Experimental Atomic Physics
Research in the Budker Group

• Tests of fundamental symmetries using atomic physics:
  • Parity
  • Time-reversal invariance
  • Permutation Postulate/Spin-Statistics Connection
  • Temporal variation of fundamental “constants”

• Applied atomic spectroscopy
  • Sensitive magnetometry and electrometry (NMR, magnetic anomalies, space,...)
  • Nonlinear optics with atoms
  • Optical properties of superfluid helium
  • “New” atomic energy levels
  • Properties of complex atoms: the rare earths, Ba
Our group
Group Demographics and Philosophy

- 6 graduate students
- 1 - 3 undergrads
- 1 staff scientist
- Lots of visitors from US and abroad; ongoing collaboration with groups in [Poland, Latvia, India, Armenia, and Russia], [LANL, NIST, LBNL, UCB Chemistry,…]
- Each student has their own project
- Lots of interactions within group
- Variety of experiences and techniques: lasers, optics, atomic beams and vapor cells, cryogenics, computer control and data acquisition, vacuum, electronics, theory, scientific writing and editing, ….
Further information:

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• budker@socrates.berkeley.edu
• Office: 273 Birge; labs: 217, 219, 221, 230, 241, and 245 Birge
Atomic Parity Nonconservation

Electromagnetic interaction
(conserves parity)
\[ \Pi \Psi (\vec{r}) = \pm \Psi (\vec{r}) \]

Weak interaction
(violates parity)
\[ \Pi \Psi (\vec{r}) \neq \pm \Psi (\vec{r}) \]

Small Modifications of the Optical Properties of Atoms

Provides Unique Low-Energy Test of the Standard Model
PNC Experiments

Electric and magnetic fields define a handedness

PNC effects show up as dependence of atom-photon interaction on handedness

Two Experiments in Progress: Dysprosium (Z=66) and Ytterbium (Z=70)
Yb Interaction Region
How constant is the fine structure “constant” \( \alpha \)?

Theories that unify gravity with other forces either allow or necessitate \( \alpha \) variation.

**Theoretical**

**Laboratory:**
- H-maser vs. Hg+ microwave clock: \( \dot{\alpha}/\alpha < 3.7 \times 10^{-14} / \text{yr} \)
- Rb vs. Cs microwave clocks: \( |\dot{\alpha}/\alpha| < 1.1 \times 10^{-14} / \text{yr} \)
- Hg+ optical vs. Cs microwave clocks: \( |\dot{\alpha}/\alpha| < 1.2 \times 10^{-15} / \text{yr} \)

**Geophysical:**
Oklo natural nuclear reactor 1.8 billion years ago:
\( |\dot{\alpha}/\alpha| < 10^{-18} / \text{yr} \)

**Astrophysical:**
\[ \dot{\alpha}/\alpha = (-7.2 \pm 1.8) \times 10^{-16} / \text{yr} \]

\[ \alpha \text{ in dysprosium}\]

Levels A and B are highly sensitive to variations in \( \alpha \):

\[ \nu \sim 3\text{–}2000 \text{ MHz} \]

\[ |\alpha/\alpha| \sim 10^{-15}/\text{yr} \Rightarrow \nu \sim 2 \times 10^{15} \text{ Hz} \]

\( \dot{\nu} \sim 2 \text{ Hz/yr} \)

\[
\begin{array}{c}
\text{rf freq. generator} \\
\text{atomic freq. standard} \\
\text{atomic beam} \\
\text{E-field plates}
\end{array}
\]

PMT

\( \nu \sim 2 \times 10^{15} \text{ Hz} |\alpha/\alpha| \)

i.e. for \( |\alpha/\alpha| \sim 10^{-15}/\text{yr} \)

\[ \Rightarrow \dot{\nu} \sim 2 \text{ Hz/yr} \]
**Goal**: Obtain highest possible sensitivity to magnetic fields.

**Use laser light to polarize atoms:**
1. Aligns magnetic dipole moments;
2. Creates preferred optical axis.

**Magnetic moments precess in magnetic field:**
Optical axis rotates → causes light polarization to rotate.

\[
\varphi = \frac{g_F \mu_B / \gamma_{rel}}{1 + (g_F \mu_B / \gamma_{rel})^2}
\]
Paraffin-coated cells look like Christmas ornaments!

Slow relaxation of atomic polarization:

\[ \gamma_{\text{rel}} \sim 1 \text{ Hz} \]

\[ \Delta B \sim 1 \mu \text{G} \sim 0.1 \text{ nT} \]
Pumping and probing with FM light

Precision magnetometry and atomic EDM measurement using spin-polarized atoms in a buffer gas at cryogenic temperatures

- Problem: to measure very small B; to measure electron EDM
- Paramagnetic atom magnetometer; He buffer gas at T=4K to increase spin-relaxation time to minutes

Measuring the Kerr effect in LHe and the LANL neutron EDM experiment

- Problem: to measure strong electric fields (50kV/cm) inside a bath of LHe at 300mK.
- Kerr effect: an initially isotropic medium acquires birefringence when electric field is applied, measure this.
Neutron EDM experiment at LANSCE
Laser spectroscopy for fundamental symmetry tests

