Dark Matter Searches with Atomic and Nuclear Clocks

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We don’t know what most (95%) of the Universe is!

Universe Mass Composition

“Normal” matter

Heavy Elements 0.03%
Neutrinos 0.3%

Stars 0.5%
Free Hydrogen and Helium 4%

Dark Matter 23%

Dark Energy 72%

NASA Figure
Could elementary particles be cold dark matter?

No known particle can be cold dark matter – Need to search for new particles.
Many theories beyond the standard model predict new particles or interactions.

Proposed solutions of fundamental physics problems (matter-antimatter asymmetry, hierarchy problem, strong-CP problem, ..) involve new particles.

Violations of fundamental symmetries and variations of fundamental constants are sourced by new particles/fields.

These new particles may contribute significantly to dark matter or they may not.

Existence of dark matter is confirmed by numerous observations and is definitive “new physics” to find. We know how much dark matter there have to be in our Galaxy.

Therefore, most of BSM searches are related to dark matter/dark sector searches.
Atomic and Nuclear Clocks as Dark Matter Detectors

How do we know that dark matter exists?
What is the experimental evidence for dark matter?

- **Keplerian motion**
- **Rotation speed (km/s)**
- **Distance from Galactic center (kpc)**
- **Δρ / ρ ≈ 10^{-4}**
- **CMB**
- **z = 1100**
- **Large-scale structures**

Кривые вращения галактик

Гравитационное линзирование
The landscape of dark matter masses

Ultra-light Town

10^{-22} \text{ eV}

\mu\text{eV}

keV

MeV

PeV

100 \text{ GeV}

H_{\text{inf}}

M_{\text{pl}}

WIMP City

The WIMPzilla

keV Cabin
Dark matter density in our Galaxy > $\lambda_{dB}^{-3}$

$\lambda_{dB}$ is the de Broglie wavelength of the particle.

Then, the scalar dark matter exhibits coherence and behaves like a wave

$$\phi(t) = \phi_0 \cos \left( m_{\phi} t + \vec{k}_\psi \times \vec{x} + \ldots \right)$$

A. Arvanitaki et al., PRD 91, 015015 (2015)

We do not know what dark matter particle mass is.

Ultralight dark matter has to be bosonic – Fermi velocity for DM with mass >10 eV is higher than our Galaxy escape velocity.
Our visible galaxy is inside of a very large dark matter halo.
Dark matter can affect atomic energy levels.

What dark matter can you detect if you can measure changes in atomic/nuclear frequencies to 19 digits?

$\nu_0$ is a clock frequency.
GPS satellites: microwave atomic clocks

Optical atomic clocks will not lose one second in 30 billion years
Applications of atomic clocks

GPS, deep space probes

Very Long Baseline Interferometry

Relativistic geodesy

Gravity Sensor

Definition of the second

Quantum simulation

Searches for physics beyond the Standard Model

How optical atomic clock works

The laser is resonant with the atomic transition. A correction signal is derived from atomic spectroscopy that is fed back to the laser.

An optical frequency synthesizer (optical frequency comb) is used to divide the optical frequency down to countable microwave or radio frequency signals.

How optical atomic clock works

Ramsey scheme

Measure: $|0\rangle$ or $|1\rangle$?

$E_1$ $\downarrow$ $E_0$

Initialize

$|0\rangle$

$|1\rangle$

$E_0$ $\downarrow$ $h\nu_0$

$E_1$

$\frac{\pi}{2}$ $\downarrow$

$\sqrt{2}$

$|0\rangle + |1\rangle$

$\frac{\pi}{2}$ $\downarrow$

Quantum projection noise: can only get $|0\rangle$ or $|1\rangle$.

Repeat many times to get probability of excitation, scan different frequencies to maximize.

$\frac{\pi}{2} = \theta = 2\Omega \tau_L$

Atom should be exactly in $\frac{|0\rangle + |1\rangle}{\sqrt{2}}$ if on resonance.

detect fluorescence

$E_2$
Atomic clocks can measure and compare frequencies to exceptional precisions!

If fundamental constants change (now) due to for various “new physics” effects atomic clock may be able to detect it.

Search for physics beyond the standard model with atomic clocks

**BEYOND THE STANDARD MODEL?**
Search for physics beyond the Standard Model with atomic clocks

- Dark matter searches
- Search for the violation of Lorentz invariance
- Tests of the equivalence principle
- Are fundamental constants constant?

Image credit: NASA

Gravitational wave detection with atomic clocks PRD 94, 124043 (2016)

Image credit: Jun Ye’s group
How to detect ultralight dark matter with clocks?


