Next Generation Radiative Neutron Decay Experiment

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Outline

1. Experimental Developments
2. Correlation Coefficient *a*
3. Theoretical Review
4. Radiative Corrections
5. Summary

Goals for Run II

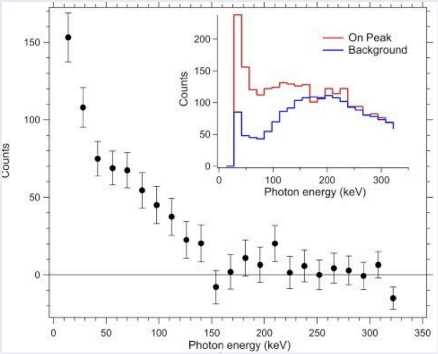
Goals

- 1% precision on branching ratio
- Measure energy spectrum

Obstacles

- Previous run systematics limited
- No response functions previously
- Inverse problem of extracting spectrum from convoluted data

Run I Spectrum



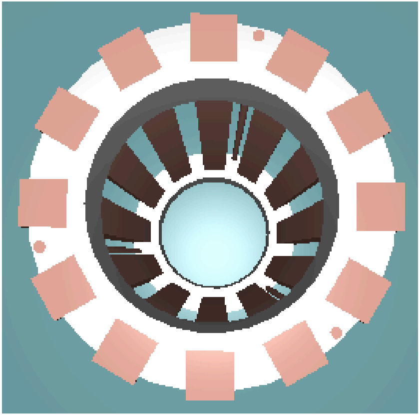
Systematics

Source of Uncertainty	Correction (%)	Uncertainty (%)
Photon detector gain drift		6.0
Analysis cut efficiencies		5.0
Monte Carlo statistics		4.0
Photon efficiency/resolution	+3.0	3.0
Beam divergence/profile		3.0
Electron bremsstrahlung	-3.0	3.0
B field registration		2.0
Mirror potential registration		1.0
Electron backscattering		0.5
Electronic artifacts		0.5
Total	-0.0	10.4

New Hardware for Run II

Improvements

- 12-Element γ Detector
  Higher statistics
  Different sensitivity to
  correlated backgrounds
- Improved beam optics
  "Active" area smaller than
  current beam
- Rigorous calibration routines
- Improved electronics
  New Gage Octopus card
  8 channels / card
  Up to 125 MHz sampling
  14-bit bipolar resolution
- Bare APD?



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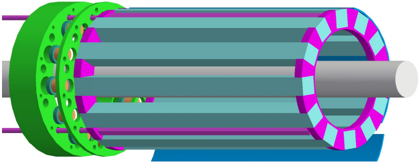

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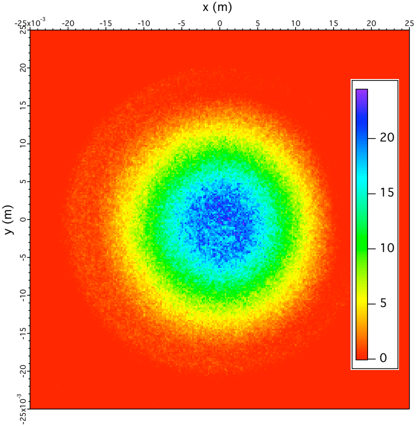

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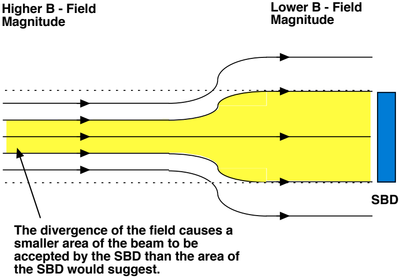

The divergence of the field causes a smaller area of the beam to be accepted by the SBD than the area of the SBD would suggest.

