Max-Planck-Institut
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Heidelberg

Towards testing physics beyond the Standard Model with the g factor of bound electrons

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A brief description of the project

Goal and context

Search for physics beyond the Standard Model (New Physics):

- Energy frontier: particle colliders (LHC). High-energy collisions. TeV

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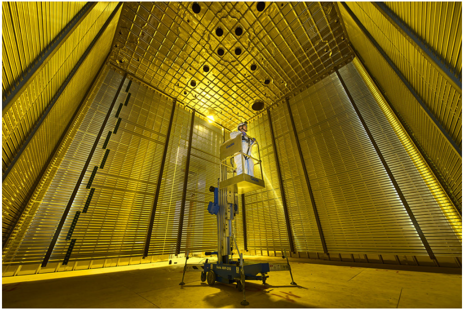

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- Precision frontier: ions (small exp.). Frequency measurements. keV

Development of bound-state QED calculations and experiments

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[V.A. Yerokhin, V.M. Shabaev, Phys. Rev. A **60**, 800 (1999)]

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[S. Sturm, F. Köhler, J. Zatorski *et al.*, Nature **506**, 467 (2014)]

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Using bound-electron g factor (Zeeman splitting) in search for New Physics

- 'Direct' method: g-factor measurements compared to Standard Model theory:
  $\rightarrow$ difference allowed by error bars gives upper limit on New Physics contribution
- 'Indirect' method: isotope shifts in the g factor (data to be acquired)
  $\rightarrow$ properties of data can be used (with care) to constrain New Physics param.
  Implemented with optical transition freq. in singly-charged ions in
  [J.C. Berengut, D. Budker, C. Delaumay, V.V. Flambaum *et al.*, Phys. Rev. Lett. **120**, 091801 (2018)]

The bound-electron g factor

Magnetic dipole moment $\boldsymbol{\mu}$ and g factor of a particle:

$$\boldsymbol{\mu} = g\frac{q\mathbf{J}}{2m}$$

q: charge m:mass $\mathbf{J}$: total angular momentum

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Calculating the bound-electron g factor

Relativistic quantum mechanics+QED (radiative corrections)
If several e^-: electron interactions
Nuclear structure corrections

Measuring the bound-electron g factor

Penning trap: precision: 10^{-11} for medium-light H-like ions
Silicon: [S. Sturm, A. Wagner, B. Schabinger *et al.*, Phys. Rev. Lett. **107**, 023002 (2011)]
Carbon: [F. Köhler, S. Sturm, A. Kracke *et al.*, J. Phys. B **48**, 144032 (2015)]
Excellent agreement with the theory
Soon to come: same precision for medium and heavy H-like ions (e.g. Ca, Xe, Pb)

A candidate for New Physics

A proposed fifth fundamental force

Massive spinless boson ϕ (mass range unknown)
Couples electrons to neutrons according to Yukawa potential

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Relevance to high-energy physics

- Electroweak hierarchy problem: Electroweak force $\gg$ Gravitational force
  Linked to the mass of the Higgs boson (radiative corrections)
  Such scalar bosons could provide a solution to this problem
- They are light (axion-like) dark matter candidates

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Yukawa potential seen by electrons

$$V_\phi(\mathbf{r}) = -\hbar c\, \alpha_{\mathrm{NP}}\, (A - Z)\, \frac{\mathrm{e}^{-\frac{m_\phi c}{\hbar}|\mathbf{r}|}}{|\mathbf{r}|}$$

- α_{NP} coupling constant
- m_ϕ mass of the boson

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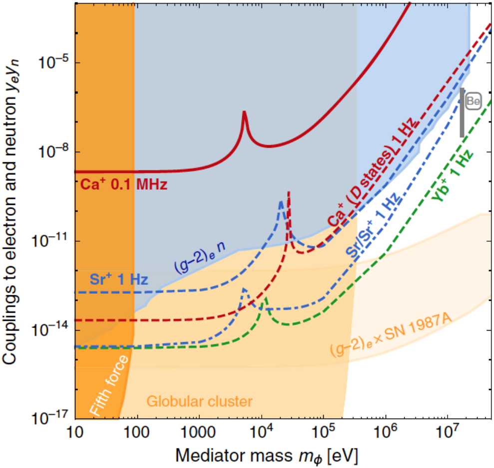
Comparing experiments and theory (& testing New Physics)

