First Observation of the Radiative Decay Mode of the Neutron

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National Research Council Postdoctoral Associate
National Institute of Standards and Technology

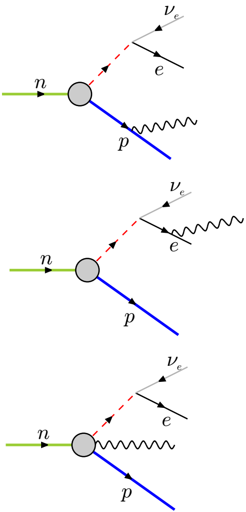
INT: Fundamental Neutron Physics Seminar
15 May 2007

Radiative Neutron Decay

Despite decades of experimental study, the radiative decay mode of neutron beta decay had never been observed

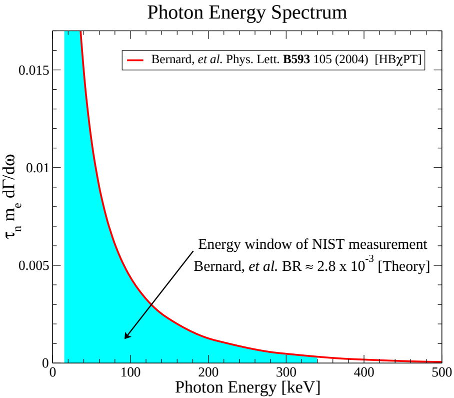
$n \longrightarrow e^- + p^+ + \overline{\nu}_e + \gamma$ Theory:

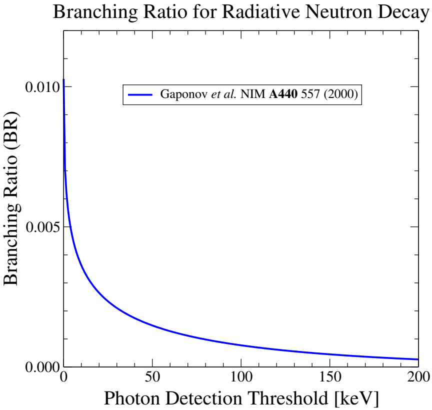
- **Glück, 1993**: Distributions of unpolarized neutron decay include bremsstrahlung photons.
- **Gaponov and Kafizov, 1995**: Explicit branching ratio and γ energy spectrum in QED framework – Proton treated as structureless charged particle.
- **Bernard, Gardner, Meißner, and Zhang, 2004**: Chiral perturbation theory framework. Includes photon emission from effective weak vertex in $\mathcal{O}(1/M)$.



Gluck, PRD **47**, 2840(1993); Gaponov and Khafizov, *Phys. Atom. Nucl.* **59**, 1213(1996); Bernard *et al.* PLB **593**, 105 (2004)

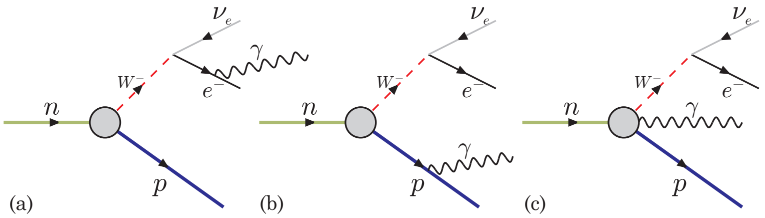
RDK Photon Spectrum and Branching Ratio





Why Study Radiative Neutron β-Decay?

- This rare branch of a fundamental decay has never been observered for the neutron
- Fundamental process in a fundamental semileptonic decay
- Determine vector (g_V) and axial-vector (g_A) weak coupling constants
- Study hadron matrix elements in $\mathcal{O}(1/M)$ ($\approx 0.5\%$)
- Test Dirac structure of the weak current through photon polarization (i.e., non V-A currents)
- Examine new class of angular correlations: e.g. $\sigma_{\mathbf{n}} \cdot \mathbf{p}_\gamma$, $\mathbf{p}_\gamma \cdot (\mathbf{p}_e \times \mathbf{p}_\nu)$, etc.



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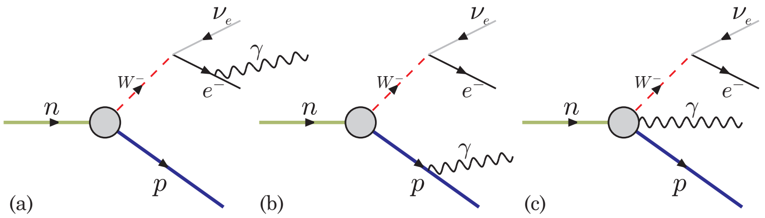

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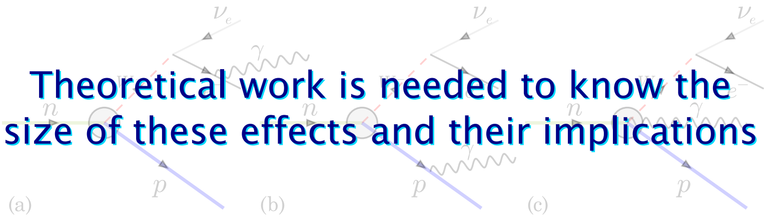