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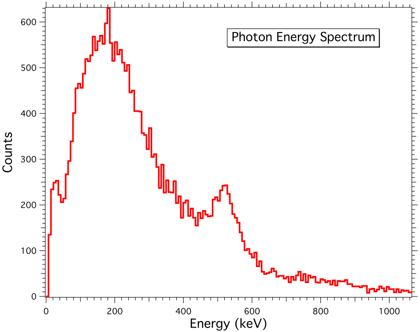

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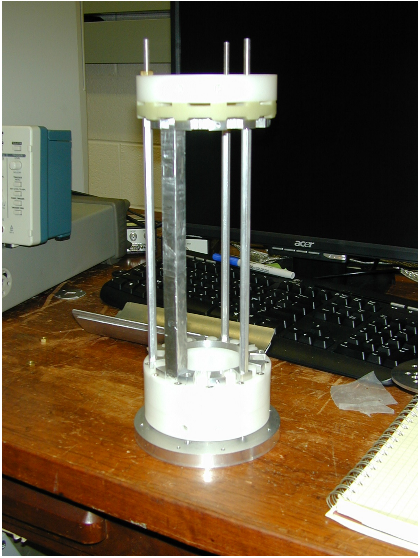
12-Element Detector

Nearly complete!

- 12 BGO crystals coupled to 12 APDs
- Requires 12 independent HV sources to individually adjust gains
- Each APD varies slightly
- 12 Preamp signals coupled to Gage Octopus cards
- Currently doing dewar tests
    - Temperature stability
    - Gain
    - Compton
    - Crosstalk noise / pickup



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Dewar Tests

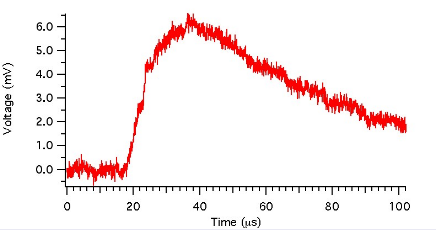
Current Work

- Test data being collected
- Learning about electronics
- Building DAQ
- Benchmarking APDs

Naive Analysis

- Adjust baseline
- Find peak channel
- Some small ripple
- Histogram these peaks
- Operational

Sample Trace



Stability Test

- Filled 5 hrs earlier
- Topped off 1 hr earlier
- Gaussian fit to histogram

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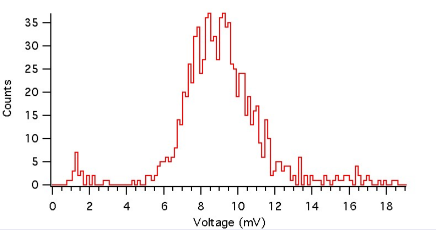
Histogram



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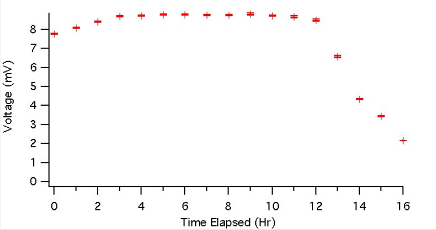
Peak vs. Time



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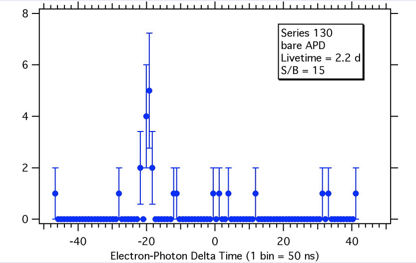
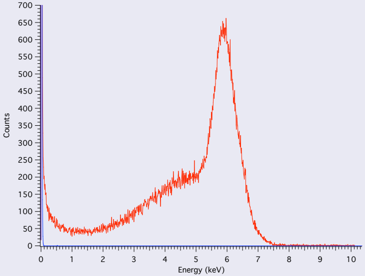
Bare APD Photon Detector

