Atomic Parity Violation and Fundamental Physics

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Plan of the talk

- Introduction of the subject
- Why it is important
- What are we trying to do
- Other issues

Parity Violation in Atoms

Glashow-Salam-Weinberg theory of electroweak interactions predicts that electron and nucleus exchange Z boson. This effectively adds to the potential energy of the one-particle relativistic Hamiltonian the term

$$H_{\mathrm{EW}} = \frac{G_\beta}{2^{3/2}} \rho_W(\vec{r}) \gamma_5 \,,$$

where γ_5 is the fifth Dirac matrix, G_β is Fermi coupling constant determined from neutron lifetime. The "weak charge density" ρ_W, is given in terms of the proton and neutron densities, ρ_p and ρ_n, respectively, as

$$\rho_W(\vec{r}) = \rho_p(\vec{r})(1 - 4\sin^2\vartheta) - \rho_n(\vec{r}) \,,$$

where ϑ is weak mixing angle, the fundamental quantity of EW theory.

Let us summarize the main features of the interaction H_{EW}.
First, it is parity violating, that is, it mixes states of different parity, namely s-state and a $p_{1/2}$ state.
Second, the interaction H_{EW} is really weak. Changing to atomic units, $r = r_A/(m_e Z\alpha)$, we find that the interaction is proportional to

$$Q_W G_\beta m_e^3 (Z\alpha)^4 \simeq m_e (Z\alpha)^2 \left[10^{-5} \left(\frac{m_e}{m_p} \right)^2 \alpha^2 \right] Q_W Z^2 \,,$$

where we substituted $G_\beta \simeq 1 \times 10^{-5} m_p^{-2}$. The factor in the square brackets on the rhs is of the order 10^{-15}. However, given that $Q_W \approx Z$, we see that for heavy atoms there is an enhancement of the interaction strength by the factor Z^3.

Why it is important?

Comparison of measurement (Gilbert at al, PRL **24**, 2680 (1985), Wood et al, Science 275, 1759 (1997)) and theory (Porsev et al, Phys. Rev. D **82**, 036008 (2010)) for parity violating transition amplitude in the cesium atom reads

$$\sin^2\vartheta = 0.2356(20)\,.$$

This is the "weighting" of the W and Z bosons:

$$m_W = \sqrt{\frac{\alpha\pi}{\sqrt{2}G_\beta \sin^2\vartheta}} \simeq 79\,\mathrm{GeV}$$

$$m_Z = m_W / \cos\vartheta \simeq 90\,\mathrm{GeV}\,.$$

The experimentally determined masses of the W and Z bosons are $m_W \simeq 80\,\mathrm{GeV}$ and $m_Z \simeq 91\,\mathrm{GeV}$, respectively.

Why it is important?

The masses of the W and Z bosons are determined from the position of resonances in high-energy electron-positron annihilation (LEP experiment).

This agreement strongly constraints the masses of hypothetical extra Z bosons favoured by speculative BSM theories.

The part of fundamental physics can still be done with table-top experiments!

The necessary input is accurate theoretical determination of atomic structure.

What are we trying to do

To develop methods and codes for accurate atomic structure calculations to improve the theoretical predictions for measured parity violation interactions.
At the present time the accuracy of theory and experiments on atomic parity violation is as follows (see B.M. Roberts, et al, Annu. Rev. Nucl. Part. Sci., **65**, 63 (2015))

Atom	Theory[%]	Experiment[%]
Cs	0.9	0.3
Yb	10	15
Tl	2.5	1.1
Pb	8	1.2
Bi	10	2

One can see that with exception of Yb, where the experiment is still ongoing, the accuracy of experiments surpasses the accuracy of theory.

What is necessary to learn

- Principles of electroweak theory
- Principles of experiments
- How to perform an atomic calculation (how to calculate atomic integrals, how to perform relativistic Hartree-Fock calculation)
- How to account for the electron correlation (coupled clusters and its extensions)

Where it is possible to go

Interaction of electric dipole moment with external field

$$H_{EDM} = d_e \vec{S}_e \cdot \vec{E}$$

The interaction is T-odd:

$$t \to -t \Rightarrow \vec{S}_e \to -\vec{S}_e \,, \quad \vec{E} \to \vec{E}$$

SM prediction for d_e is effectively zero ($d_e \approx 10^{-43} e\, cm$).
Measurement in Thalium atoms, PRL **88**, 071805, yields $d_e < 1.6 \times 10^{-27} e\, cm$.
Measurement in Thorium Monoxide molecule, Nature **562**, 355 (2018) yields $d_e < 1.1 \times 10^{-29} e\, cm$.
Assume that

$$d_e = ek \frac{M_{\mathrm{w}k}}{M^2}$$

where $k \approx 1$, $M_{\mathrm{w}k} \simeq 100\, GeV$ and M is the scale of new physics.
Then the above experiment yields $M > 10^5\, TeV$.
The exclusion achieved at LHC is about $M > 1\, TeV$.
We are still at the beginning of fun...