L \simeq 32\ \text{m},\ G \simeq 1\ \text{m},$$
$$\ell = 2(L+G) \simeq 66\ \text{m},$$
$$\tau = \ell/c \simeq 220\ \text{ns}.$$

2. Perform 2-pass FEL gain in a 2-bunch cooper RF linac experiment as well as cavity ring-down measurements for both the low-gain XFELO and the high-gain XRAFEL schemes.

3. Demonstrate the x-ray optical cavity tolerance and stability requirements for future operation with the high repetition rate electron beam from a SCRF linac.

G. Marcus, F.-J. Decker, G. L. Gassner, et al, 39th Free Electron Laser Conf., Hamburg 2019, doi:10.18429/JACoW-FEL2019-TUD04

Summary and Outlook

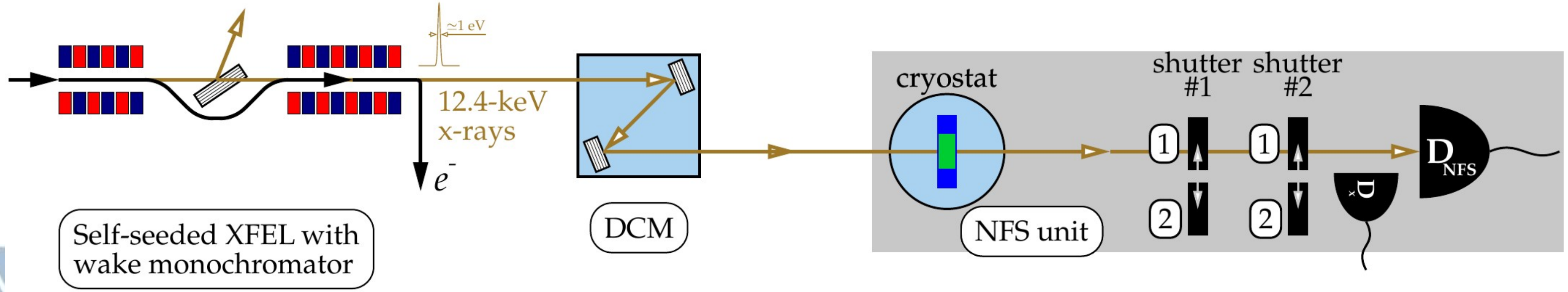
- The long-lived nuclear transition of ^{45}Sc was resonantly excited from the ground to the long-lived 12-4-keV excited state by 12.4-keV x-rays for the first time.

- The resonance energy that was known before the experiment to an uncertainty of ± 50 eV was determined with a sub-eV accuracy as 12,389.59$^{\pm 0.15(\mathrm{stat})}_{+0.12(\mathrm{syst})}$ eV.

- High repetition-rate, narrow-band XFELs is an ideal platform to drive and study long-lived nuclear resonances at energies of hard X-rays. Development of XFELOs is greatly desired.

- Successful resonant excitation of the ^{45}Sc resonance opens up new horizons for ultra-high precision spectroscopy, extreme metrology in the regime of hard x-rays, and for a solid state ^{45}Sc nuclear frequency standard (Mössbauer nuclear clock).

- This was the first step. The next steps (NFS etc.) will be as exciting but not easier. The first ^{45}Sc NFS experiment is planned for October 2024 at EuXFEL.



