Low energy probes of high energy physics

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Nuclear Particle Astrophysics Seminar, Yale University
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Introduction

• The Standard Model provides an extremely successful framework for describing the known particles and their interactions

• However, several significant questions remain unanswered:
  
  • How do neutrinos acquire mass?
  
  • What is the origin of the matter/antimatter asymmetry?
  
  • What is the nature of dark matter and dark energy?
  
  • What is the microscopic nature of gravity?

Answering these questions is a key goal of particle physics in the coming years!
“Low energy” experiments

- While the SM was primarily developed at accelerators, non-accelerator experiments are increasingly important for probing BSM physics

- Will describe two “low energy” techniques:
  - Searches for neutrinoless double beta decay ($0\nu\beta\beta$) with EXO
    
    Are neutrinos Majorana particles?
    What is the absolute neutrino mass scale and how do they acquire mass?
    Is the neutrino mass mechanism related to the matter/antimatter asymmetry?

  - Searches for new short-range forces using optically levitated microspheres
    
    What is the microscopic nature of gravity?
    What is the nature of dark matter and dark energy?
I: Searching for neutrinoless double beta decay ($0\nu\beta\beta$) with EXO
Neutrino masses

• Our most direct evidence for physics beyond the Standard Model comes from neutrinos

• Oscillation experiments indicate neutrinos have small, non-zero masses

• “See-saw” models provide a natural way to obtain small $m_{\nu}$:

$$m_{\nu} \approx \frac{m^{2}_{q,l}}{m_{R}}, \quad m_{R} \sim 10^{15} \text{ GeV}$$

• In some models, may also account for the baryon asymmetry

• A key test is whether neutrinos are Majorana particles ($\nu = \bar{\nu}$)

Comparison between SM fermion masses:

- Neutrinos
- $d$, $s$, $b$
- $u$, $c$, $t$
- $e$, $\mu$, $\tau$

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0νββ

- Double beta decay is the most sensitive probe of the Majorana nature of the neutrino
- If neutrinos are Majorana particles, decay can proceed with no emitted neutrinos (0νββ)

Observation of 0νββ would provide:
- A beyond the Standard Model, lepton-number violating process
- Imply neutrinos are Majorana particles
- Constrain absolute neutrino mass scale

ββ energy spectrum:

2νββ

Nuclear binding energies, A = 136:

Normalized event rate

Normalized electron energy (Kₑ/Q)

2% FWHM

Normalized to 1


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EXO-200 TPC

- The EXO experimental program is searching for the 0νββ of $^{136}\text{Xe}$
- EXO-200 consists of a radiopure time projection chamber (TPC) filled with ~175 kg liquid Xe, enriched to 80.6% $^{136}\text{Xe}$
EXO-200 TPC

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![EXO-200 TPC image]
EXO-200 detector

- Detector installed at WIPP facility near Carlsbad, NM (~1600 mwe)
- TPC additionally surrounded by active and passive shielding
Background rejection

- Energy resolution of $\sigma_E = 1.4\%$ after accounting for charge/light anticorrelation
- $\beta\beta$ signal deposits energy at single location, backgrounds are multi-site
- Single-site fraction is $\sim 20\%$ in $0\nu\beta\beta$ region of interest for $\gamma$ backgrounds

Energy spectrum, $^{228}\text{Th}$ calibration:

- Counts / 16 keV
- Energy (keV)

$^{228}\text{Th}$ calibration data, single site (SS):

- Single site
- Data
- Monte Carlo

$^{228}\text{Th}$ calibration data, multiple site (MS):

- Multi site
- Monte Carlo

$Q_{\beta\beta} = 2458$ keV
EXO-200 data

• EXO-200 acquired ~2 years of physics data between Oct. 2011 and Sept. 2013 with a total exposure of 100 kg yr (Phase 1)

• Several major physics results so far:
  