Parameters of the hypothetical fifth force

- $\alpha_{\text{NP}} = y_e y_n / 4\pi$ coupling constant with y_e & y_n couplings of 'new' bosons to electron & neutron
- m_ϕ mass of the boson

Regions above the curves are excluded by corresponding measurements

J.C. Berengut *et al.*, Phys. Rev. Lett. **120**, 091801 (2018)



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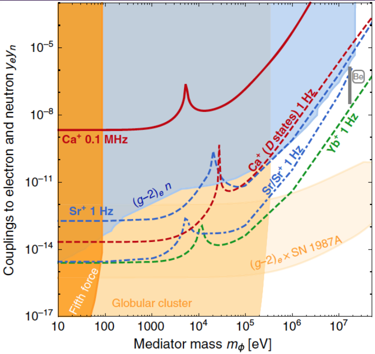

Consider experimental and theoretical values for the g factor of a given ion
Find the largest discrepancy allowed by the error bars
Set that discrepancy as largest value possible for New Physics contribution to g factor

Implementation with H-like $^{28}\mathrm{Si}^{13+}$

Experiment: $g = 1.995\,348\,959\,10(7)(7)(6)$
[S. Sturm *et al.*, Phys. Rev. A **87**, 030501(R) (2013)] $\rightarrow 1.995\,348\,959\,2$

Theory: $g = 1.995\,348\,958\,109(584)$
[A. Czarnecki *et al.*, Phys. Rev. Lett. **120**, 043203 (2018)] $\rightarrow 1.995\,348\,957\,5$

Contrib. from New Physics is bounded by 1.7×10^{-9}

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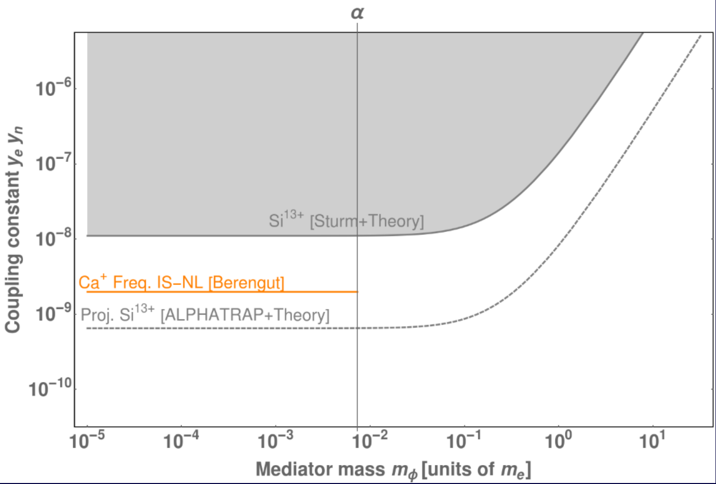


Isotope shifts and the King representation

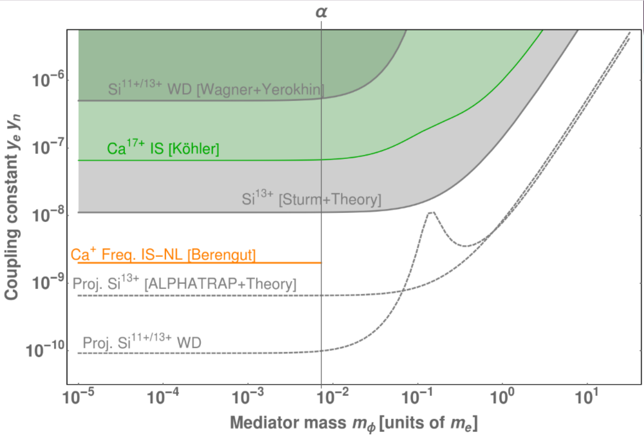
Isotope shift

Isotope shift measures difference in a given quantity between two isotopes of given ion

Isotope shifts and the King representation

Isotope s

Isotope s ... given ion



Bounds from the isotope shift in the Li-like Ca^{17+} g factor

Experiment: [F. Köhler *et al.*, Nat. Commun. **7**, 10246 (2016)]
Theory: [V.M. Shabaev *et al.*, Phys. Rev. Lett. **119**, 263001 (2017)]

Idea to measure isotope shift in g factor of highly charged ions with super-high precision: [S. Sturm *et al.*, Eur. Phys. J. Special Topics 227, 1425 (2019)]

Isotope shifts and the King representation

Isotope shift

Isotope shift measures difference in a given quantity between two isotopes of given ion