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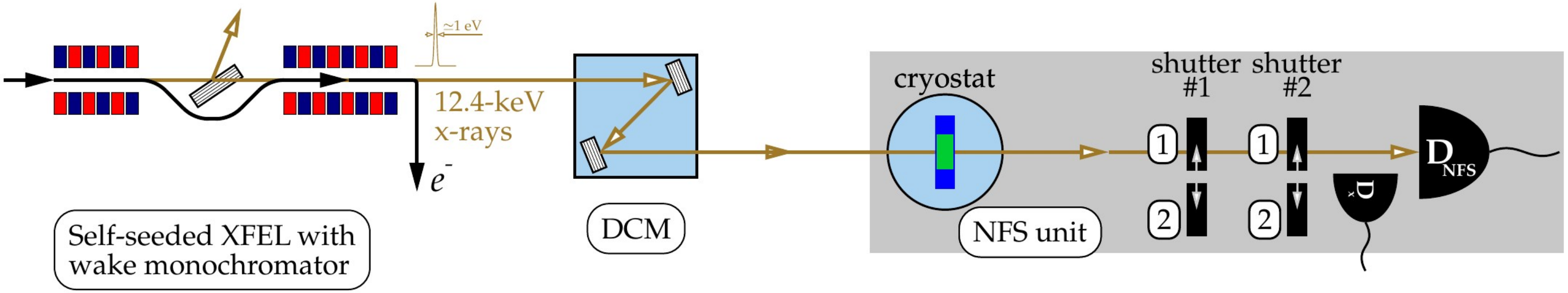
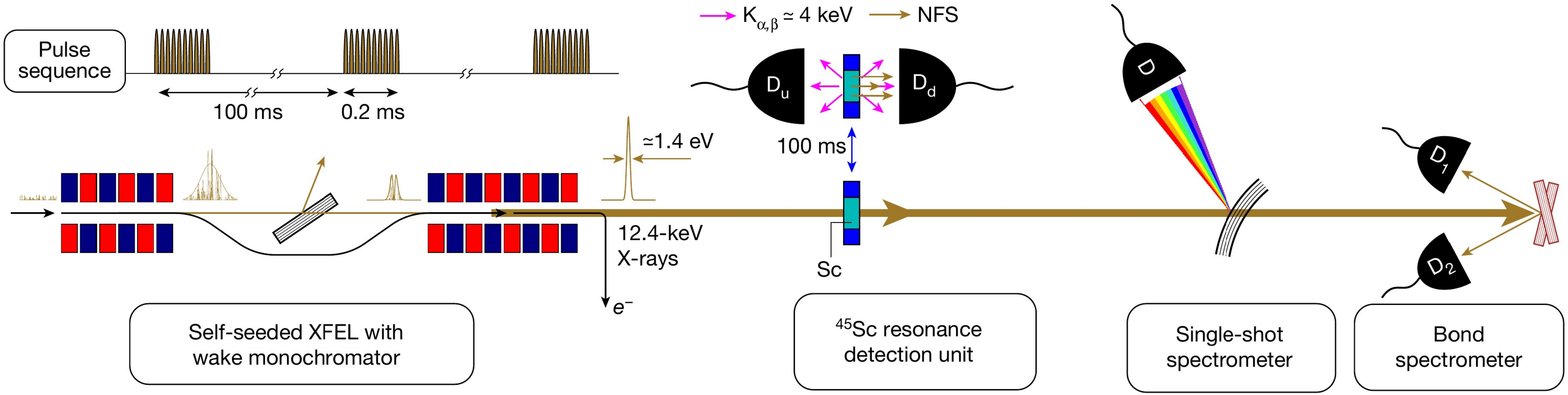


Thank you very much for your attention!

