Precision Probes of New Physics with Nuclear and Atomic Physics

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Grand Challenge of High Energy Physics
Standard Model experimentally established

We know there is new physics out there

Matter? Universe? Dark Matter

Dark Energy Hierarchy

Where is this new physics?
Where is this New Physics?
Mass? Strength?

0

Strong Physics Case

Gravity

Colliders

Gravitational Waves, Dark Matter, Dark Energy

10^{19} \text{ GeV}
(Quantum Gravity)
Where is this New Physics?
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Mass
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1
Colliders

Gravitational Waves, Dark Matter, Dark Energy

How?

Statistics, Amplification, Quantum Sensing
Outline

1. The GANDHI Experiment
2. Magnetic Bubble Chambers
3. Directional Detection with NV Centers
4. Conclusions
GAmma Nuclear Decays Hiding from Investigators Experiment (GANDHI)

Surjeet Rajendran
with

Giovanni Benato, Alexey Drobizhev and Hari Ramani

Proof of Concept:
Rupak Mahapatra (TAMU)
Missing Energy in Gamma Cascades

Aim: Single Event for Discovery

How well can we do?

Baryonically coupled $\phi$, mass $\lesssim$ MeV
Outline

1. Nuclei
2. Setup
3. Theory/Reach
Nuclei
Nuclei

Lifetime, Cascade Efficiency, Availability

$^{60}$Co

$\beta (99.88\%)$

1.17 MeV

$^{60}$Ni

$\beta$

$t_{1/2} \sim 5$ years

Similar energy Gammas

Parity of States -> scalars and vectors

$^{24}$Na

$\beta (99.85\%)$

2.75 MeV

$^{24}$Mg

$t_{1/2} \sim 15$ hr

Medical Isotope
Setup
Scintillator
~ $10^4$/MeV

Observe Individual Event
No pile up

High Event Rate
Fast Scintillator

Plastics or Crystals
~ ns response

~ 30 radiation lengths

Plastics: ~ 10 m, cheap, make large modules

Crystals: ~ 2 m, harder to grow. CMS E-cal

Initial Goal: $10^{-11}$
Eventual Goal: $10^{-14}$
Protocol

Signal

1. Observe $\beta$ activity consistent with initial decay

2. Within $\sim$ ns, observe 1$^{st}$ $\gamma$ in inner module

3. In that $\sim$ ns, no other energy in detector

Backgrounds?
Intrinsic Background for $^{60}$Co

Can $2^{\text{nd}} \gamma$ fake $1^{\text{st}}$?

Energy Resolution

Produce both. Confuse 1.33 MeV $\gamma$ for 1.17 MeV $\gamma$

Requiring single $\gamma$ only eliminates background

Soft $\beta$ to 2+ and Soft Compton $\gamma$

Populate 2+ @ $10^{-3}$.

Soft $\beta + $ Soft 1.33 MeV = $\beta$ to 4+ and 1.17 $\gamma$?

Soft $\beta + $ Energy Resolution of 1.33 MeV?
Geometry

Soft $\beta$ to 2+ and Soft Compton $\gamma$

Geometry separates $\beta$ & $\gamma$.

Confusion only if both hit same scintillator ($\sim$ cm)

Simulated reach $\sim 10^{-11}$

Possible Elimination?

Separate source from inner module.
Require well separated $\beta$ & $\gamma$

Absent in $^{24}$Na where $E_1 >> E_2$
Energy Resolution

Soft $\beta$ to 2+ and mis-measured energy

Measure energy from light yield (LY)

Light yield set by quantum efficiency of photodetector (Q)

Plastic Scintillators: $LY \sim 10000$/MeV

PMT: $Q \sim 0.25$

\[
LY \times E \times Q \pm \sqrt{E \times LY \times Q} \implies E_m
\]

Simulated reach $\sim 10^{-11}$

Absent in $^{24}$Na where $E_1 >> E_2$
Other Backgrounds

Detector Dead Volumes?

Well calibrated inner modules

Radiation Damage < $10^4$ Grays

Further limit through separation

Radioactive Contaminants

Long lived $\beta$ at right energy?

None for $^{24}\text{Na}$. 

$^{40}\text{K}$ for $^{60}\text{Co}$ - mBq/gm in some plastics.