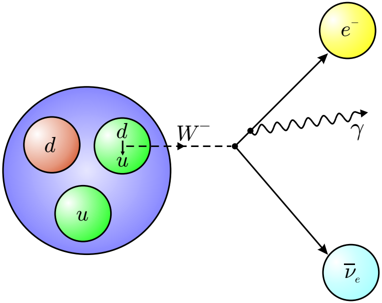
(a) (b) (c)

Theoretical work is needed to know the size of these effects and their implications

Radiative Decay of the Neutron

Goal:

Measure photon and electron in coincidence with delayed proton



Experimental Challenges

- Long τ_n (885.7 ± 0.8 s)
- Small branching ratio
- Large γ backgrounds
- Isolate from backgrounds: external bremsstrahlung

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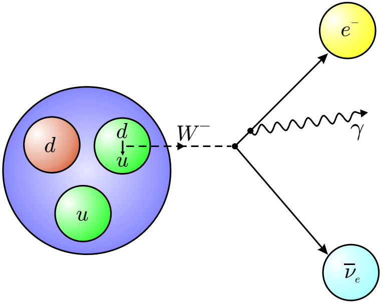

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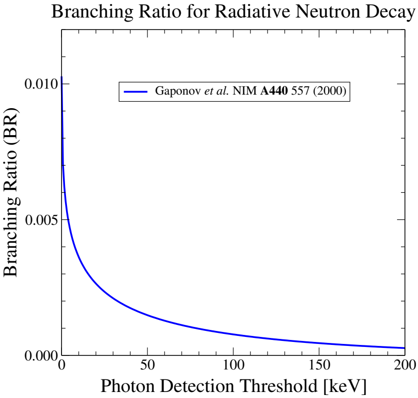

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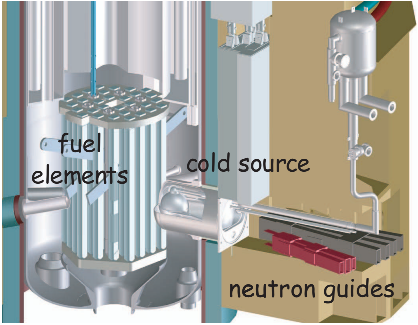

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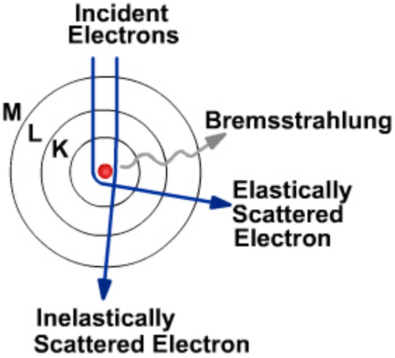

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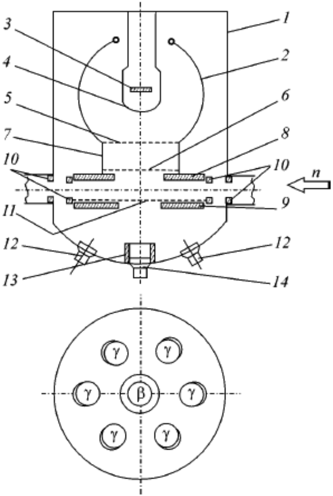
Neutron Radiative Decay at ILL



M. Beck[1] , J. Byrne[2], R. U. Khafizov[3], V. Yu. Kozlov[1], Yu. A. Mostovoi[3], O. V. Rozhnov[4], N. Severijns[1], and V. A. Solovei[4]

1 Katholieke Universiteit Leuven
2 University of Sussex
3 Russian Research Centre Kurchatov Institute
4 Petersburg Nuclear Physics Institute

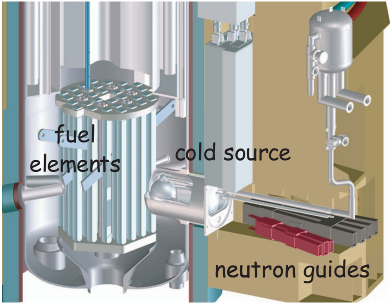
$$BR \leq k\frac{N_T}{N_D}(\epsilon_\gamma \Omega f)^{-1}$$

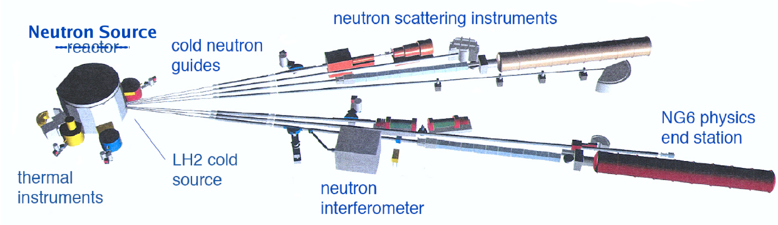
$$\boxed{BR < 6.9 \times 10^{-3} \quad (90\%\,\text{C.L.})}$$

Beck et al, *JETP Lett*. 76 (2002)

