Radiative decay of the free neutron

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Abstract.
The theory of quantum electrodynamics predicts that beta decay of the neutron into a proton, electron, and antineutrino should be accompanied by a continuous spectrum of soft photons. We recently reported the first observation of this radiative decay mode of the neutron, measured by recording photons in coincidence with both the electron and proton emitted in neutron decay. The experiment was performed on the NG-6 Fundamental Physics Beam Line at the National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR). A new experiment is under development to measure both the branching ratio and energy spectrum for radiative decay with a relative standard uncertainty of a few percent. We briefly review the fundamental neutron physics program at the NCNR and describe the new radiative decay experiment.

Keywords: beta decay; neutron; NIST; photodiode; radiative; spin filters; standard model; weak interactions
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1. INTRODUCTION

The theory of quantum electrodynamics (QED) predicts that beta decay of the neutron into a proton, electron, and antineutrino is accompanied by the emission of an inner-bremsstrahlung (IB) photon. While IB had been measured in nuclear beta decay and electron capture decays, only recently did we report the first observation of the radiative decay mode of the free neutron [1]. We determined a branching ratio of $(3.13 \pm 0.34) \times 10^{-3}$ in the energy region between 15 keV and 340 keV, where the uncertainty is dominated by systematic effects. The value is consistent with the theoretical prediction of 2.81×10^{-3} from either a QED calculation [2] or heavy baryon chiral perturbation theory [3]. The characteristic energy spectrum of the radiated photons, which differs from the uncorrelated background spectrum, is also consistent with the calculated spectrum. A detailed description of this experiment is in progress. In this proceeding, we provide further information about this experiment, the facility in which it was conducted, and a discussion of plans for a precision measurement of the branching ratio and energy spectrum for neutron radiative decay.

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2. THE NIST FUNDAMENTAL NEUTRON PHYSICS PROGRAM

Nearly forty years ago a research reactor was constructed at the U.S. National Bureau of Standards (NBS) in Gaithersburg, Maryland. (NBS was renamed NIST in 1988). In 1989 a cold neutron guide hall was added to the original NBS reactor. Whereas the facility is primarily used for condensed matter physics and materials science, the Neutron Interactions and Dosimetry group (NIST Physics Laboratory) operates several beam lines for fundamental neutron physics [4]. The NG-6 beam line presently has the highest fluence rate beam for fundamental neutron physics in the USA. The NCNR has begun construction of a second guide hall [5]; as part of this work we expect that a new beam line with a substantially higher fluence rate will become available for fundamental physics. We briefly review some aspects of the program, which includes studies of beta-decay, nucleon-nucleon interactions, nucleon structure, and few-body nuclear physics, and the development of neutron spin filters based on polarized ^{3}He gas.

The key parameters of neutron beta-decay are the neutron lifetime and the coefficients that quantify the correlations between the decay particle momenta and/or the neutron spin. An in-beam measurement of the neutron lifetime using a trap for the decay protons yielded a value of (886.3 $\pm$ 3.4) s [6]. A new method for measuring the lifetime is also in progress [7]. In this approach, ultracold neutrons are produced by down conversion of cold neutrons in superfluid helium. The ultracold neutrons are stored in a magnetic trap and their decay is detected using the scintillation produced by the charged decay products. A 0.89 nm monochromatic beam line (NG-6U) is currently dedicated to this experiment.

In addition to lifetime measurements, two measurements of the time-reversal violating D coefficient in neutron beta-decay have been performed. The first yielded $D < 2 \times 10^{-3}$ [8, 9]; the second experiment is expected to have a statistical uncertainty nearly an order of magnitude smaller and analysis is in progress. On the longer term, an experiment to measure the electron-antineutrino correlation coefficient is under development [10, 11] and expected to be performed within a few years.

In the area of nucleon-nucleon interactions, a measurement of the parity-violating rotation of neutron spin in liquid ^{4}He was performed, yielding a statistically limited null result of $\phi_{\text{PNC}} = (0.8 \pm 1.4) \times 10^{-6}$ rad/m [12]. This angle of rotation is related to short range weak interactions between quarks. A modified apparatus is currently on the NG-6 beam line [13].