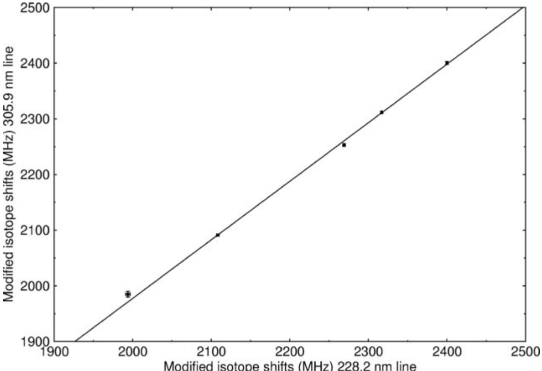
King representation

Take a certain number (≥ 3) of pairs of isotopes

King plot: Isotope Shift in 2 quantities (x/y axis) 1 point for each pair of isotopes

e.g. 2 g factors in an ion $\left(g_1^A - g_1^{A'}\right)/\mu_{AA'}$ and $\left(g_2^A - g_2^{A'}\right)/\mu_{AA'}$

where $\mu_{AA'} = 1/M_A - 1/M_{A'}$ inverse reduced mass of nuclei



(from M. Avgoulea *et al.*, Hyperfine Interact. 171, 217 (2006))

Experimental graph gives a straight line: why?

Isotope shifts at the (Standard Model) leading order

Shift in the g factor of a level i between isotopes A and A'

$$g_i^{AA'} = g_i^A - g_i^{A'}$$

Two largest Standard Model contributions to the isotope shift

- Leading order contribution to the mass shift:
  $K_i \mu_{AA'}$ where $\mu_{AA'} = 1/M_A - 1/M_{A'}$ inverse reduced mass of nuclei
- Leading order contribution to the field shift:
  $F_i \delta \left\langle r^2 \right\rangle_{AA'}$ where $\delta \left\langle r^2 \right\rangle_{AA'}$ difference in nuclear charge radii

F_i and K_i are purely electronic coefficients

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King plot at the leading order

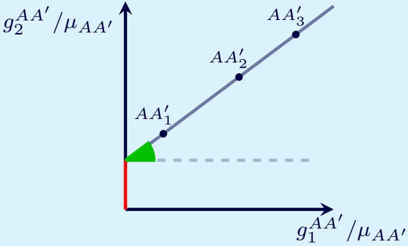
Take four different isotopes A, A'_1, A'_2, A'_3 & two different e^- states 1 and 2

At the SM leading order

$$\frac{g_2^{AA'}}{\mu_{AA'}} = \frac{F_2}{F_1}\frac{g_1^{AA'}}{\mu_{AA'}} + \left(K_2 - \frac{F_2}{F_1}K_1\right)$$

which explains why the Isotope Shift data is linear (previous slide)

If isotope shift $g_i^{AA'}$ calculated at leading order → linear graph



Isotope shifts and New Physics at the leading order

The hypothetical fifth force which we consider acts between neutrons and electrons!

Introduce New Physics contribution to g factor

$$g_i^{AA'} = K_i \mu_{AA'} + F_i \delta \langle r^2 \rangle_{AA'} + \alpha_{\mathrm{NP}} X_i \left(A - A'\right)$$

where X_i is a purely electronic factor (computed on earlier slide)

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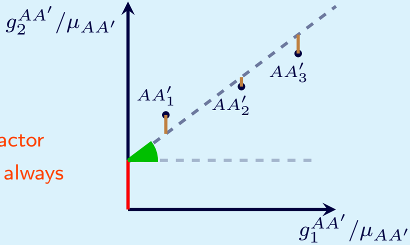
King plot in the presence of New Physics at the Standard Model leading order

$$\frac{g_2^{AA'}}{\mu_{AA'}} = \frac{F_2}{F_1}\frac{g_1^{AA'}}{\mu_{AA'}} + \left(K_2 - \frac{F_2}{F_1}K_1\right) + \alpha_{\rm NP}\left(\frac{X_2}{X_1} - \frac{F_2}{F_1}\right)\frac{A-A'}{\mu_{AA'}}$$

At SM leading order: King nonlinearity is a signature of New Physics
→ New Physics can be constrained from

- Experiment: Isotope Shift data
- Theory: New Physics contrib. to g factor

At SM leading order: better exp. precision always
→ better bounds on New Physics



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For extremely high experimental accuracy: King nonlinearities can be expected to be caused by subleading Standard Model nuclear corrections to the g factor