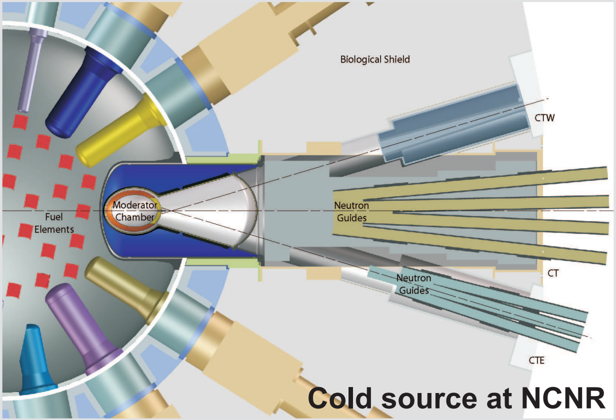
NIST Center for Neutron Research

20 MW split-core research reactor, peak neutron fluence rate $= 4 \times 10^{14}$ cm^{-2} s^{-1}





NIST Center for Neutron Research – Cold Neutron Source



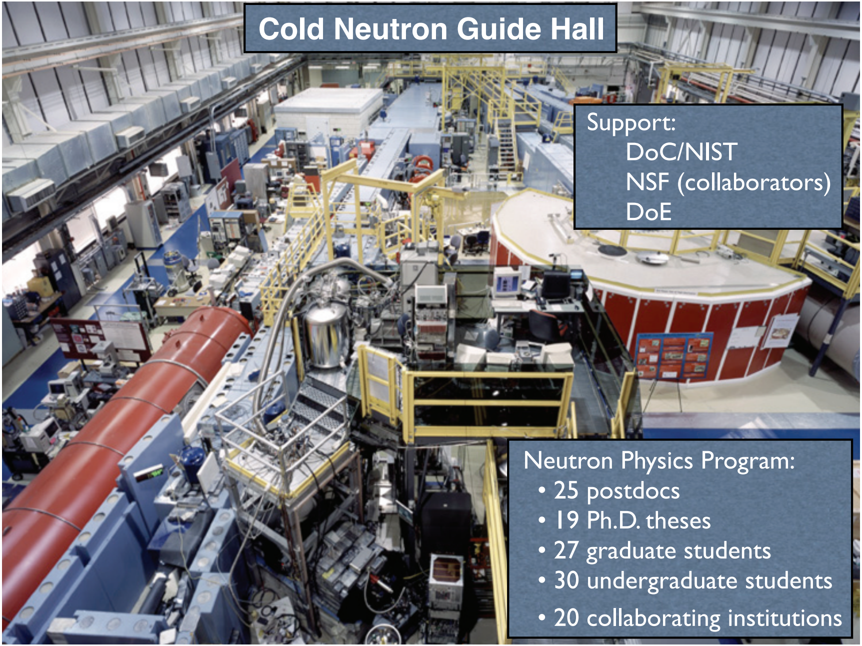
Cold source at NCNR

Neutrons partially thermalize in a cold source

- NCNR, liquid hydrogen (eff. 20K)
- Slow neutrons have larger probability of decaying in the detector

- neutron temp ≈ 40 K
- neutron energy ≈ 3.4 meV
- neutron velocity ≈ 800 m/s
- neutron flux (typ. ≈ 10^9 cm^2 s^{-1})

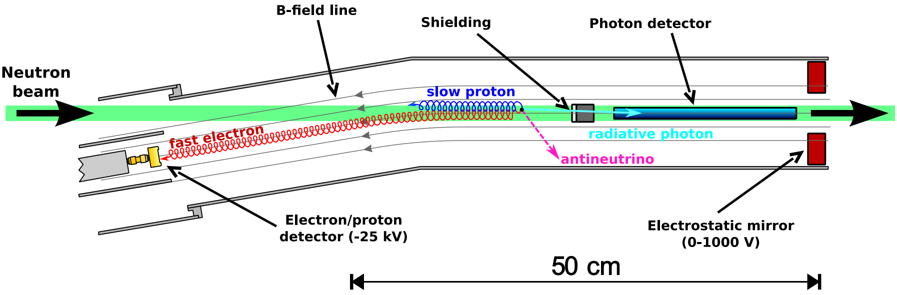
Cold Neutron Guide Hall



Support:
- DoC/NIST
- NSF (collaborators)
- DoE

Neutron Physics Program:
- 25 postdocs
- 19 Ph.D. theses
- 27 graduate students
- 30 undergraduate students
- 20 collaborating institutions

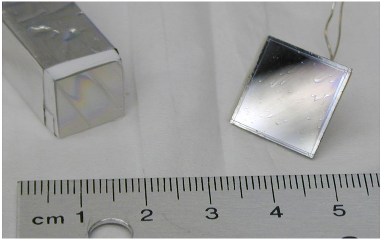
Experimental Setup

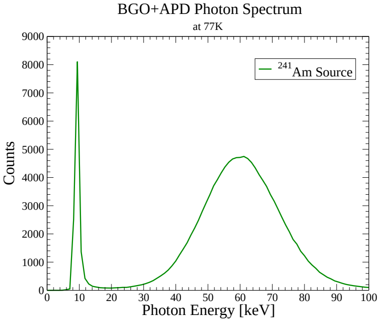


- 4.6 Tesla axial magnetic field traps charged charged decay products to tight cyclotron orbits – provides large solid-angle coverage
- Delayed electron-proton coincidence trigger strongly rejects uncorrelated photon background
- Electrostatic mirror turns around “wrong-way” protons
- Waveform-based DAQ