  • **Discovery of 2νββ in ^{136}Xe [2011]**
    

  • **First limits on 0νββ in ^{136}Xe [2012]**
    

  • **Precision measurement of 2νββ T_{1/2} [2013]**
    

  • **Search for 0νββ in first 2 years of data [2014]**
    

  • **Search for Majoron emitting 0νββ decay modes [2014]**
    

  • **Measurement of decay ion fraction and mobility [2015]**
    

  • **Search for 2νββ decays to excited states of daughter nuclei [2015]**
    

• Additional 3 years of data (Phase 2) starting in Mar. 2016
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0νββ search

Single- and Multi-site energy spectra and fit:

0νββ ROI

Single site

Multi site


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0νββ search

Fit to single-site spectrum near 0νββ ROI:

Backgrounds in ± 2σ ROI:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Th chain</td>
<td>16.0</td>
</tr>
<tr>
<td>U chain</td>
<td>8.1</td>
</tr>
<tr>
<td>Xe-137</td>
<td>7.0</td>
</tr>
<tr>
<td>Total</td>
<td>31.1 ± 3.8</td>
</tr>
</tbody>
</table>

Data
Best Fit
Rn
LXe bgd
n-capture

232 Th (far)
Vessel
0νββ
2νββ

\[ T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{25} \text{ yr} \]
\[ \langle m_{\beta\beta} \rangle < 190 - 450 \text{ meV} \]
(90% C.L.)

Comparison to other isotopes

**Current limits, $^{76}$Ge vs. $^{136}$Xe:**

- **GERDA Limit**
- **KK&K 68% CL**
- **GERDA Sensitivity**
- **EXO-200 Limit**
- **KamLAND-Zen Limit**

**Current limits, $^{130}$Te vs. $^{136}$Xe:**

- **CUORE-0a Cuorente Limit**
- **KamLAND-Zen Limit**
- **EXO-200 Limit**

**EXO-200:** *Nature 510 (2014) 229*

**GERDA:** *PRL 111 (2013) 122503*

**KamLAND-Zen:** *PRL 110 (2013) 062502*

**KK&K Claim:** *Mod. Phys. Lett., A21 (2006) 1547*

**CUORE:** *PRL 115 (2015) 102502*
Current and projected sensitivity

Projections for Phase 2:
- Data taking begins Mar 2016
- Hardware improvements:
  - Improved energy resolution (1%)
  - “Deradonator”
- Demonstrated analysis improvements:
  - $^{137}$Xe rejection
  - Improved SS/MS discrimination
- Expect factor of ~3 improvement in sensitivity in 3 years
Current and projected sensitivity

Current and projected sensitivity to $\langle m_{\beta\beta} \rangle$ [90% CL]

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nEXO being designed to fully probe inverted mass ordering
nEXO design concept

- Large, homogenous LXe TPC enables exposure and low background needed for next-generation searches
- Technology demonstrated in EXO-200, but becomes more powerful in nEXO due to self-shielding

nEXO detector conceptual design:

- Charge readout tiles
- Light sensors
- Field shaping rings

nEXO:
- 140 cm
- ~5000 kg

EXO-200:
- 40 cm
- ~150 kg

Self-shielding:
- 2.5MeV γ attenuation length (8.5cm)
Background simulation

- Have performed detailed background simulations for nEXO
- Assumes measured activity for detector materials and projected hardware improvements
- This procedure builds on experience from EXO-200 and was validated using EXO-200 data

**Simulated nEXO spectrum near single-site ROI:**

![Simulated nEXO spectrum chart]

- Full 4.8 tonnes, 5 yr
- Central 1 tonne only, 5 yr

$$T_{1/2}^{0\nu\beta\beta} = 1.8 \cdot 10^{27} \text{ yr}$$
Current and projected sensitivity to $\langle m_{\beta\beta} \rangle [90\% \text{ CL}]$