$\Delta t_{e-\gamma}$ histogram



^{55}Fe 5.899 keV X-Ray



- Detects lower energy (100 eV threshold)
- Higher rate. BR [0.10-10 keV] $\approx 6.4 \, \mathrm{x} \, 10^{-3}$ (theory)
- High S/B in runs
- Small surface area
- Faster response time

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ep Physics

- Photon philosophy
  Record first, ask questions later
- Many *ep* events collected with no energetic photon recorded
- Is there more information in our *ep* data?
- Over 10^7 total *ep* events recorded

Decay Rate

- Unpolarized neutron decay rate (tree level)

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \quad \propto \quad p_e E_e (E_0 - E_e)^2 \left(1 + a\frac{p_e \cos\theta_{e\nu}}{E_e}\right)$$

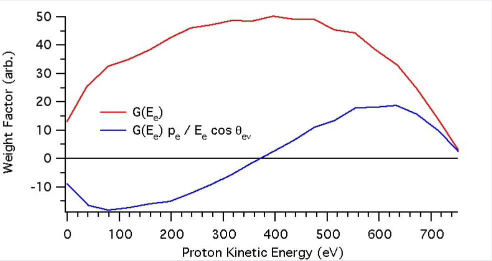
- Use Monte Carlo to integrate over all variables except E_p

$$\frac{d\Gamma}{dE_p} = f_1(E_p) + a \cdot f_a(E_p)$$

Proton Energy Dependence

- $f_a(E_p)$ term has strong proton energy dependence
- Experiment sensitive to proton energy can be made sensitive to *a*
- Electrostatic mirror does this in a very crude fashion

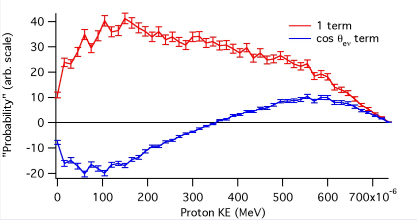
Dependence vs. Proton KE



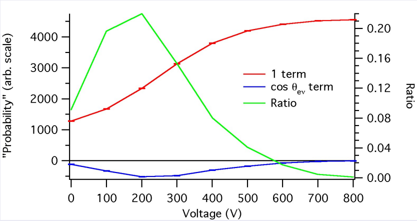
Phase Space Dependence

- Apparatus only sensitive to fraction of total available phase space
- Changes with mirror voltage
- Summing over proton energy yields contribution at particular voltage

0 V



f_1 and f_a vs. Voltage



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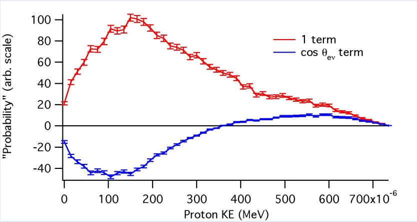
200 V



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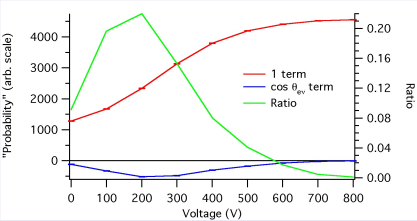

Phase Space Dependence

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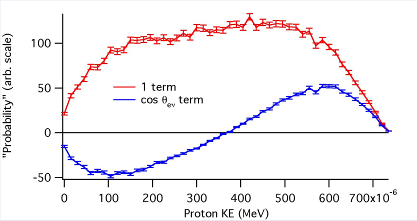
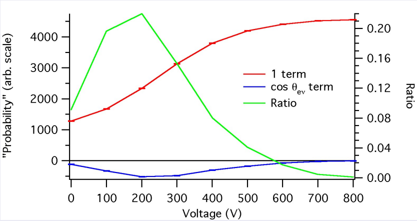
800 V



