QSNET Quiz Questions

Quantum Technologies for Fundamental Physics
2023 Winter School, Cambridge

National Physical Laboratory, University of Sussex

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1 Quick-fire Questions

(Given live in the room, but provided with the answer sheet)

2 Terminology and Nomenclature

Using the metrological definitions below, assign the most relevant concept to statements A) to J):

Instability: an estimate of the noise exhibited by measurements of a physical quantity (statistical uncertainty).

Accuracy: an estimate of how well a measurement of a physical quantity can be corrected to the "true" value of that quantity (systematic offset uncertainty).

Realisability: an estimate of the practicality (or in some cases, possibility) of constructing, running, or maintaining an experimental apparatus or sensor to measure a physical quantity.

A) A feature of a data set measured by Allan Deviation, $\sigma_y(\tau)$, and other M-sample variance statistics.

B) There is a high degree of confidence in the averaged value of the transition frequency.

C) The cooling and clock transitions for a given ion species can be easily excited with current technology.

D) All known systematic offsets to the clock's transition frequency are compensated in real time or in post-processing.

E) Optical frequency standards have higher Q-factors than microwave frequency standards.

F) Portable optical atomic clocks are not yet commercially available.

G) A geodetic measurement was conducted to evaluate the frequency shift on the clock due to gravity.

H) The clock transition is based on a transition in a rare, metastable isotope of an actinide-series element.

I) Oscillations in fundamental constants have been excluded at certain power levels for certain frequencies.

J) Optical atomic clocks are better candidates than microwave ones for the future redefinition of SI second.

[5]

As an additional exercise, consider how the additional concepts below might influence the selection, design, and operation of optical and microwave atomic clocks for use in fundamental physics research, as well as in international timekeeping, satellite navigation, geodesy, etc.:

Repeatability: the degree of agreement across time between the measured values of a physical quantity using the ***same*** experimental apparatus or sensor

Reproducibility: the degree of agreement between the measured values of a physical quantity using ***different*** experiment apparatuses or sensors

Reliability: the likelihood that a system will perform in accordance with requirements when used in the specified operating conditions.

Robustness: the ability of a system to continue operating in non-ideal operating conditions, or with a fault in a sub-system or component.

Resilience: the ability of a system to recover from failures or disruptions, including speed of recovery and system fidelity after recovery.

3 Short Answer Questions

a) Outline the advantages of using frequency standards based on optical frequencies compared with using frequency standards based on microwave frequencies. [2]

b) Conversely, outline some of the advantages of using microwave frequency standards or a hydrogen maser flywheel oscillator rather than optical frequency standards. [2]

c) What are the advantages of a clock based on an optical lattice of neutral atoms compared with a clock based on a singly-charged trapped ion? What are the disadvantages? [4]

d) What additional challenges might be involved in building a frequency standard based on a highly charged ion? What advantages might it offer in the context of searching for BSM physics? [3]

e) What additional challenges might be involved in building a frequency standard based on transitions between rotational or vibrational states in a trapped molecule / ion? What advantages might it offer in the context of searching for BSM physics? [3]

f) Outline one advantage and one disadvantage of using an atomic clock based on a transition between electron energy levels which exhibits a narrow natural linewidth. [2]

g) When might the Allan Deviation be a more suitable measure of instability than the Standard Deviation? What extra information does it provide? [3]

h) What is the motivation for attempting to detect changes in fundamental physical "constants" which are dimensionless, rather than dimensionful? [2]

i) How many independent, dimensionless parameters can be generated from the set:

$$\{e, \hbar, c, k_B, G, M_{\odot}, S_{Au}\}$$

where S_{Au} is the Seebeck coefficient of gold, measured in V/K (volts per kelvin) [4]

4 QSNET clocks

Species	Transition Wavelength	K_α	K_μ	Fractional Inaccuracy (approximate)	Fractional Instability (approximate)
$^{251}Cf^{+17}$	485 nm	-43.5	0.0	1.0×10^{-18} (target)	$2.0 \times 10^{-15}/\sqrt{\tau}$ (target)
$^{251}Cf^{+17}$	618 nm	47.0	0.0	5.0×10^{-19} (target)	$3.0 \times 10^{-15}/\sqrt{\tau}$ (target)
$^{171}Yb^{+}$(E3)	467 nm	-5.95	0.0	3.0×10^{-18}	$1.0 \times 10^{-15}/\sqrt{\tau}$
$^{171}Yb^{+}$(E2)	436 nm	1.00	0.0	3.0×10^{-17}	$1.0 \times 10^{-14}/\sqrt{\tau}$
^{87}Sr	698 nm	0.06	0.0	2.0×10^{-18}	$5.0 \times 10^{-17}/\sqrt{\tau}$
^{133}Cs	32.6 mm	2.83	1.0	2.0×10^{-16}	$2.0 \times 10^{-14}/\sqrt{\tau}$
CaF	17.0 μm	0.00	0.5	8.0×10^{-18} (target)	$1.0 \times 10^{-15}/\sqrt{\tau}$ (target)
N_2^+	2.31 μm	0.00	0.5	4.0×10^{-18} (target)	$1.0 \times 10^{-14}/\sqrt{\tau}$ (target)