**Normal ordering**
- EXO-200 current (Nature 2014)
- EXO-200 final (Projected)

**Inverted ordering**

**nEXO, 10 yr**

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EXO-200 and nEXO summary

- Searches for $0\nu\beta\beta$ provide the most sensitive test of the Majorana nature of the neutrino
- EXO-200 has performed one of the most sensitive $0\nu\beta\beta$ searches to date
- nEXO, the 5 tonne successor to EXO-200 is in the R&D phase
- If the neutrino is Majorana and the mass ordering is inverted, nEXO will observe $0\nu\beta\beta$
- nEXO also has substantial discovery potential for the normal mass ordering by improving sensitivity by an order of magnitude in $\langle m_{\beta\beta}\rangle$
- There is significant possibility to probe beyond the Standard Model physics by observing $0\nu\beta\beta$ in the coming years!
II: Searching for new short-range forces using optically levitated microspheres

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Non-Newtonian forces

- Although we often assume the $1/r^2$ law for gravity is valid at all distances, there is substantial motivation to search for deviations at $\ll 1$ mm

Large extra dimensions:

[Diagram showing large extra dimensions with a mention of Sci. Am. (2003)]


Exchange forces from new scalars (moduli, dilatons, ...):

[Diagram showing exchange forces]

Kaplan and Wise, JHEP 08, 037 (2000)

Dark energy ("fat" gravitons, screened scalars, ...):

$\Lambda \sim 2$ meV

($\sim 80$ μm)

e.g., Sundrum, Phys. Rev. D 69, 044014 (2004)

Given the large number of mechanisms for generating such forces, this is an interesting (and largely unexplored) parameter space for new physics!
One convenient parameterization for the non-Newtonian potential is the Yukawa form:

\[ V(r) = -\frac{Gm_1 m_2}{r} \left( 1 + \alpha e^{-r/\lambda} \right) \]

Current experimental constraints on non-Newtonian forces:

- Constraints weaken substantially at \(<<1 \text{ mm}\) (e.g. \(\alpha \lesssim 10^{10}\) for \(\lambda = 1 \ \mu\text{m}\))
- New techniques may allow improved sensitivity at \(\sim 1 \ \mu\text{m}\)
Experimental constraints

• One convenient parameterization for the non-Newtonian potential is the Yukawa form:

\[ V(r) = \frac{Gm_1 m_2}{r^{1+\alpha}} e^{-r/\lambda} \]

Current experimental constraints at short distance:

- Decca et al., PRL 94, 240401 (2005)
- Sushkov et al., PRL 107, 171101 (2011)
- Geraci et al., PRD 78, 022002 (2008)
- Kapner et al., PRL 98, 021101 (2007)

Theory regions adapted from PRD 68, 124021 (2003)
Optical levitation

- Suspending test mass with an “optical spring” offers several advantages:
  - Test mass can be isolated from surroundings and cooled optically
  - Dielectric spheres between \( \sim 10 \text{ nm} - 10 \text{ \(\mu\)m} \) can be used
  - Position can be controlled and measured precisely with optics
  - Control over 3D optical potential enables differential measurements
  - At high vacuum, extremely low dissipation is possible: \( Q \sim 10^{12} \) at \( 10^{-10} \text{ mbar} \)


*Geraci et al., PRL 105, 101101 (2010)*
Experimental setup

- Developed setup capable of levitating SiO$_2$ microspheres with $r = 0.5$-$5$ μm
- Microspheres are levitated in vacuum chamber with $\lambda = 1064$ nm, ~few mW trapping laser
- Have demonstrated trapping times of >2 weeks at $\sim 10^{-7}$ mbar

Photograph of experimental setup:

Simplified optical schematic:

- Trapping laser (1064 nm)
- Imaging laser (650 nm)
- Input optics
- Vacuum chamber
- Output imaging optics
Microsphere neutralization

- Have demonstrated controlled discharging with single $e$ precision
- Measure microsphere response to oscillating electric field while flashing with UV light
- Once neutral, have not observed spontaneous charging in more than $10^6$ s

**Example of discharging process:**

![Graph showing discharging process](image)

**Electrode cross-section:**

![Diagram of electrode cross-section](image)