A neutron interferometer is being used for studies of nucleon structure and few-body nuclear physics. An experiment is in progress to measure the charge radius of the neutron using a novel approach [14]. The neutron interferometer allows the precise measurement of phase shifts from materials, from which scattering lengths can be accurately determined. Highly precise measurements for hydrogen, deuterium, and ^{3}He have been reported [15, 16, 17]. Currently an experiment is in progress to measure the spin-dependence of the n-^{3}He scattering length using a nuclear spin-polarized ^{3}He cell. Spin-exchange optical pumping is used to polarize a precise, flat-windowed cell off line, which is stored in the interferometer with a relaxation time of one week.

Finally, we develop and apply polarized ^{3}He neutron spin filters for fundamental physics [18]. The advantages of ^{3}He spin filters include low gamma-ray background and the ability to polarize broadband, large-emittance beams without adding additional beam

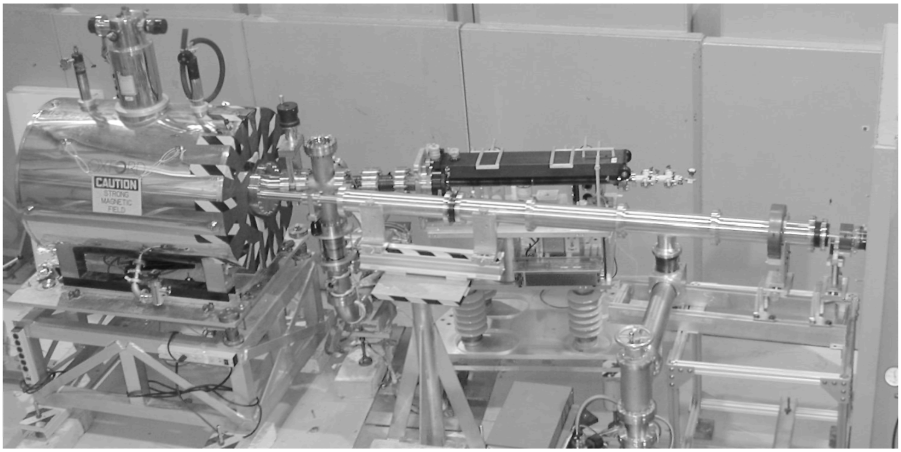

FIGURE 1. The superconducting magnet and associated apparatus used for the neutron lifetime and neutron radiative decay experiments on the NG-6 beam line at the NCNR.

divergence. In addition, spin filters allow for highly accurate measurements of neutron polarization, which is essential for measurements of spin correlation coefficients. In a recent experiment to measure the parity violating asymmetry in the emission of gamma rays by hydrogen, a ^{3}He spin filter using cells developed at NIST was employed to polarize a large area neutron beam [19].

3. NEUTRON RADIATIVE DECAY

The experimental challenge in detecting neutron radiative decay is to distinguish the low rate of radiative decay events at observable energies from the intense photon background associated with a neutron beam. The branching ratio above 15 keV is only about 3×10^{-3}, which coupled with the long neutron lifetime makes the rate of detectable photons quite small. Our apparatus allows the detection of a photon and electron in coincidence followed by a delayed proton, thereby reducing the probability of uncorrelated background events. A strong magnetic field constrains the proton and electron to cyclotron orbits, which increases the solid angle for detection and minimizes correlated backgrounds. An electrostatic mirror is used to vary the rate of detected electron-proton coincidences without changing the uncorrelated photon background rate, thus providing a signature for the detection of radiative decay and an important systematic check on possible backgrounds. Our first measurement of neutron radiative decay had a total relative standard uncertainty of 11 %, with a statistical contribution of only 3.4 % [1].

Both the neutron lifetime experiment and the radiative decay experiment employed a superconducting magnet with a bend at one end to steer charged decay particles into a surface barrier detector. Fig. 1 shows a photograph of this apparatus on the NG-6 beam line. The neutron beam enters the magnet from the right, and the electron and proton from neutron decay are guided by the magnet field into a detector located in the off-axis

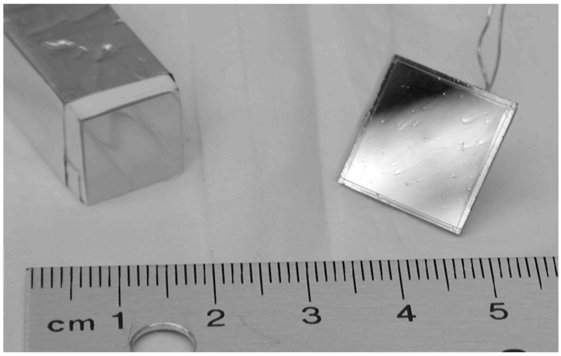

FIGURE 2. The end of a 20 cm long scintillating crystal and its associated avalanche photodiode.

port also visible on the right.