Photon Detection

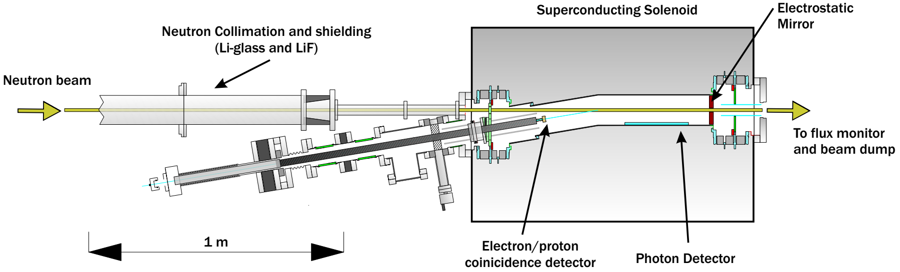
Bismuth germanate (BGO) crystals coupled to avalanche photodiodes (APDs)





- APD gain **increases**, noise **decreases** with cooling
- Light yield of crystals **increases** with cooling
- Large crystals (10-20 cm in length) available at reasonable cost
- APDs operate in high ($>$ 4 Tesla) magnetic field
- Stable operation over two months of data-taking

Experimental Apparatus



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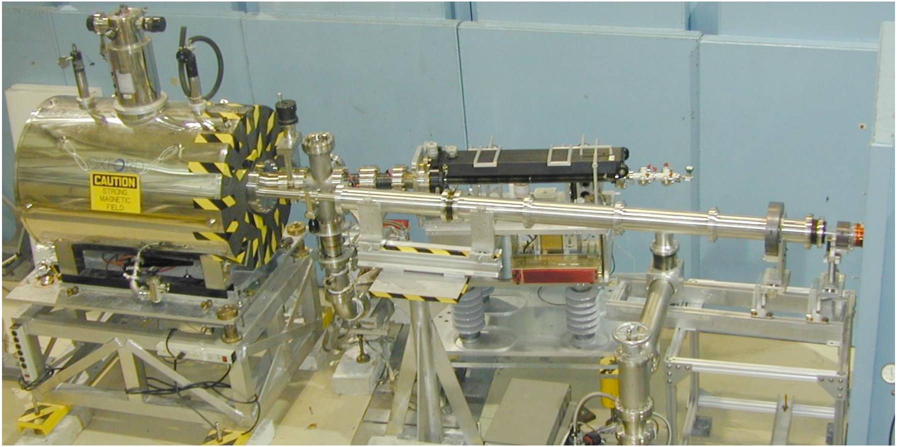
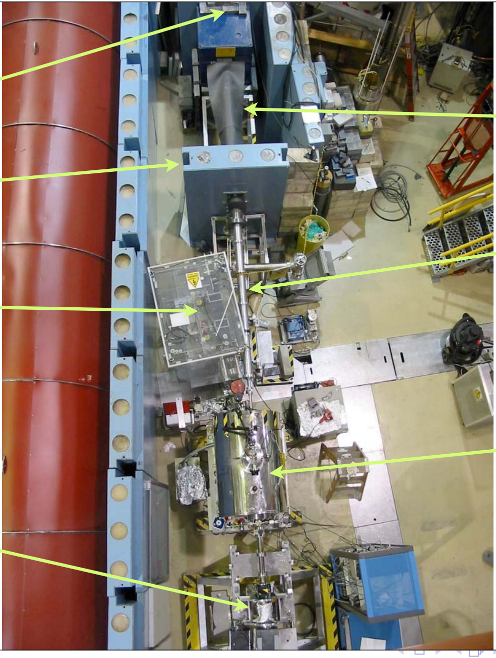