**Photo of electrodes:**

![Image of electrodes](image)
Force sensitivity

- Can also use observed single e steps to perform absolute calibration of force sensitivity for each microsphere *in situ*

- Low pressure force sensitivity limited to: \( \sigma_F = 5 \times 10^{-17} \text{ N Hz}^{-1/2} \)

- Currently limited by laser jitter and imaging noise

- Pressure limited sensitivity at \( 10^{-9} \text{ mbar} \):
  \[ \sigma_F \sim 10^{-21} \text{ N Hz}^{-1/2} \]
  i.e., near the quantum limit:
  \[ \sigma_F \sim \sqrt{\hbar (m \omega^2)} \]
Attractor

- Need attractor that can be placed at \( \sim \mu m \) separations from microsphere
- Spatially varying density allows reduction of backgrounds
- Stage allows cantilever to be swept \( \sim 100 \mu m \) in all 3 DOF at >10 Hz
Expected backgrounds

- If unscreened, differential Casimir force between Au and Si can present dominant background
- Coating attractor with Au shield layer (0.5 to 3 μm thick) can sufficiently suppress this background
- Background due to surface “patch potentials” should be subdominant for expected face-to-face separations

Calculation of differential Casimir force:

\[
\text{Differential Casimir force } [\text{N}] = \frac{A}{s+t} [\mu \text{m}]
\]

Calculation of force due to patch potentials:

\[
\text{Force due to patch potentials } [\text{N}] = \frac{2.5}{s} [\mu \text{m}]
\]
Expected sensitivity

- Have calculated expected sensitivity to Yukawa strength parameter, $a$, as a function of length scale, $\lambda$
- Assumptions:
  
  **Face-to-face separation, $s$:**
  - 0.2 $\mu$m (dashed) or 2 $\mu$m (solid)

  **Force sensitivity:**
  - $\sigma_F = 5 \times 10^{-17}$ N Hz$^{-1/2}$ (blue)
  - $\sigma_F =$ pressure limited at $10^{-9}$ mbar (red)
  - 10$^6$ s integration time

  **Backgrounds:**
  - At or below noise level, Au shield thick enough to suppress Casimir background

- Substantial improvement over existing limits may be possible at 0.5–40 $\mu$m
Additional applications

• Hidden sector dark matter
  • New forces mediated by dark photons or light millicharged particles
  • Heavy, stable millicharged particles bound in matter

• Neutrality of matter (is $|q_e + q_p + q_n| > 0$ ?)

• Also Casimir force, mesoscopic QM, surface characterization,…
Microsphere neutrality

- Have performed a search for millicharged particles (|q| << 1e) bound in the microspheres
- Stable, millicharged particles could be produced in the early universe and form bound states that can be searched for in terrestrial matter
- Neutralize microspheres (so that \( n_e = n_p \)) and search for residual fractional charge

Residual charge measurement for an example microsphere:

\[ V_{\text{peak}} = 10 \text{ V} \]

\[ V_{\text{peak}} = 500 \text{ V} \]
Heavy millicharged particles

- Repeated search with 10 microspheres ($m \approx 0.1$ ng each)
- Statistically significant residual response consistent with permanent dipole coupling to small E-field gradients
- Sensitivity to single fractionally charged particles with charge as small as $5 \times 10^{-5}$ e

![Measured residual response:](image.png)

![Limits on abundance of millicharged particles:](image.png)


*Kim et al., PRL 99 161804 (2007)*

This work
Summary

- Levitated microspheres can enable novel searches for a variety of models of new physics beyond the Standard Model

- Can probe significant amounts of unexplored parameter space for new forces coupling to mass at length scales from 0.5 – 40 μm

- Also will enable sensitive searches for dark photons, millicharged particles, and chameleon dark energy models

- $0\nu\beta\beta$ offers an additional powerful probe of BSM neutrino physics

- There is substantial possibility for discovery of beyond the SM physics in the coming years at the “low energy” frontier!