Supplementary Slides

Experimental Setup and Experiment Execution



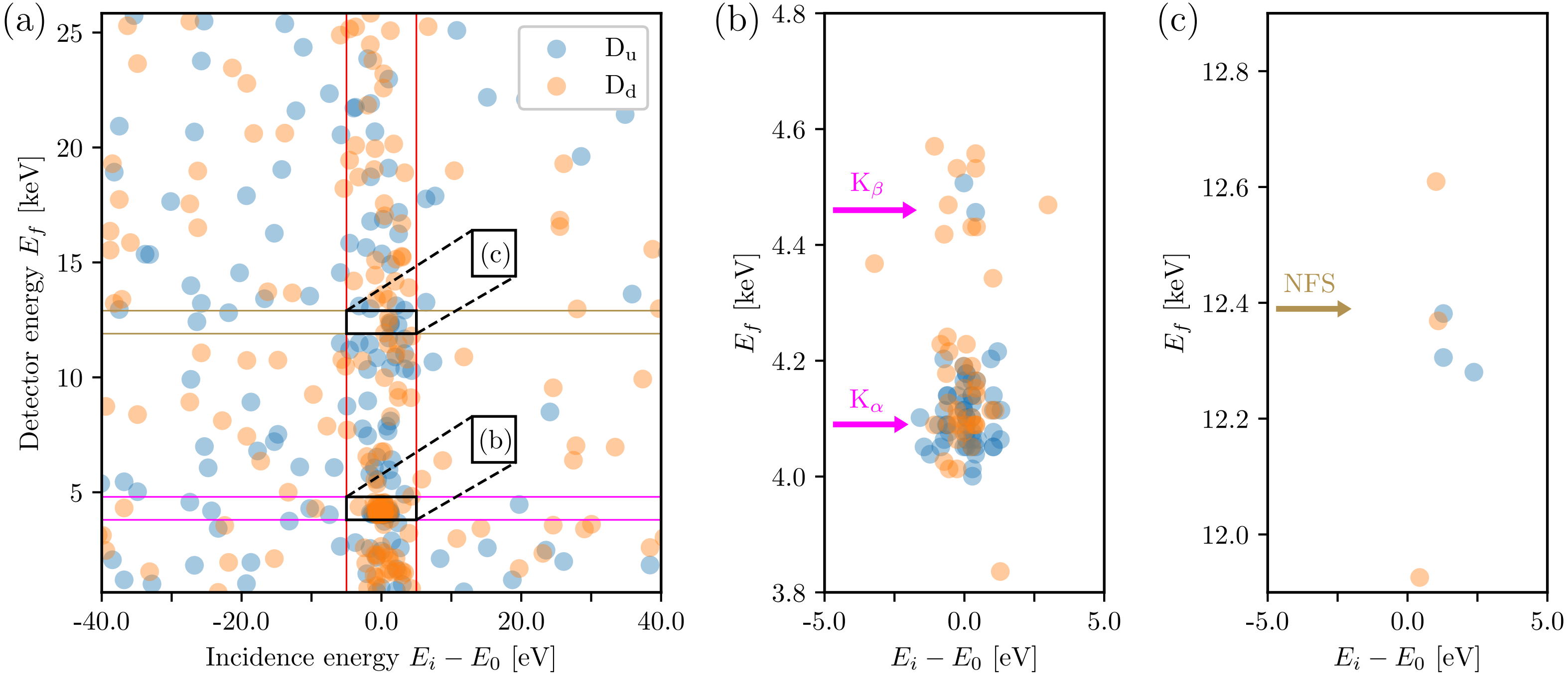
Eu XFEL provided for the experiment:
⇒0.2-ms pulse trains every 100 ms
⇒$\simeq 5 \times 10^{14}$ ph/s/eV ⇒ 1.4 W
⇒$\simeq 0.7$ ph/s/Γ_0
⇒tunable in a ± 50 eV range.

Target: ⇒a 25-μm Sc-metal foil; ⇒moved between irradiation and detection locations every 100 ms (transient time $<$20 ms); ⇒water and air cooled.

⇒Single-shot relative resolution and stability $<$50 meV; ⇒Bond spectrometer absolute resolution $<$300 meV.

Detectors D_1-D_2 had very low background $<$2 counts/10000 s since they ⇒were inhibited during irradiation; ⇒placed 12-mm off the 12.4-keV beam; ⇒had $<$150-eV energy resolution.

Searching for ^{45}Sc Resonance



(a) Counts from the D_u and D_d x-ray detectors plotted as the energy E_f of the detected X-ray photons versus incident X-ray photon energy $E_i - E_0$. The photons were recorded in a time window of about 20-80 ms after every pulse-train excitation.

(b) Close-up of the 4.3-keV ROI, showing two clusters of counts centered at the energies of Sc K_α (4.09 keV) and K_β (4.46 keV) fluorescence. This is a direct confirmation of detection of the ^{45}Sc resonance.