End of NG-6

Biological shield

Proton detection

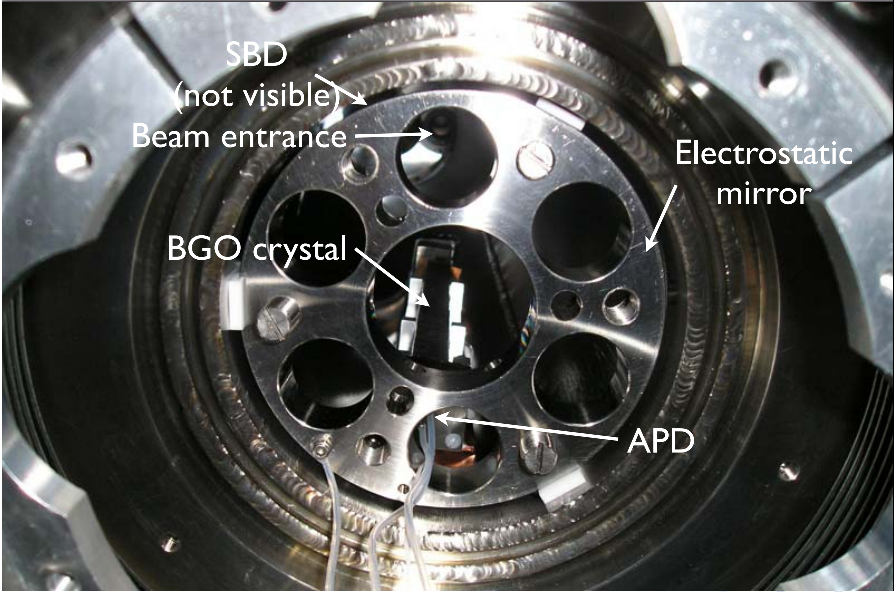
Beam Dump/ Monitor

Guide tubes

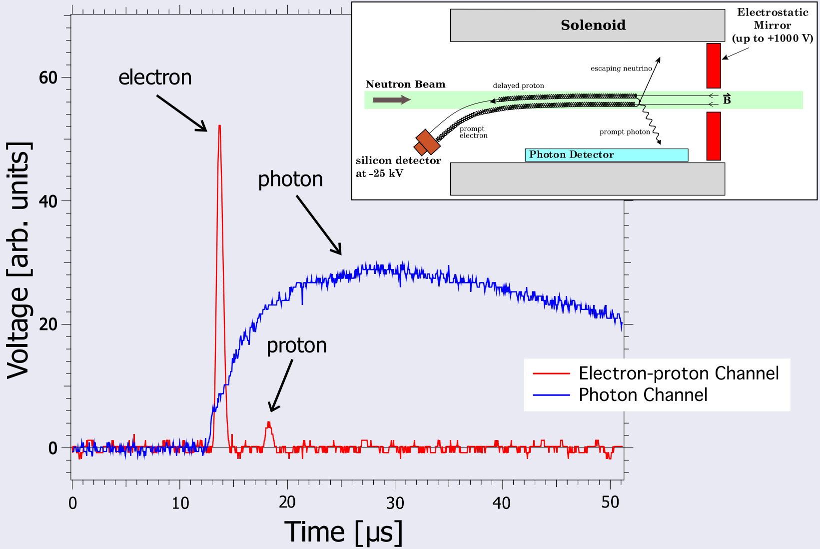
Collimator

Solenoid w/ Photon det.

BGO and APD

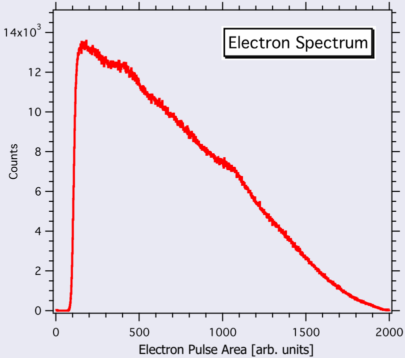

SBD
(not visible)
Beam entrance
Electrostatic mirror
BGO crystal
APD

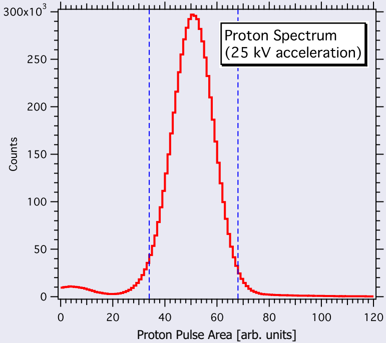
Waveform-Based DAQ



Electron and Proton Energy Spectra

Obtained from waveforms (before cuts)

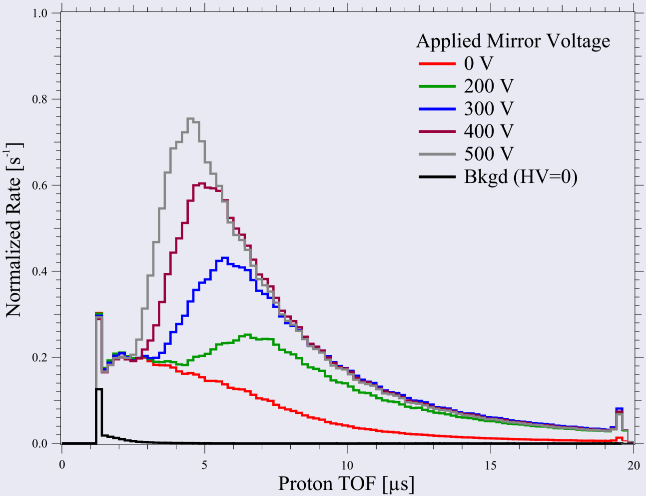




Electron-proton delayed coincidence rate: 5 s^{-1} - 20 s^{-1}

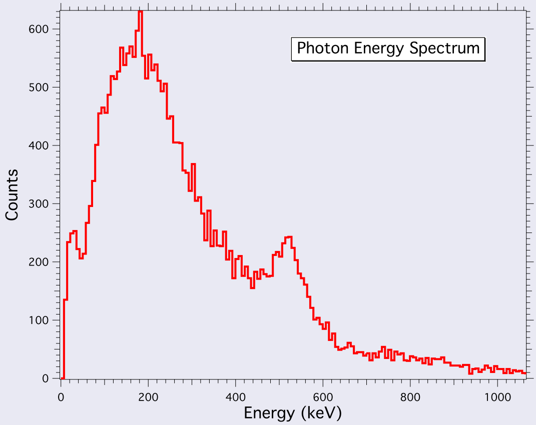
Electron-Proton Timing Spectra

Varying the electrostatic mirror potential allows sampling different regions of the proton's phase space:



Photon Energy Spectrum

with ep delayed coincidence requirement



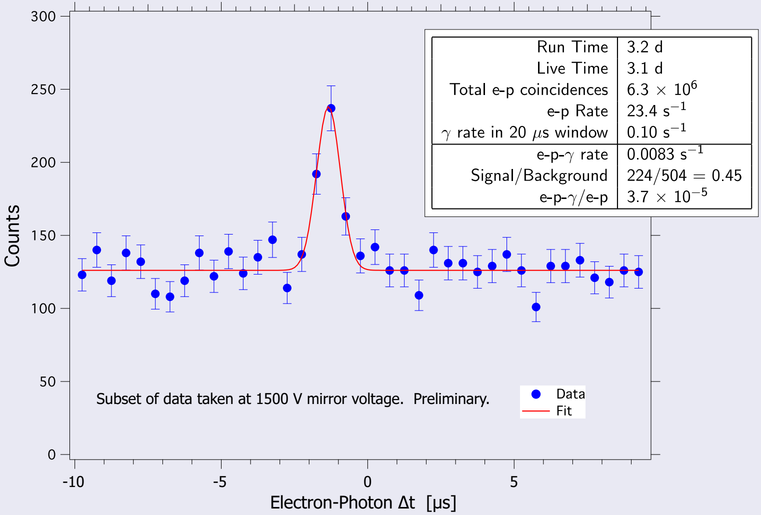
- Photon "singles" rate ≈ 100 s^{-1}
- Photon rate with e-p requirement: 0.02 s^{-1} - 0.08 s^{-1}