Atomic & nuclear energy levels will oscillate so clock frequencies will oscillate

Dark matter field \( \phi(t) = \phi_0 \cos \left( m_\phi t + k_\phi \times \vec{x} + \ldots \right) \)

couples to electromagnetic interaction and “normal matter”

It will make fundamental coupling constants and mass ratios oscillate

Can be detected with monitoring ratios of clock frequencies over time (or clock/cavity).
Ultralight dark matter

\[ \frac{\phi}{M^*} O_{SM} \rightarrow \mathcal{L}_\phi = \kappa \phi \left[ + \frac{d_e}{4e^2} F_{\mu\nu} F^{\mu\nu} \right] \ldots \]

\[ \alpha = \alpha^{SM} + \delta \alpha \]

Dark matter

\[ \phi(t) = \phi_0 \cos \left( m_\phi t + \bar{k}_\phi \times \bar{x} + \ldots \right) \]

DM virial velocities \( \sim 300 \text{ km/s} \)

Then, clock frequencies will oscillate!

<table>
<thead>
<tr>
<th>( \tau ) [s]</th>
<th>( f = 2\pi/m_\phi ) [Hz]</th>
<th>( m_\phi ) [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 10^{-6} )</td>
<td>1 MHz</td>
<td>( 4 \times 10^{-9} )</td>
</tr>
<tr>
<td>( 10^{-3} )</td>
<td>1 kHz</td>
<td>( 4 \times 10^{-12} )</td>
</tr>
<tr>
<td>( 1          )</td>
<td>1</td>
<td>( 4 \times 10^{-15} )</td>
</tr>
<tr>
<td>( 1000       )</td>
<td>1 mHz</td>
<td>( 4 \times 10^{-18} )</td>
</tr>
<tr>
<td>( 10^6       )</td>
<td>( 10^{-6} )</td>
<td>( 4 \times 10^{-21} )</td>
</tr>
</tbody>
</table>

One oscillation per second

One oscillation per 11 days
Ultralight dark matter

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Measure clock frequency ratios:

\[ \frac{\delta (\nu_2/\nu_1)}{(\nu_2/\nu_1)} \sim \frac{d_e (K_2 - K_1)}{K_2 - K_1} \kappa \phi(t) \]

Result: plot couplings \( d_e \) vs. DM mass \( m_f \)

Sensitivity factors to \( \alpha \)-variation
Clock measurement protocols for the dark matter detection

Make a clock ratio measurement over time $\Delta \tau$

Make N such measurements, preferably regularly spaced

Need excellent SHORT term stability

Detection signal:
A peak with monochromatic frequency $f = \frac{2\pi}{m_\phi}$ in the discrete Fourier transform of this time series.

A. Arvanitaki et al., PRD 91, 015015 (2015)
Clock measurement protocols for the dark matter detection

Single clock ratio measurement: averaging over time $\tau_1$
Make N such measurements, preferably regularly spaced

Detection signal:
A peak with monochromatic frequency $f = 2\pi/m_\phi$ in the discrete Fourier transform of this time series.
Hunting for topological dark matter with atomic clocks

A. Derevianko¹* and M. Pospelov²,³

Dark matter clumps: point-like monopoles, one-dimensional strings or two-dimensional sheets (domain walls).

If they are large (size of the Earth) and frequent enough they may be detected by measuring changes in the synchronicity of a global network of atomic clocks, such as the Global Positioning System.

GPM.DM collaboration: Roberts at el., Nature Communications 8, 1195 (2017)

European fiber-linked optical clock network. Search for transient variations of the fine structure constant and dark matter using fiber-linked optical atomic clocks; B M Roberts et al. New Journal of Physics, Volume 22, September 2020 (figures below).

Constraints on the transient variation of the fine-structure constant $\alpha$ as a function of the transient duration, $\tau_{\text{int}}$. The secondary horizontal axis shows the corresponding length scale, $d = v g \tau_{\text{int}}$. 

![Map of global sensor network](image1)

![Graph showing constraints on transient variations](image2)
How to improve laboratory searches for the variation of fundamental constants & dark matter?

Improve atomic clocks: better stability and uncertainty

Ion chains

Large ion crystals

3D optical lattice clocks

Measurements beyond the quantum limit

Entangled clocks

Image credits: NIST, Innsbruck group, MIT Vuletic group, Ye JILA group
Clocks based on new systems

Clocks with ultracold highly charged ions: much higher sensitivity

Piet Schmidt, Quantum science seminar #18
First demonstration of quantum logic spectroscopy at PTB, Germany
Nature 578 (7793), 60 (2020)
Enhancement factors for current clocks

\[ K = \frac{2q}{E_0} \]

Cavity: part of the clock laser systems
Effective \( K = 1 \)

\[ K(Sr^+) = 0.4, \quad K(Yb^+) = 0.3 \]

\[ K(Hg) = 0.8, \quad K(Yb^+E2) = 1 \]

\[ K(Al^+) = 0.01, \quad K(Sr) = 0.06, \quad K(Ca^+) = 0.1 \]

\[ K(Hg^+) = -2.9 \]

\[ K(Yb^+E3) = -6 \]

\[ \frac{\partial}{\partial t} \ln \frac{v_2}{v_1} = (K_2 - K_1) \frac{1}{\alpha} \frac{\partial \alpha}{\partial t} \]
What is different for the nuclear clock?