- **Motivation: BEV exp**
- **Lifetimes, branching ratios, new levels, polarizabilities (Ba)**
- **Unusually large polarizabilities**
  (100 times; for \( n<10 \), only smaller than 2s,2p of H)

- “new” opposite-parity levels
- Electron EDM exp
- Noncontact circuit board testing
Probed States

Laser Excitation
559 - 569.5 nm

Fluorescence
~ 435 nm

$6s6p \, ^1P_1$
$6s6p \, ^3P_{0,1,2}$

Laser Excitation 554.7 nm

$6s^2 \, ^1S_0$

Even Parity  Odd Parity

Even Parity

Odd Parity

Ba oven

Ba beam

Pulsed dye laser (559-569.5 nm)

Pulsed dye laser (554.7 nm)

interaction region
electric field plates and magnetic coil

magnetic shield

interference filter
color glass

PMT
What is the experiment?

A test of the spin statistics theorem (SST) for photons.

What is the SST?

<table>
<thead>
<tr>
<th>Bosons</th>
<th>Fermions</th>
</tr>
</thead>
<tbody>
<tr>
<td>( J = 0, 1, 2, \ldots ) ( \iff ) ( \text{SST} ) ( \Rightarrow ) ( J = \frac{1}{2}, \frac{3}{2}, \frac{5}{2} \ldots )</td>
<td></td>
</tr>
<tr>
<td>(</td>
<td>\Phi\rangle ) Symmetric wrt exchange</td>
</tr>
<tr>
<td>Add exchange amplitudes with ‘+’</td>
<td>Add exchange amplitudes with ‘−’</td>
</tr>
<tr>
<td>( [a, a^\dagger] = 1 )</td>
<td>( {a, a^\dagger} = 1 )</td>
</tr>
<tr>
<td>Superposition, Bose condensation, Superfluidity</td>
<td>Pauli Excl, Neutron stars, Periodic table</td>
</tr>
</tbody>
</table>
Barium

\[ |e\rangle, \quad \hat{\epsilon}_2, \Omega_2 \]

\[ 35934 \text{ cm}^{-1}, \quad 5d6d, \quad ^3D_1 \]

\[ W_{\text{measured}} = W_+ + \nu W_- + W_{\text{backgrounds}} \]

\[ \Rightarrow \nu \leq \nu_{\text{limit}} = \frac{W_{\text{backgrounds}}}{W_-} \]

\[ \Rightarrow \nu_{\text{limit}} \propto W_{\text{backgrounds}} \times \frac{\Gamma \Delta^2}{D_1^2 D_2^3 I^2} \]

\[ \hat{\epsilon}_1, \Omega_1 \]

\[ 6s^2, \quad ^1S_0 \]

\[ 18060 \text{ cm}^{-1}, \quad 6s6p, \quad ^1P_1 \]

\[ |f_\pm|^2 \]

\[ \frac{4}{\Delta^2} \]

\[ \frac{\omega_{ge}}{2} \]

\[ \Omega_1 \]
Design: VV Yashchuk
Built by: A Vaynberg
Oven Housing w/Collimator

- 1.04"
- 0.28"
- 0.05"
- 1.58"
- 0.70"
- 0.82"
- 1.22"
- 1.70"
Chamber
Assuming non-resonant background,

\[ W_{\text{backgrounds}} \sim 10^2 \text{ Hz}, \]

Beam density \( n \sim 10^{10} \text{ at/cm}^3 \),

Fermi rate \( W_- \sim 10^5 \text{ Hz}, \)

Interaction volume \( V \sim 1 \text{ cm} \times 1 \text{ mm}^2 \)

\[ \Rightarrow \nu_{\text{limit}} \sim \frac{W_{\text{backgrounds}}}{W_- n V} = 10^{-11} \]

Search for Exchange-Antisymmetric Two-Photon States

D. DeMille, D. Budker, N. Derr, and E. Devaney

small violations of this selection rule by studying transitions in atomic Ba. We set a limit on the probability \( \nu \) that photons are in exchange-antisymmetric states: \( \nu < 1.2 \times 10^{-7} \).
Experimental Atomic Physics
Research in the Budker Group
Papers we wrote/published in 2004

- D. Budker, L. Hollberg, D. F. Kimball, J. Kitching, S. Pustelny, and V. V. Yashchuk, Investigation of microwave transitions and nonlinear magneto-optical rotation in anti-relaxation-coated cells; *physics/0408009*
- **Review article:** E. B. Alexandrov, M. Auzinsh, D. Budker, D. F. Kimball, S. M. Rochester, and V. V. Yashchuk, Dynamic effects in nonlinear magneto-optics of atoms and molecules; to appear in a Special Issue of JOSA B on Nonlinear and Integrated Magneto-Optics; *physics/0405049*
- **Comment:** D. Budker and S. M. Rochester, A relation between electromagnetically induced absorption resonances and nonlinear magneto-optics in Lambda-systems; *physics/0310066*. (Accepted to Phys. Rev. A)
- A. O. Sushkov, E. Williams, V. V. Yashchuk, D. Budker, and S. K. Lamoreaux, Kerr effect in liquid helium at temperatures below the superfluid transition, to appear in Phys. Rev. Letters; *physics/0403143*
We want **YOU** !