Summary of Cuts

Waveform-based DAQ allows us to perform many cuts to separate signal from background:

proton energy	2 FWHM
electron energy	> 35 keV (hardware threshold)
photon energy	$\approx$ 15 keV - $\approx$ 340 keV
e-p timing	2.5 μs - 20 μs
e-γ timing	2 FWHM
e-p baseline cut	e-p waveform must return to baseline

Electron-Photon Timing Spectrum

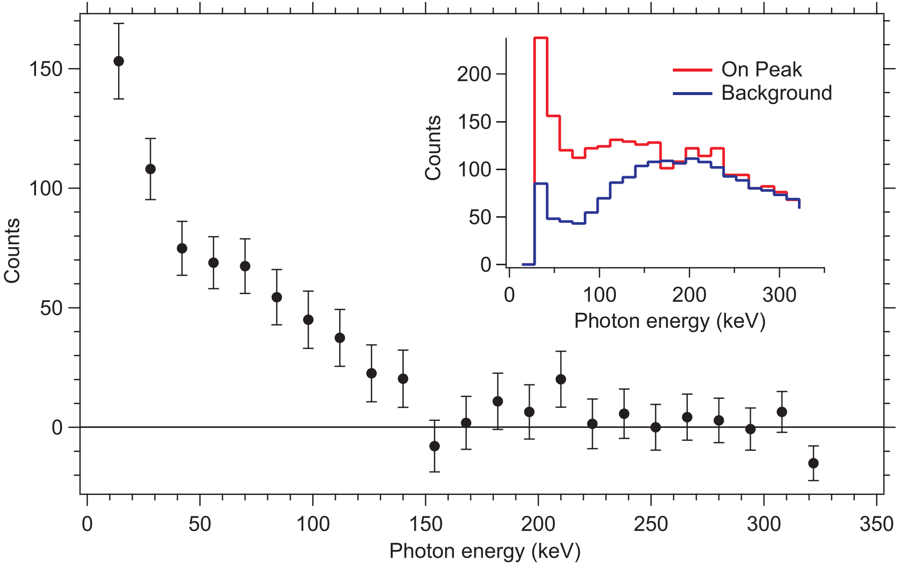


Run Time	3.2 d
Live Time	3.1 d
Total e-p coincidences	6.3×10^6
e-p Rate	$23.4\ s^{-1}$
γ rate in 20 μs window	$0.10\ s^{-1}$
e-p-γ rate	$0.0083\ s^{-1}$
Signal/Background	$224/504 = 0.45$
e-p-γ/e-p	3.7×10^{-5}

Subset of data taken at 1500 V mirror voltage. Preliminary.

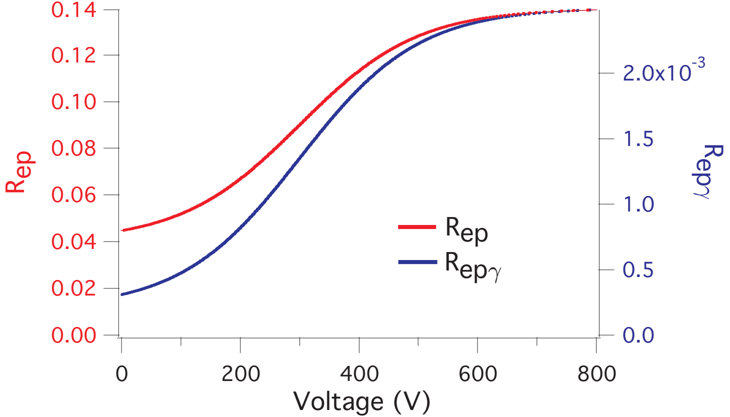
includes e-p coincidence requirement

Photon Energy Spectrum (on eγ timing peak)



Event Rates vs. Mirror Voltage

Varying mirror voltage adjusts R_{ep} and $R_{ep\gamma}$ rates by reflecting protons



Ratio $R_{ep}/R_{ep\gamma}$ is a constant for all potential backgrounds except external bremsstrahlung.