a) The caesium primary frequency standard is based on an energy transition between the hyperfine levels of the ground state of ^{133}Cs. Why are hyperfine transitions sensitive to both α and μ? [3]

b) Only considering the "sensitivity" columns, which ratio would you use to search for variations in α? Which ratio would you use to search for variations in μ? [3]

c) Now considering all the properties of the clocks given in the table, why might the ratios you gave as answers to question 4b) NOT be the best available for constraining fast variations in α and μ? Which ratios would you use when accounting for **all** properties of the clocks? [3]

d) Which ratios are least sensitive to changes in α? Which are least sensitive to changes in μ? Why would we want to include these ratios in a data campaign to constrain variations in α and μ? [3]

e) The QSNET project is a collaboration between several institutes across the UK. How might the clocks across different QSNET sites be linked and their frequencies compared? What additional noise might be introduced? [2]

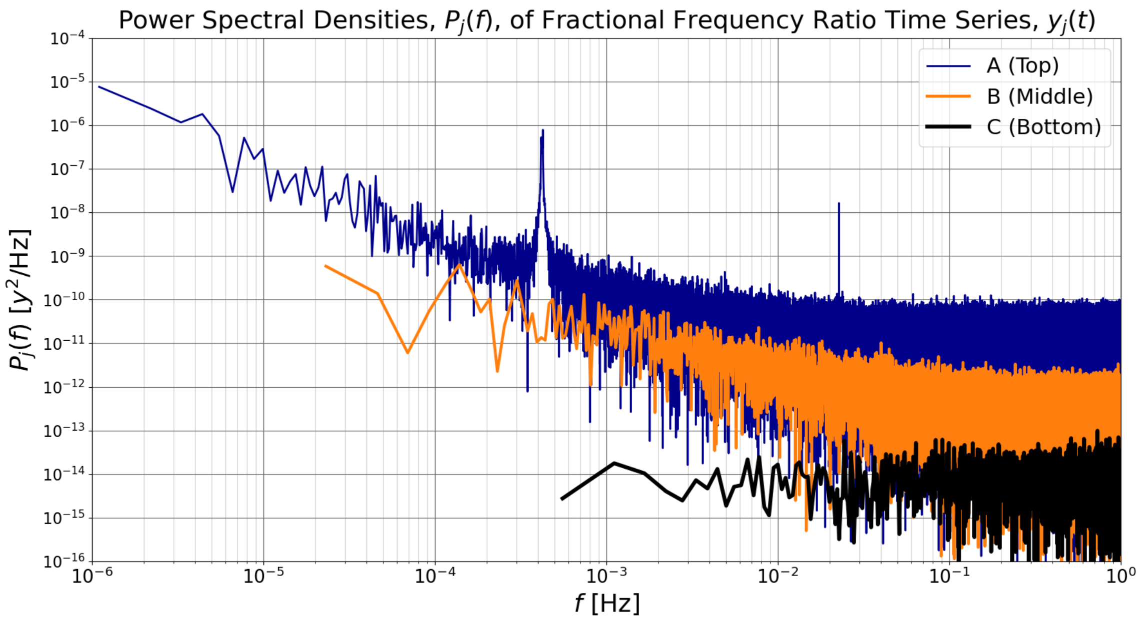
f) What BSM effects could be probed with a geographically distributed network of clocks, that could not be probed using a collection of clocks at one laboratory or institute? [2]

5 Noise Estimation

The noise on a signal is often categorized into "colours" based on the power-law behaviour of the signal's power spectral density, $P_y(f)$. The table below illustrates some of the common noise types arising in frequency metrology, with H, W, X, Y, and Z all representing constants of proportionality:

Noise Colour	Frequency Dependence	Comments
White	$P_y(f) \approx H$	Constant power across all frequencies
Blue	$P_y(f) \approx Wf$	Often used for dithering in image processing
Violet	$P_y(f) \approx Xf^2$	Can arise from differentiating white frequency noise
Pink	$P_y(f) \approx Yf^{-1}$	Also known as "flicker" noise
Red	$P_y(f) \approx Zf^{-2}$	Can arise from integrating white frequency noise