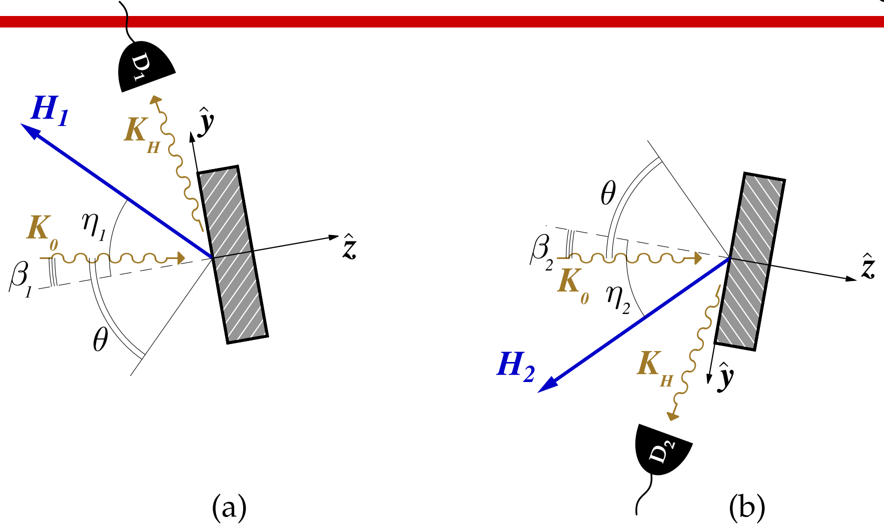
(c) Close-up of the 12.4-keV ROI. NFS signal at 12.4 keV is statistically insignificant. NFS is the prime next goal.

Measurement of ^{45}Sc Nuclear Resonance Transition Energy

The ^{45}Sc nuclear resonance transition energy E_0 previously known to an uncertainty of $\simeq \pm 50$ eV only, was determined with more than a hundred times higher accuracy as

$$E_0 = 12{,}389.59^{\pm 0.15(\mathrm{stat})}_{+0.12(\mathrm{syst})}\ \mathrm{eV}$$

using Bond technique.



(a) (b)

Bond technique uses Bragg diffraction of X-rays with wavevector K_0 from atomic planes with diffraction vectors (a) $H_1 = (8\ 0\ 0)$ and (b) $H_2 = (0\ 8\ 0)$ from a Si crystal. The crystal is rotated by $\beta = \beta_1 + \beta_2$ between the angular positions of the (8 0 0) and the (0 8 0) Bragg reflections. X-ray wavelength $\lambda = 2\pi/K_0$ and photon energy E are calculated from the know crystal lattice parameter a_{Si} using modified Bragg's law:

$$\lambda = \frac{hc}{E} = \frac{a_{\mathrm{Si}}}{4}\sin(\pi/4 + \beta/2)\,. \qquad (1)$$

W.L. Bond, Acta Crystallogr. 13 (1960) 814.