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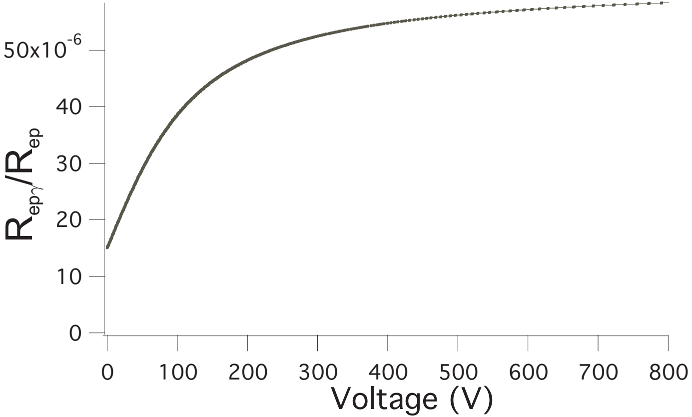

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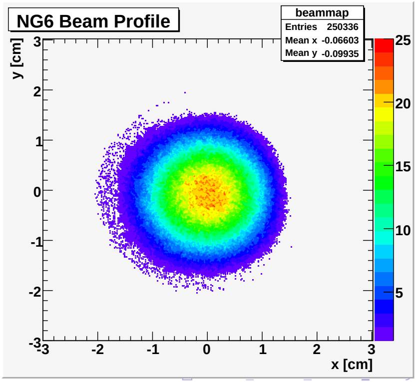
Monte Carlo Event Generation and Particle Transport

Necessary to extract branching ratio and understand systematics

- **Brute-force particle tracking**:
  - Lorentz force equation with E and B field maps
  - 4th order Runge-Kutta
  - Accounts for all drift mechanisms ($\nabla\vec{B}$, $\vec{E}\times\vec{B}$, curvature, ...)
  - Don't forget special relativity!

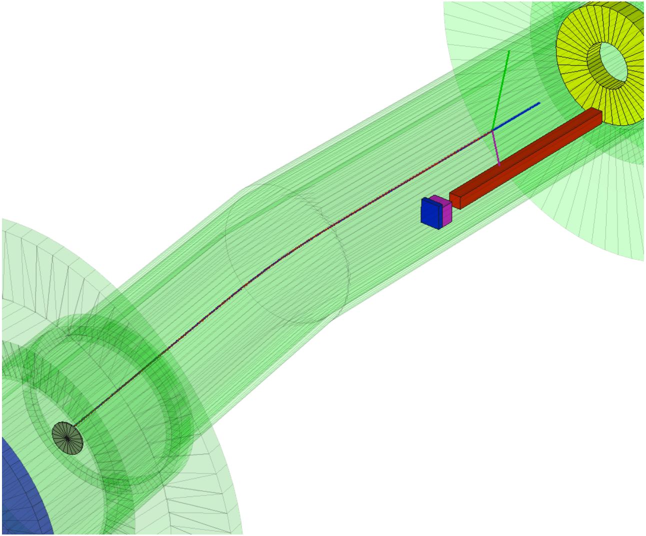
- **Adiabatic transport**:
  - Assumes drift forces negligible
  - Trace $\vec{B}$-field lines to detector
  - Adiabatic assumption for momenta



Inputs for both methods:

- $\vec{B}$ and $\vec{E}$ field maps
- apparatus geometry
- beam profile and divergence

Monte Carlo Modeling



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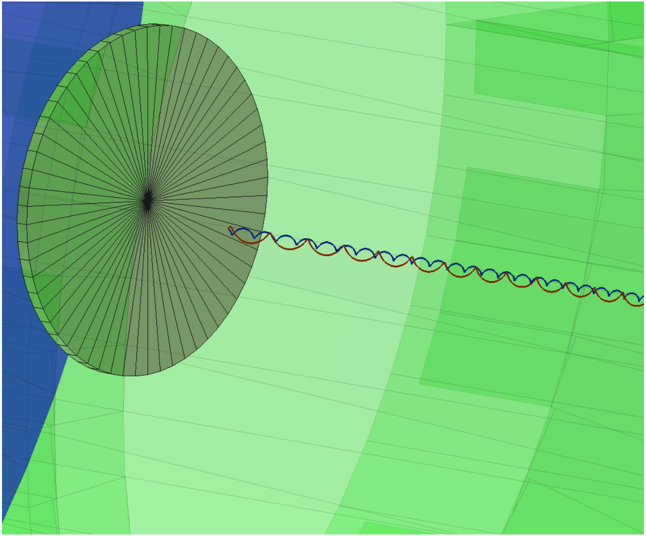
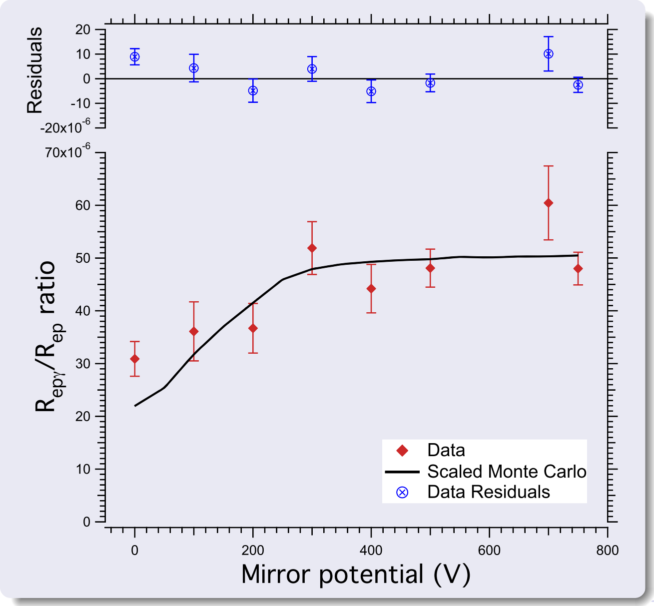