f_1 and f_a vs. Voltage

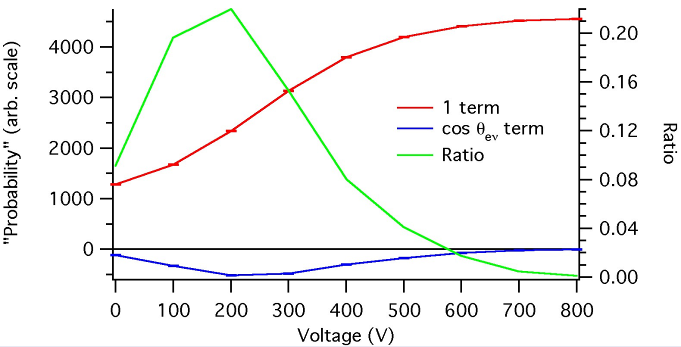


Weak Dependence

- Highest sensitivity $\approx 25\%$
- $a \approx 0.1$

- 2.5% sensitive at best
- $> 10^7$ *ep* events!

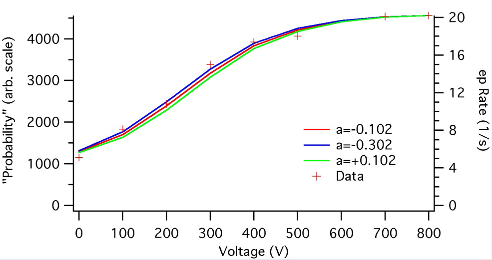
f_1 and f_a vs. Voltage



Preliminary Comparison to Data

- Current data doesn't constrain *a*
- Found run to run deviations
- Ratio method insensitive to deviations
- Illustrates low sensitivity
- A consistency check

Ratio vs. *a*



- More to come!

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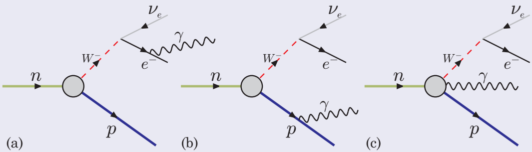
Radiative Decay Matrix Element

Tree-level Feynman Diagrams



- (a), (b) QED calculable and (c) require HBχPT EFT

$$
\begin{aligned}
\mathcal{M}_{\text{QED}} \quad = \quad & i\frac{eg_V}{\sqrt{2}}\Bigg[\bar{u}_e(p_e)\frac{(2p_e\cdot\epsilon + \not\epsilon\;\not p_\gamma)}{2p_e\cdot p_\gamma}\gamma_\mu(1-\gamma_5)v_{\bar{\nu}}(p_\nu) \\
& \times\bar{u}_p(p_p)\gamma^\mu(1-\lambda\gamma_5)u_n(p_n) \\
- \quad & \bar{u}_e(p_e)\gamma_\mu(1-\gamma_5)v_{\bar{\nu}}(p_\nu) \\
& \times\bar{u}_p(p_p)\frac{(2p_p\cdot\epsilon + \not\epsilon\;\not p_\gamma)}{2p_p\cdot p_\gamma}\gamma^\mu(1-\lambda\gamma_5)u_n(p_n)\Bigg]
\end{aligned}
$$

Intuition

- Proton bremsstrahlung small contribution.
- Electron $\mathcal{O}(1)$ proton $\mathcal{O}(q/m_p)$
- Electron term only, is it correct? NO
- Use both, is this correct? YES
- What's wrong with intuition? NOTHING
- What's the resolution?

$$\frac{d\Gamma}{d^8X} = (1+3\lambda^2)\left[\frac{f_1(X)}{(p_e\cdot p_\gamma)^2} + \frac{f_2(X)}{(p_e\cdot p_\gamma)(p_p\cdot p_\gamma)} + \frac{f_3(X)}{(p_p\cdot p_\gamma)^2} \right.$$
$$\left. + a\left(\frac{f_1(X)}{(p_e\cdot p_\gamma)^2} + \frac{f_2(X)}{(p_e\cdot p_\gamma)(p_p\cdot p_\gamma)} + \frac{f_3(X)}{(p_p\cdot p_\gamma)^2}\right)\right]$$