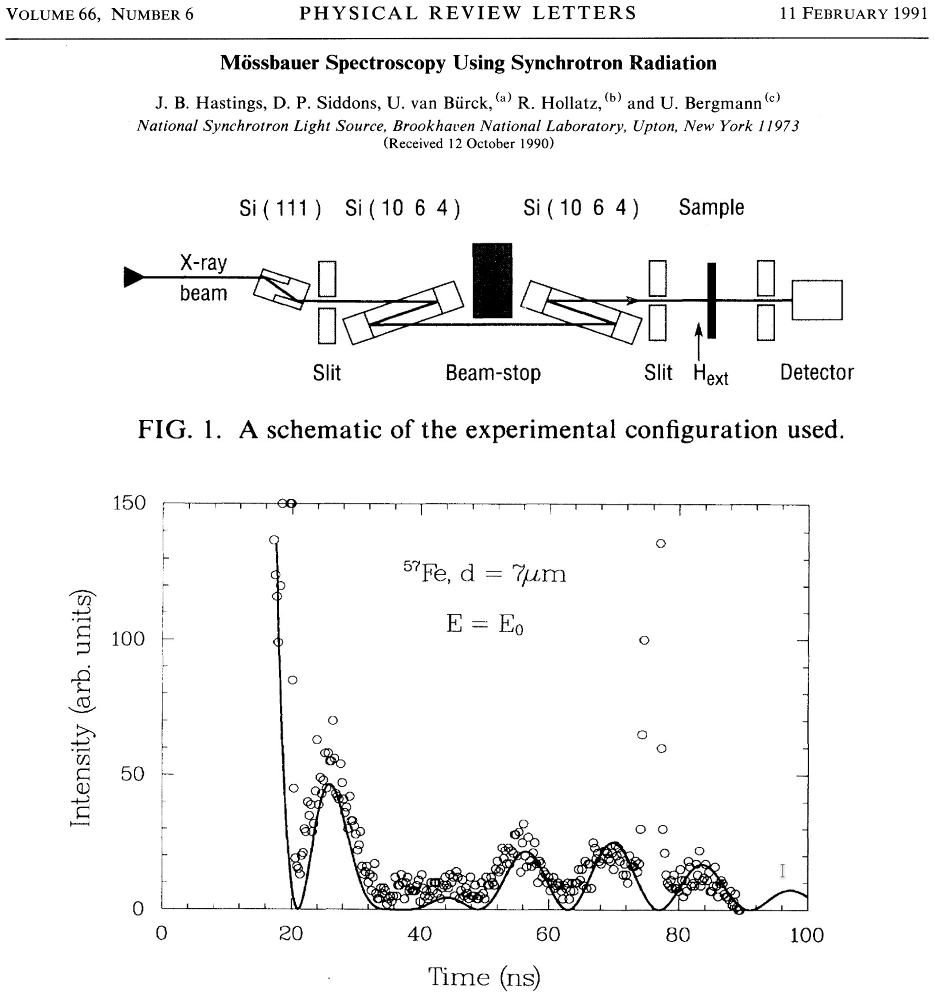
^{45}Sc Parameters

Parameters of ^{45}Sc, taken from or based on Ref. [31] unless otherwise stated, with updated values measured or used in this work highlighted in colored boxes.

Parameter	Notation	Magnitude
Ground state		
Spin & parity	I^π_g	$7/2^-$
Magnetic moment	μ_g	$+4.756487(2)\ \mu_\mathrm{N}$
Quadrupole moment	Q_g	$-0.22(1)$ b
Isotopic abundance	η	100%
Excited state		
Energy	E_0	12,400(50) eV [31,48,49] 12,389.59$^{\pm 0.15(\mathrm{stat})}_{+0.12(\mathrm{syst})}$ eV
Lifetime	τ_0	470(6) ms [10,31,50]
Natural line width	$\Gamma_0 = \hbar/\tau_0$	1.40(2) feV
Quality factor	$Q = E_0/\Gamma_0$	$8.85(10)\times 10^{18}$
Multipolarity		M2
Spin & parity	I^π_e	$3/2^+$
Magnetic moment	μ_e	$+0.368(5)\ \mu_\mathrm{N}$ [51]
Quadrupole moment	Q_e	$+0.318(22)$ b [51]
Internal conversion (IC) coefficients	α, α_K	632(71), 474 [31,50,52] 424, 363 [37]
Cross section	σ_0	$1.26(15)\times 10^{-20}$ cm^2 $1.9(5)\times 10^{-20}$ cm^2

[10] R.E. Holland, F.J. Lynch, K.E. Nystén, PRL 13 (1964) 241-243.
[31] Burrows, T. W., Nuclear Data Sheets 109, 171-296 (2008).
[37] Kibedi, T., et al., NIM A 589, 202-229 (2008).
[48] Freedman, M. S., et al., Phys. Rev. 140, B563-B565 (1965).
[49] Porter, F. T., et al., Phys. Rev. 146, 774-780 (1966).
[50] Blaugrund, A. E., et al., Phys. Rev. 159, 926–930 (1967).
[51] Gangrsky, Y. et al. Hyperfine Interact. 171, 209–215 (2006).
[52] Jones, K. W. and Schwarzschild, Phys. Rev. 148, 1148–1150 (1966).