(1) Much higher sensitivity

(2) Nuclear clock is sensitive to coupling of dark matter to the nuclear sector of the standard model
Th nuclear clock: Exceptional sensitivity to new physics

Possible 4-5 orders of magnitude enhancement to the variation of $\alpha$ and but orders of magnitude uncertainty in the enhancement factors.

It is crucial to establish actual enhancement!
Ultralight dark matter

Dark matter coupling to the Standard Model

\[
\mathcal{L}_\phi = \kappa \phi \left[ + \frac{d_e}{4e^2} F_{\mu\nu} F^{\mu\nu} - \frac{d_g}{2g_3} G^A_{\mu\nu} G^{A\mu\nu} \right]
\]

- photons
- gluons
- electrons
- quarks

Nuclear clock:
additional couplings of dark matter to standard model via \(d_g\) and \(d_m\) (quark)

A. Arvanitaki et al., PRD 91, 015015 (2015)
Cosmological relaxation of the electroweak scale is an attractive scenario addressing the gauge hierarchy problem.

Its main actor, the relaxion, is a light spin-zero field which dynamically relaxes the Higgs mass with respect to its natural large value.

Continued collaboration with Gilad Perez’ particle physics theory group.

Relaxion-Higgs mixing angle as a function of the relaxion mass.
A relaxion window and the available parameter space for the light relaxion, current and projected constraints.
Recent progress in atomic theory

Very recent … past year
Numerous applications that need precise atomic data

Particle physics:
- Searches for dark matter and other "new" physics

Atomic clocks

3D Image: Ye group and Steven Burrows, JILA

Ultracold atoms
- Quantum computing and simulation

Numbered circles:
1. 9:00
2. 10:00
3. 11:00
4. 12:00
5. 1:00
6. 2:00
7. 3:00
8. 4:00
9. 5:00
10. 6:00
11. 7:00
12. 8:00

-Numbered circles:
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Types of physics:
- Particle physics:
- Astrophysics
- Nuclear and hadronic physics - extracting nuclear properties
- Plasma physics
- Quantum computing and simulation
- Ultracold atoms
- Atomic clocks
University of Delaware team & collaborators

- We have been developing high precision atomic codes and applying them to solve completely different problems for over 20 years
- All codes are written by UD team and collaborators (Charles Cheung, Mikhail Kozlov, Sergey Porsey, Marianna Safronova, Ilya Tupitsyn)
- Because we have several \textit{ab initio} codes we can estimate how accurate numbers are – we are the only group to routinely publish reliable uncertainties

Present UD team computer resources: 550 cores, 12.7Tb of memory

We can compute atomic data for any atoms/ions with 1-5(6) valence electron
Recent theory progress in predicting properties of highly-charged ions:
New parallel code – we can now run 100x larger problems!

High-resolution Photo-excitation Measurements Exacerbate the Long-standing Fe XVII-Oscillator-Strength Problem


Experiment:

$$3C \left( [(2p^5)_{1/2} 3d_{3/2}]_{J=1} \rightarrow [2p^6]_{J=0} \right)$$

$$3D \left( [(2p^5)_{3/2} 3d_{5/2}]_{J=1} \rightarrow [2p^6]_{J=0} \right)$$

<table>
<thead>
<tr>
<th>S(3C)</th>
<th>S(3D)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11217</td>
<td>0.03183</td>
<td>3.582</td>
</tr>
<tr>
<td>0.1124</td>
<td>0.03198</td>
<td>3.573</td>
</tr>
<tr>
<td>0.11240</td>
<td>0.03199</td>
<td>3.572</td>
</tr>
<tr>
<td>0.11241</td>
<td>0.03198</td>
<td>3.573</td>
</tr>
<tr>
<td>0.11233</td>
<td>0.03201</td>
<td>3.567</td>
</tr>
<tr>
<td>0.11221</td>
<td>0.03212</td>
<td>3.552</td>
</tr>
<tr>
<td>0.1122(2)</td>
<td>0.0321(4)</td>
<td>3.55(5)</td>
</tr>
</tbody>
</table>

Energies (eV) 825.67 812.22
A (s⁻¹) 2.238(4) × 10¹³ 6.10(7) × 10¹²
Γ (meV) 14.74(3) 4.02(5)

Full correlation of 10 electrons – nothing else to include at this level of accuracy!
Recent theory progress in predicting properties of highly-charged ions

Accurate prediction of clock transitions in a highly charged ion with complex electronic structure
First configuration interaction calculation for 60 electrons with all shells open!