where X is all the kinematic variables

Resolution

- The gauge invariant trick

$$\sum_{\text{polarizations}} \epsilon_\mu^* \epsilon_\nu \to -g_{\mu\nu}$$

  can only with diagrams that are gauge invariant
- Electron diagram alone is NOT gauge invariant
- Electron diagram and proton diagram together are gauge invariant $\Rightarrow$ Trick works
- To use only electron diagram $\Rightarrow$ "brute force"
- Input ϵ_μ polarization explicitly
- "Brute force" on electron diagrams
  = gauge invariant trick on both diagrams (tree level)
- $\mathcal{O}(1)$ proton contribution "illusory" $\to$ cancels

Polarized Neutron Radiative Decay

- Calculation for unpolarized neutron
- Add polarization P by

$$u_n^s(p_n) \to \frac{1 + \gamma_5 \not{P}}{2} u_n^s(p_n)$$

- Decay rate is

$$\begin{aligned} \frac{d\Gamma}{d^8X} &= (1 + 3\lambda^2)\left[g_1(X) + a g_2(X)\right. \\ &+ \left.\mathbf{P} \cdot (A g_3(X)\mathbf{p_e} + B g_4(X)\mathbf{p}_\nu + A g_5(X)\mathbf{k})\right] \end{aligned}$$

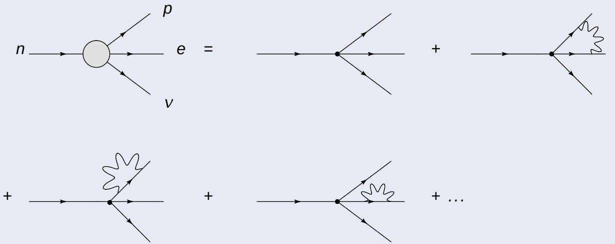
  where a, A, B are familiar from non-radiative decay
- Photon - neutron polarization coefficent is A, not unexpected, electron bremsstrahlung and lowest order

Outline

Neutron Decay Vertex

- Neutron decay begins with g_V^0 and g_A^0 at tree level
- Higher order loops correct g_V^0 and g_A^0
- Infrared divergences
- Bremsstrahlung diagrams needed

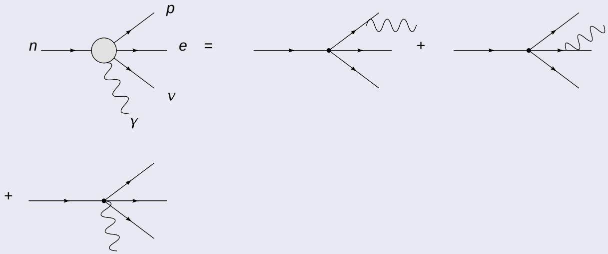
3-Body Final States



Bremsstrahlung

- Radiative decay experiment is just this subset
- With energy windows, hard / soft photon cutoff is explicit
- Cutoff can vary by design

4-Body (Bremsstrahlung) Final States



+loops

Generalization

- Neutron decay is 3-body tree level diagram + loops with bremsstrahlung diagrams (with their subsequent loops) “incoherently" added to decay rate
- Expect $g_V^0 \rightarrow g_V$
- g_A hard to calculate, measure λ
- Radiative decay just a subset though!
- Why not $g_V^0 \rightarrow g_V'$ and measure λ' from only radiative decays?
- Energy dependent radiative corrections established in ^{3}H β-decay
  S. Gardner et al., Phys. Lett. B **598**, 188 (2004)

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Summary

- Upgrade to new detector is underway
- Experiment is slightly sensitive to *a*, requires understanding systematics very well
- Provides more diagnostic checks
- Calculation confusion cleared up
- Calculation applied to polarized neutron system (tree level)
- Seeing vertex bremsstrahlung and measuring radiative corrections will likely require NLO calculations (HBχPT and recoil order terms)