^{57}Fe Nuclear Forward Scattering Demonstrated in 1991

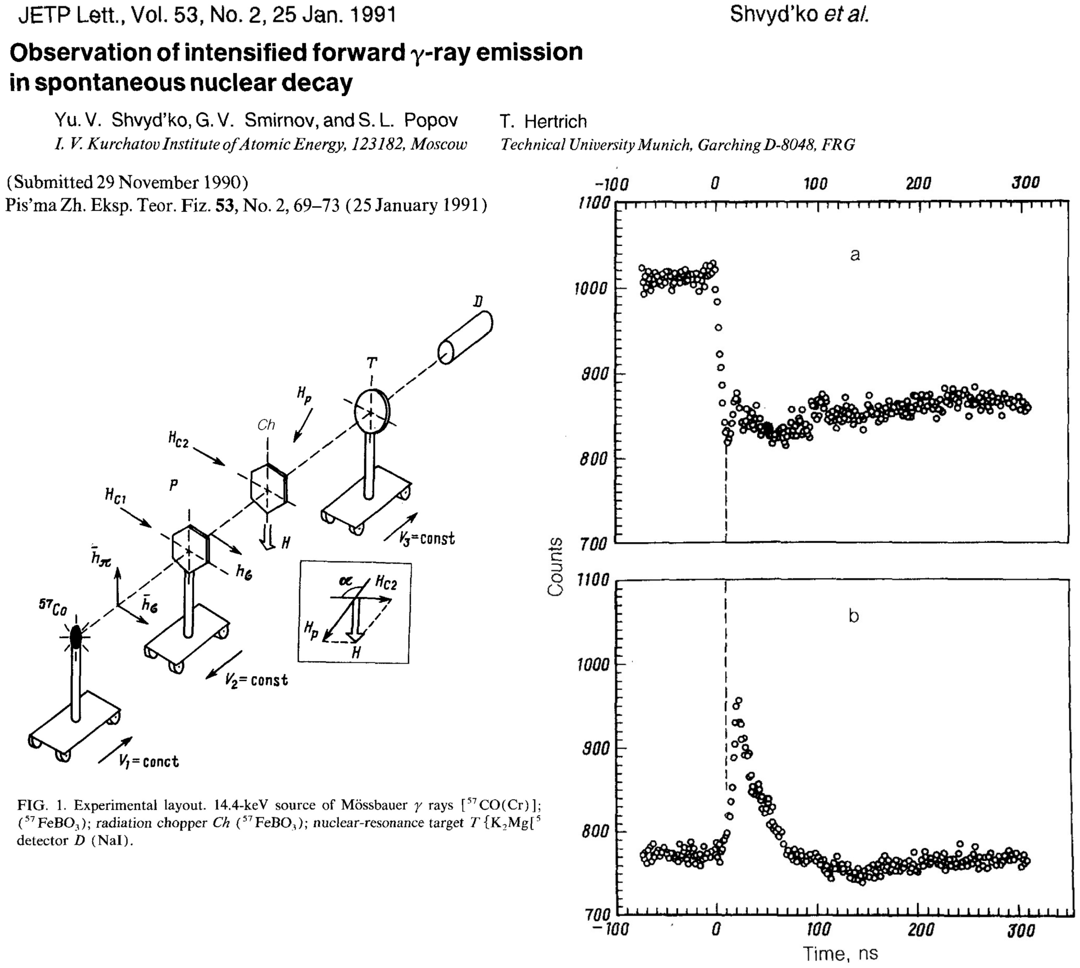


VOLUME 66, NUMBER 6 PHYSICAL REVIEW LETTERS 11 FEBRUARY 1991

Mössbauer Spectroscopy Using Synchrotron Radiation

J. B. Hastings, D. P. Siddons, U. van Bürck,[a] R. Hollatz,[b] and U. Bergmann[c]
National Synchrotron Light Source, Brookhaven National Laboratory, Upton, New York 11973
(Received 12 October 1990)

FIG. 1. A schematic of the experimental configuration used.



JETP Lett., Vol. 53, No. 2, 25 Jan. 1991 Shvyd'ko *et al.*

Observation of intensified forward γ-ray emission in spontaneous nuclear decay

Yu. V. Shvyd'ko, G. V. Smirnov, and S. L. Popov
I. V. Kurchatov Institute of Atomic Energy, 123182, Moscow

T. Hertrich
Technical University Munich, Garching D-8048, FRG

(Submitted 29 November 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **53**, No. 2, 69–73 (25 January 1991)

FIG. 1. Experimental layout. 14.4-keV source of Mössbauer γ rays [^{57}CO(Cr)]; (^{57}FeBO$_3$); radiation chopper *Ch* (^{57}FeBO$_3$); nuclear-resonance target *T* {K$_2$Mg[^{5}
detector *D* (NaI).