Clock transitions???
E1 transitions???

Previous predictions (FAC):

<table>
<thead>
<tr>
<th>E1 Transition</th>
<th>Rate (s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4f^{12} 5s^2 3F_4 - 4f^{13} 5s^3 3F_4$</td>
<td>71 0.2</td>
</tr>
<tr>
<td>$4f^{12} 5s^2 3F_4 - 4f^{13} 5s^3 3F_3$</td>
<td>48 1.2</td>
</tr>
<tr>
<td>$4f^{12} 5s^2 F_2 - 4f^{13} 5s^1 F_3$</td>
<td>163 3</td>
</tr>
</tbody>
</table>

Hendrik Bekker, FAC calculations, private communication vs. new results

New computations in progress: all strong E1 transitions;
Between $4f^{12} 5s^2 - 4s^{12} 5s5p$ and $4f^{13} 5s - 4f^{13} 5p$ configurations
Optical clocks based on the $^{15+}\text{Cf}$ and $^{17+}\text{Cf}$ ions

$^{249}\text{Cf}$ I = 9/2 (351 y)

$^{250}\text{Cf}$ I = 0 (13.1 y)

$^{251}\text{Cf}$ I = 1/2 (898 y)

$\Delta K \approx 110$

New project at University of Delaware in collaboration with computer science

Computer, Calculate!

Applications in science and engineering
- quantum information
- degenerate quantum gases
- atomic clocks
- precision measurements
- plasma physics
- astrophysics
- studies of fundamental physics

High-Precision Atomic Physics Portal

Building on:
- CI+MBPT/Ci+all-order program package and expertise
- Portal technology (Science Gateways, Hubzero,...)
- Parallel programming methodology
Classify atomic calculations by difficulty level

Caesium

Closed shells
Can be approximated by a mean field

Single valence electron
Classify atomic calculations by difficulty level

**Group 1**
Calculations we can do “routinely”, with default parameters

- 1 – 2(3) valence electrons
- Can automate: already done for 1 valence electron

**Group 2**
Calculations that require expert knowledge

- (3)/4-6 valence electrons or special cases with more valence electrons
- Only calculations of wave functions requires expert knowledge

**Group 3**
No precision methods exist: exponential scaling with the number of valence electrons

- Half-filled shells and holes in shells
- Method development in progress, need new ideas – machine learning
Codes for monovalent systems are completely automated
OpenMP version just has been developed

**COMPUTER, CALCULATE Th^{3+}!**

- Dirac-Hartree-Fock
- Basis set code
- LCCSD core
  - LCCSD valence
  - LCCSDpT valence
  - Matrix element code + scaled versions

Only need to input:
- Which isotope?
- Core shells
- Which electronic states you need
- Which properties you need

LCCSD
Linearized
Single Double
Couple Cluster
method

All up to
n=10-12
spdf

All allowed

Analysis code that makes a summary with uncertainties – in latex
Online Portal will provide:

A: Transition matrix elements, transition rates, branching ratios, lifetimes; E1, E2, and M1 matrix elements

B: Dynamic polarizabilities & magic wavelength

C: Many other data (hyperfine constants, etc).
Computations-of –the fly from online requests.

Uncertainty estimates will be provided for all data.

Code release, tutorials, online workshops, guest scientists & future international portal collaborations

Plan to release version 1 of the portal next month, December 2020
Next release: more monovalents, all alkaline-earth metals: Be, Mg, Ca, Sr, Ba, Ra & similar ions: Al+, etc.
Email me which atoms/ions/data would you like to see included into the portal project.
Atomic & nuclear clocks: 
Great potential for discovery of new physics

Many new developments coming in the next 10 years!

Need NEW IDEAS how to use quantum technologies for new physics searches
Research scientist: Sergey Porsev
Graduate students: Charles Cheng, Aung Naing, Adam Mars, Hani Zaheer

Online portal collaboration, Electrical & Computer Engineering:
Prof. Rudolf Eigenmann, graduate student: Parinaz Barakhshan
Prof. Bindiya Arora, GNDU, India

Senior Research Associate position (with postdoc experience) is available now
Another postdoc position will become available in January
Contact Marianna Safronova (msafrono@udel.edu) for more information

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Thorium nuclear clocks for fundamental tests of physics
Thorsten Schumm, TU Wein
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