Consider the graph below displaying three simulated power spectral densities, $P_j(f)$, such as those that might describe the time fractional frequency ratios, $y_j(t)$, arising from the analysis of data acquired from optical and microwave atomic clocks.



a) Estimate the white frequency noise level, H, of dataset C. [1]

b) Assume that dataset C corresponds to $\mathrm{Cf}^{+17}/\mathrm{Cf}^{+15}$ frequency ratio data and that no peaks are statistically significant. Having estimated the noise level, to what level of power would you constrain oscillations in α? [Hint: Look at Table 1 for values of K_α] [2]

c) What noise types are present in dataset B, and over what frequency ranges?
Bonus: estimate the coefficients for each noise type [2 (+2)]

d) What noise types are present in dataset A, and over what frequency ranges?
Bonus: estimate the coefficients for each noise type [3(+3)]

e) Besides BSM physics, describe two other plausible physical processes that could cause significant oscillations in atomic clock ratio data. Briefly outline how you would attempt to distinguish signals due to these processes from signals due to BSM phenomena. [2]

f) For a bin-width of $\Delta f = 10.5\ \mu$Hz, what would you estimate as the oscillation amplitude of the peak at f = 23 mHz, assuming Fig 2 is a 1-sided spectrum, such that $A(f) = \sqrt{P(f) * \Delta f}$.
How would this change if Fig 2 showed only the positive frequencies of a 2-sided spectrum? [3]

g) Estimate the full-width at half-maximum (FWHM) of the broadened peak at $\Delta f = 417\ \mu$Hz.
Assuming this peak to result from wave-like cold dark matter, what information could you extract about the properties of the dark matter from the linewidth of the peak?
(Hint: what differentiates ***cold*** dark matter from other types?) [2]