$R_{ep\gamma}/R_{ep}$ Ratio vs. Mirror Potential



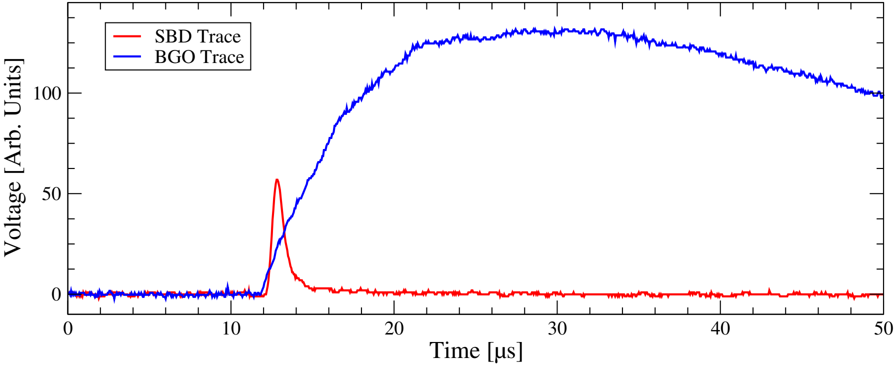
Branching Ratio Result (15 keV $\leq E_\gamma \leq$ 340 keV)

$$\mathrm{BR}_{\mathrm{RDK\ I}} = (3.13 \pm 0.34) \times 10^{-3}$$
$$\mathrm{BR}_{\mathrm{theory}} = 2.81 \times 10^{-3}$$

Systematic	**Correction (%)**	**Uncertainty(%)**
photon drift/calibration		6.0
analysis cut efficiencies		5.0
MC stats		4.0
photon detection efficiency and resolution	3.0	3.0
beam divergence and 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 Systematic	**0**	**10.4**
Statistical		**3.4**
Total Uncertainty		**10.9**

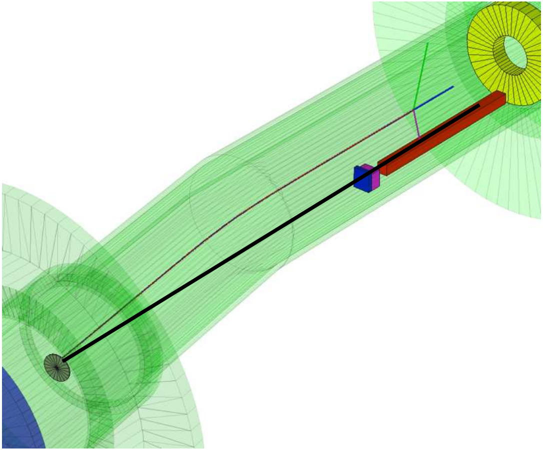
“Pathological” e-p events

- Electron-proton coincidence trigger greatly reduces uncorrelated backgrounds, but correlated backgrounds can produce a false signal.
- Both beam and high-voltage related events can produce false coincidences, but they are highly suppressed by cuts.



External Electron Bremsstrahlung

- Effect mitigated by limited line of sight
- MCNP modeling of production and transport through materials



Conclusions

We have observed the radiative decay mode of the neutron:

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- Spectrum shape and branch consistent with theoretical prediction
- Rates consistent with predicted BR and Monte Carlo models and behavior vs. mirror potential demonstrates influence of photon on the recoiling proton's momentum distribution

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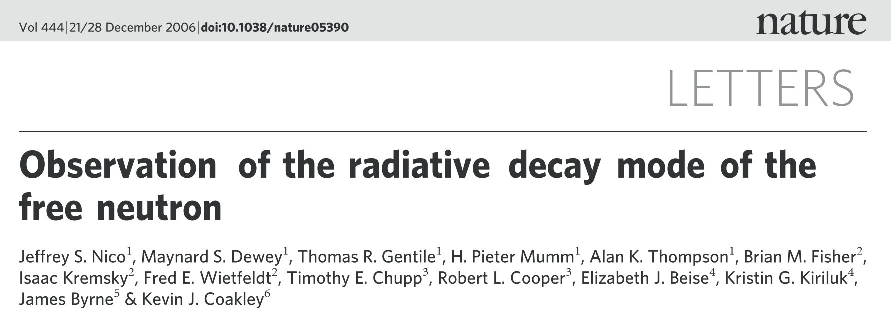

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nature

LETTERS

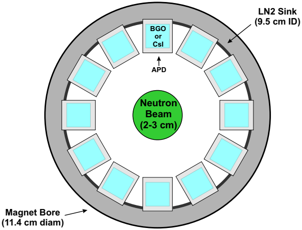
Observation of the radiative decay mode of the free neutron

Jeffrey S. Nico[1], Maynard S. Dewey[1], Thomas R. Gentile[1], H. Pieter Mumm[1], Alan K. Thompson[1], Brian M. Fisher[2], Isaac Kremsky[2], Fred E. Wietfeldt[2], Timothy E. Chupp[3], Robert L. Cooper[3], Elizabeth J. Beise[4], Kristin G. Kiriluk[4], James Byrne[5] & Kevin J. Coakley[6]

RDK II: Precision Measurement of Branching Ratio and Photon Spectrum

Goal: 1% measurement

- 12-element photon detector array to increase solid angle
- 12 independent channels of electronics
- Higher statistical accuracy
- More thorough investigation of systematic effects
- Improve signal-to-background



Collaborators

NIST

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