Higher-order finite nuclear size correction

[S.G. Karshenboim and V.G.Ivanov, Phys. Rev. A **97**, 022506 (2018)]

Nuclear polarisation

[A.V. Nefiodov, G. Plunien, and G. Soff, Phys. Rev. Lett. **89**, 081802 (2002)]

Nuclear shape deformation

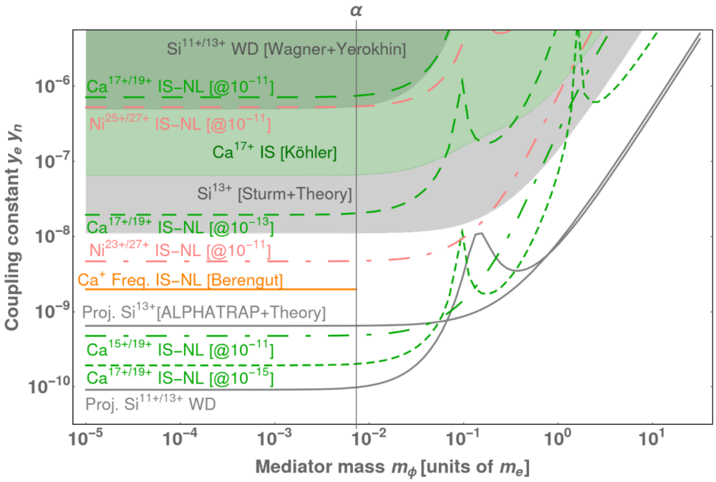
[J. Zatorski, N.S. Oreshkina, C.H. Keitel, and Z. Harman, Phys. Rev. Lett. **108**, 063005 (2012)]

Higher-order nuclear mass correction

[K. Pachucki, Phys. Rev. A **78**, 012504 (2008)]

$\rightarrow$ Should not be interpreted as New Physics!

Tests with the isotope shift:



The (specific) weighted difference

The weighted difference

$\delta_{\xi_s} g = g_{2s_{1/2}} - \xi_s g_{1s_{1/2}}$ $\delta_{\xi_p} g = g_{2p_{1/2}} - \xi_p g_{1s_{1/2}}$

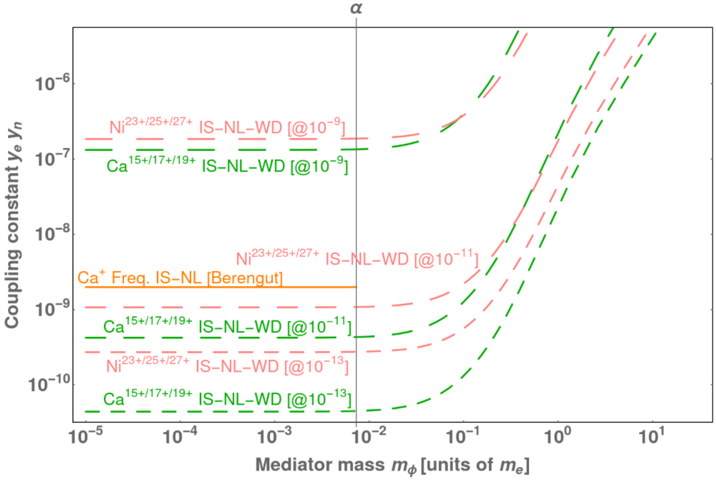
ξ_s and ξ_p coefficients optimised to cancel the finite-nuclear-size contributions in $\delta_\xi g$

[V.M. Shabaev, D.A. Glazov, M.N. Shabaeva *et al.*, Phys. Rev. A **65**, 062104 (2002)]

Goal: more stringent tests of QED

$$\xi_{s_{1/2}} \simeq \frac{1}{8} \qquad \xi_{s_{1/2}} \simeq \frac{3}{128} (Z\alpha)^2$$

Tests with the isotope shift and the weighted difference



Outlook

Summary

Two main methods to obtain bounds on New Physics from g-factor spectroscopy

- 'Direct' method: g-factor measurements compared to Standard Model theory:
  $\rightarrow$ some existing bounds but less stringent than other atomic results
  Improvements envisioned but demand strong progress from theory
- 'Indirect' method: isotope shifts in the g factor
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  Competitive bounds possible with realistic exp. precision

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Perspectives

Other proposed types of new particles and interactions
$\rightarrow$ (they need to affect the bound-electron g factor)
e.g.: $B - L$ gauged symmetry, chameleon models

Thank You