6 Strontium Lattice Clock

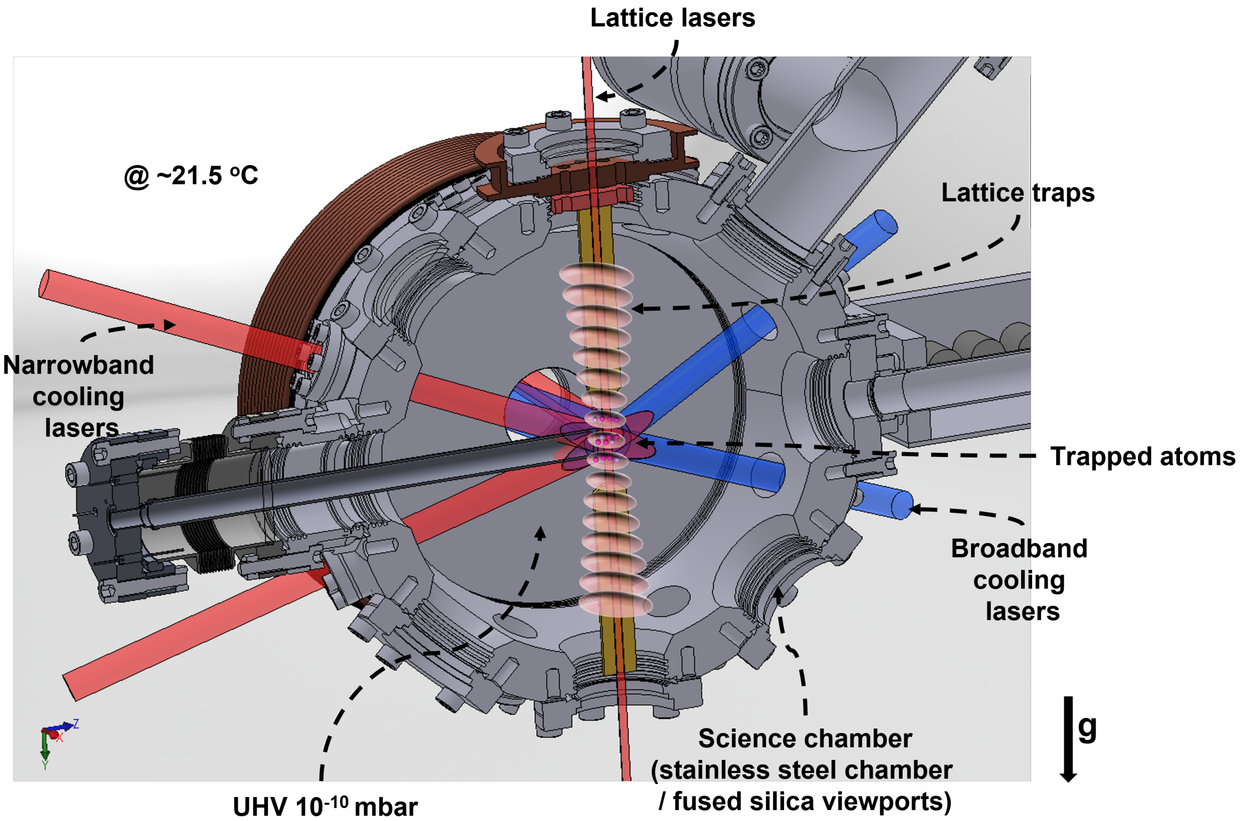


Figure 1: Physics package for NPL-Sr1 optical lattice clock.

The tables below describe systematic effects in a ^{87}Sr optical lattice clock that perturb the clock transition frequency effects, methods for determining the frequency shifts caused by the effects, and techniques for reducing the uncertainty in these measurements to achieve greater accuracy in the evaluation of the clock transition frequency.

a) Pair up each systematic effect shift with the measurement that could be made to determine the frequency shift it would cause. The accompanying image (see Fig. 1) of the strontium optical lattice clock may give some clues as to the frequency shifts and offsets being measured. [3]

Systematic Effect	Measurement	Method for Reducing Measurement Uncertainty
Relativistic redshift	Frequency difference between interleaved servos at different lattice depth.	Increase knowledge of local geopotential
Zeeman Effect	Temperature measurement at the location of trapped atoms.	Tuned s- p- wave cancellation
Blackbody Radiation	Frequency difference between interleaved servos containing different atom numbers.	Operate the optical lattice trap at a shallow trap depth
Lattice shift	Differential frequency measurement of two stretched clock states of interest.	Increase vacuum quality
Cold collisions	The average lifetime of the trapped atom cloud	Realize in-situ thermometry
Background Gas Collisions	Height of the atom cloud above a conventionally adopted equipotential	Use clock states with lower sensitivity to B-fields; Calibrate B-field sensitivities

b) Pair up each measurement with an appropriate method for reducing the uncertainty in the measurement of the frequency shift caused by the systematic effect. [3]

c) The frequency shift caused by Black-body radiation (BBR) is one of the dominant sources of uncertainty in most optical atomic clocks. Describe how BBR introduces uncertainty into the frequency measurement of the clock transition in an optical lattice clock. [3]

Bonus Question A: Signal Interpretation and Attribution

a) Connect each physical phenomenon to the features it could cause in atomic clock frequency ratio data. Be aware that some features could be explained by more than one phenomenon, and some phenomena could give rise to more than one feature described.

b) Where a signal has multiple possible causes, explain how you would try to determine the degree to which each cause is contributing to the effect.

Signal Detected in Frequency Ratio Data
Peak in $P_y(f)$ at $f = 11.6$ μHz
Peak in $P_y(f)$ at $f = 7.7$ mHz
$P_y(f) \propto f^{-1}$ at low frequencies
Year-on-year drift in the value of f_1/f_2
Temporary jump or step in the value of f_1/f_2
Permanent jump or step in the value of f_1/f_2
Discrepancy in the value of f_1/f_2 across a network of clocks

Potential Cause for Detected Signal
Coherent, scalar, cold dark matter
Earth moving through a high-density region of dark matter
Dilaton or other Kaluza-Klein field
Quintessence or 5$^{\text{th}}$ force
Daily temperature changes
Gravitational effects due to tides
Inaccurate measurements of systematic frequency offsets
Uncompensated drift in laser reference cavities
Flicker noise from lab electronics
Failure of temperature control in clock laboratory