Demand well separated $\beta$ and $\gamma$ in central module, ns timing
Triggers

@ $10^{-11}$, not as hard as LHC

@ $10^{-14}$, comparable to LDMX

Cosmic Rays

Veto event with energy outside inner module

Require well separated $\beta$ and $\gamma$ in inner modules within $\sim$ ns

Many radiation lengths separate inner module from environment
Theory/Reach
Model

\[ \mathcal{L} \supset g_p \phi \bar{\Psi}_p \Psi_p + \mu^2 \phi^2 \]

Need Branching fraction in E2 transitions.

Similar to \( \gamma \) transitions

\[ H^\phi_{\text{int}} = g_p R^i_p R^j_p \nabla_i \nabla_j \phi \quad H^\gamma_{\text{int}} = e R^i_p R^j_p \nabla_i \epsilon_j \]

\[ \frac{\Gamma_\phi}{\Gamma_\gamma} \sim \frac{g_p^2}{e^2} \]

Poor constraints on baryonic forces > 100 keV

Relevant for light dark matter experiments

Potentially cause Type 2 Supernova
Reach

- ROI = $E_\gamma \pm 1 \sigma$
- ROI = $E_\gamma \pm 2 \sigma$
- ROI = $E_\gamma \pm 3 \sigma$
- ROI = $E_\gamma \pm 4 \sigma$

--- No bkg; $^{24}$Na
Probe Past Supernova?
(> $10^{12}$/s)

Not limited by availability of source. Complex Handling!

Avoid pile up?

Resolve individual events - hard to get good energy resolution beyond ns response times

Geometric Separation of Events

Hard Limit: Trigger Electronics!

Better Nuclear Levels?

Gamma Cascades in forbidden channels? Enhanced branching fraction for scalars?

**Axions: M1 transitions - $^{65}$Cu -> $^{65}$Ni?**
Magnetic Bubble Chambers

with

Phil Bunting, Giorgio Gratta, Michael Nippe, Jeffrey Long, Rupak Mahapatra and Tom Melia
The Dark Matter Landscape

What about this range?

Coherence time of signal too short for phase measurement to work. Energy deposition too small to be been using conventional WIMP calorimeters

Need amplification of deposited energy (meV - keV)

Challenge: Need large target mass. Rare dark matter event. Requires amplifier stability > years
Consider magnet with all spins aligned

Spins now in metastable excited state with energy 
$\sim g \mu B$

Dark Matter collides, deposits heat. Causes meta-stable spin to flip

Spin flip releases stored Zeeman energy (exothermic). Released energy causes other spins to flip, leading to magnetic deflagration (burning) of material.

Amplifies deposited energy. Like a bubble chamber. Is this possible? Stability?
Single Molecular Magnets

Will not happen in a ferromagnet - spins are strongly coupled.


Organo-Metallic complexes. Central metal complex surrounded by organic material.

Weak coupling between adjacent metal complexes - but still large density

Each molecule acts as an independent magnet

Recently discovered systems. Few 100 known examples. Can make large samples. Magnetic deflagration experimentally observed and well studied in Manganese Acetate complexes
Magnetic Deflagration

System well described by 2 level Hamiltonian.
Two states separated by energy barrier.

Turn on magnetic field, metastable state decays to ground state through tunneling

\[ \tau \propto \tau_0 \exp \left( \frac{U_{\text{eff}}}{T} \right) \]

Ultra-long lived state at low temperature - localized heating rapidly decreases life-time, decay results in more energy release.
Condition for Deflagration

Initially heat region of size $\lambda$ to $T$

- Thermal Diffusion, lowers $T$
  \[ \tau_D \propto \lambda^2 \]

- Spin flips, releases energy, increases $T$
  \[ \tau \propto \tau_0 \exp \left( \frac{U_{\text{eff}}}{T} \right) \]

Deflagration occurs as long as we heat a sufficiently large region

$U_{\text{eff}}$ and $\tau_0$ sets the detector threshold. Short $\tau_0$ and small $U_{\text{eff}}$ means tiny energy deposit will sufficiently heat up material to trigger deflagration. Low threshold

Known examples with $\tau_0 \sim 10^{-13}$ s, $U_{\text{eff}} \sim 70$ K, enabling 0.01 eV thresholds
Detector Stability

High energy (> MeV) background from radio-active decays.

Detect MeV events using conventional means. Actual background at low energy very low - forward scattering of Compton events.

Problem: MeV events will constantly set off detector. Reset time vs operation time? Big problem for bubble chambers like COUPP.

Expected background $\sim 1/(m^2 \text{s})$. Initial detector size $\sim (10 \text{ cm})^3$ (kg mass), 1 background event $\sim 100 \text{s}$

With precision magnetometers, don’t need entire crystal to flip.

Within $\sim 10 \mu\text{s}$, flame $\sim 10 - 100 \mu\text{m}$. Visible with SQUID.

Shut off $B$, turn off fuel. Deflagration stops. Lose $\sim (10 - 100 \mu\text{m})^3$ of volume every 100 s.
Potential Reach

\[ \mathcal{L} = -\frac{1}{4} \left( F_{\mu\nu} F^{\mu\nu} + F'_{\mu\nu} F'^{\mu\nu} \right) + \frac{1}{2} m_\gamma^2 A'_\mu A'^\mu - e J_{\gamma M}^\mu ( A_\mu + \varepsilon A'_\mu ) \]

Absorption obtained from photoabsorption. Exposure of 1 kg-year
Trial using Mn-Ac

Two sets of Mn12-Ac and Hall sensors

One with μCi Am 241 α source
One without source

Metastability? Deflagration?
Results

Avalanche only observed with source

Mn12-Ac has high threshold (~ few MeV) - using new materials now
Directional Detection of Dark Matter with Crystal Defects

with
Misha Lukin, Alex Sushkov, Ron Walsworth and Nicholas Zobrist
Neutrinos and WIMPs have similar scattering topologies - rare, single particle collision with detector.

Sun produces neutrinos. Irreducible background.

Challenge: Big Target Mass. Need directional detection at solid state density.
Tell-tale damage cluster well correlated with direction of initial ion, localized within $\sim 50$ nm
Collision Aftermath

Tell-tale damage cluster well correlated with direction of initial ion, localized within ~ 50 nm

Results of TRIM simulation, 30 keV initial ion

O(200 - 300) vacancies and interstitials, lattice potential ~ 30 eV

Damage cascade well correlated with direction of input ion

Need nano-scale measurement of damage cascade
Nitrogen Vacancy Center in Diamond

Vacancy electron’s transitions can be optically studied.

Collect light

Electronic levels sensitive to crystal environment ~ 50 nm scale

~ 1 per (30 nm)$^3$ of NV centers in bulk diamond demonstrated

Nano-scale measurements experimentally demonstrated. Active development of sensors by many groups around the world.

Can this be used for directional detection? What is the effect of the damage cascade on a NV center?

Note: similar phenomenology applies to F-centers of Metal Halides
Damage leads to strain in crystal. Strain shifts transition line

\[
\text{Strain: } \nabla u \propto \frac{1}{r^3} \times O(100 \, \text{to} \, 300)
\]

(Hooke’s Law)

TRIM simulation of damage cascade - calculate strain using Hooke’s law

NV center shift ~ 100 kHz @ 30 nm
Natural line width ~ kHz

Single NV center has sensitivity to cascade!
**Detector Concept**

Large detector, segments of thickness ~ mm

NV center density ~ 1 per (30 nm)$^3$

Conventional WIMP scattering ideas (scintillation, ionization etc.) to localize interesting events

Expect few events/year that could be WIMP or neutrinos

Pull out segments of interest. Conventional schemes localize events to within mm

Micron-scale localization by simply shining light - damaged area will have measurable frequency shifts

For nano-scale resolution, apply external magnetic field gradient - hence need segmentation
Results

Take crystal. Grid of NV centers with density 1 per (30 nm)$^3$

Run ~ 1000 TRIM simulations, get cascade for each. Can grid distinguish direction (including head vs tail)?

More damage in tail vs head used for discrimination. Above 10 keV, efficiency > 80%, false positive < 4%

5 σ detection with few events!
Conclusions
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Gravity

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Quantum Gravity

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Technology Outlook

Dramatic Evolution in Colliders in the 20\textsuperscript{th} century

Why?

Humanity mastered electromagnetism in the 1900s

Now, at the anvil of quantum control

Time to find weakly coupled physics!