Bonus Question B: Magic Optical Lattice

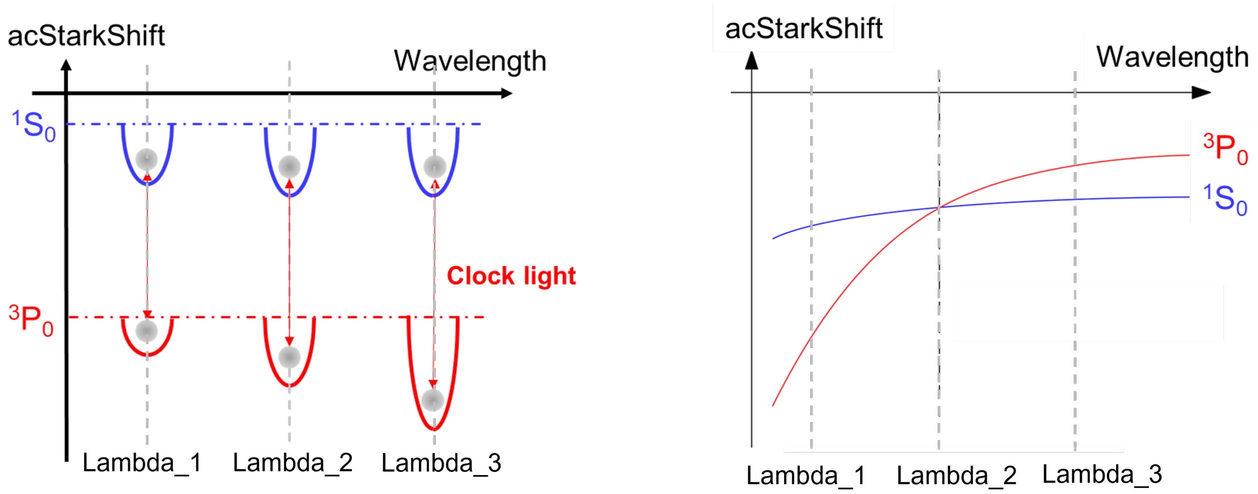


Figure 2: Left: atomic clouds are trapped at different optical lattices. Right: $^1S_0$ and $^3P_0$ are ^{87}Sr clock states. Their energy levels are perturbed by an AC Stark shift caused by the lattice laser light field.

a) Explain the mechanism by which neutral atoms can experience forces with a dependence on light intensity.

b) How is an optical lattice trap formed?

c) How is it possible to achieve Doppler-free spectroscopy using a cloud of atoms in a lattice trap?

d) Please identify which wavelength (λ_1, λ_2, or λ_3) is the "magic lattice" wavelength i.e. the wavelength at which the Stark shifts are equal for the two clock states.

e) What is the main benefit of operating the lattice at the magic wavelength in the atomic clock?

Bonus Question C: Lattice Clock Spectroscopy

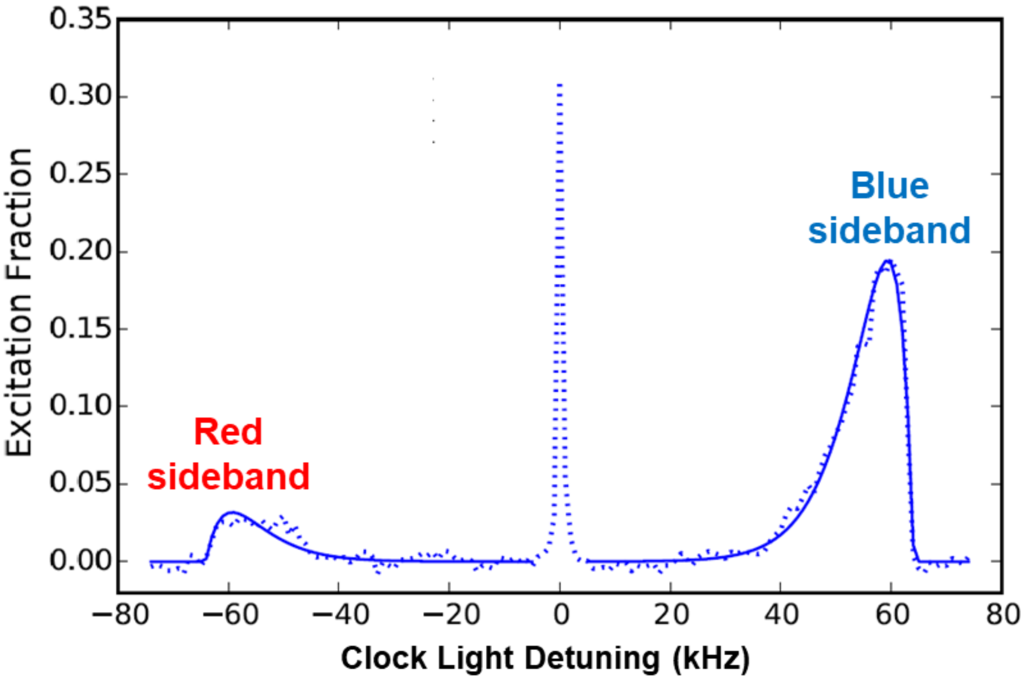


Figure 3: A representative spectroscopic result of acquired by interrogating the ^{87}Sr lattice clock. The central peak (carrier) is based on the resonance clock frequency measurement.

a) In figure 3, please specify the reason for the existence of two sidebands.

b) What information can be extracted from the sideband spectroscopy signal?

c) Specify 2 physical factors related to the measured clock spectroscopy linewidth.

d) What are the advantages of a vertical lattice configuration as opposed to a horizontal lattice?