For the first experiment, the photon detector consisted of a single bismuth germanate (BGO) scintillating crystal, 20 cm by 1.2 cm by 1.2 cm, coupled to a 1.35 cm by 1.35 cm avalanche photodiode (APD). Further details on the particle and photon detection methods are being reported elsewhere [20]. Fig. 2 shows a photograph of the end of a scintillating crystal and an APD.

With this single element, we intercepted less than 2 % of the emitted radiative decay photons. We operated the experiment for three reactor cycles (7 weeks each), with three months of total live time. Much higher detection efficiency is required to accurately measure the spectrum of the radiative decay photons. In the next experiment we will employ a 12-element detector. Assuming the electrostatic mirror is set to reflect all protons, we should obtain a radiative decay event rate of $\approx 0.01\ s^{-1}$ for the 15 keV to 340 keV energy range. For three months of live time, this should yield nearly 10^5 events. However, the radiative decay process is infrared divergent, hence the lowest statistical uncertainty will be obtained in the lower energy windows. For example, nearly 20 % of the radiative decay events will occur between 20 keV and 30 keV, which yields a statistical uncertainty of 0.7 %. However, for a 20 keV window centered at 120 keV the event rate will be an order of magnitude smaller, and thus the uncertainty will be roughly three times larger.

In the energy range below $\approx$ 100 keV, the rate from background photons was comparable to the radiative decay rate, which roughly increases the uncertainty by a factor of 1.4. The background is dominated by a broad peak centered at 160 keV, which we presume to be from backscatter of higher energy gamma rays, originating either directly from the reactor or from interactions of scattered neutrons. To decrease this rate we are improving the collimation of the neutron beam to minimize scattered neutrons and improving the shielding of the photon detector from reactor gamma rays. We are currently modeling the neutron beam to develop a scheme that minimizes the loss in flux from additional collimation. Only experimental tests will reveal how much the background is reduced by these improvements. An additional motivation for good definition of the neutron beam is our plan to accurately measure the neutron flux through the apparatus, which will allow us to determine not only the branching ratio but also the absolute radiative decay rate.

A new detector consisting of 12 scintillator-APD elements arranged on a cylinder that surrounds the neutron beam is under development. A solid piece of G10-FR4 (a fiberglass laminate epoxy resin system combined with a glass fabric substrate) was machined with shallow slots for the APDs, which were cut in such a way that the G10 only contacts the support base of the APD, not the sensitive sides of the silicon. The thermal contraction of G10 is well matched to the APD substrate, which minimizes stress upon cooling to liquid nitrogen temperature. Small brass springs are used to push the crystals against the APDs.

As discussed in Ref. [20], we are also considering the use of avalanche photodiodes for direct detection of radiative decay photons in the energy range 0.1 keV - 10 keV. Coupled with the scintillation-based detector, this capability would allow us to measure the spectrum over three orders of magnitude in photon energy. Due to lower background in this energy range, as well as the much shorter rise time as compared to that obtained from scintillation, preliminary tests on the beam line indicate that the background can be reduced by at least an order of magnitude. The largest drawback of this approach is the relatively small detection area per APD compared to the scintillator-APD combination. We have recently tested a 2.8 cm by 2.8 cm APD [21], which has four times the area of our current APDs, and obtained a 0.15 keV threshold. The combination of higher branching ratio and better signal to background could yield a comparable radiative decay measurement for a single large area APD as compared to a single scintillator-APD unit.

An additional issue with direct detection is the calibration of the detector. This calibration is straightforward for the scintillator based system as most of the photons, in particular the lower energy photons that dominate the spectrum, are detected with nearly 100 % efficiency. (Note that the light collection, quantum efficiency of the APD, etc. only affect the size of the detector response, while the efficiency is simply related to the absorption of photons by the scintillator.) For direct detection with APDs the detection efficiency decreases rapidly above 5 keV as the mean free path exceeds the thickness of the silicon [22]. At energies below 1 keV the efficiency is affected by absorption in the SiO_2 layer on the APD, but this $\approx 0.1\ \mu$m thick layer can be removed [23]. In addition there are smaller variations in the responsivity associated with variations in the collection efficiency of electron-hole pairs [24]. We will need to develop a method to calibrate the response of an APD, in particular at the low end of the detection range where the radiative decay probability is increasing rapidly.

4. CONCLUSION

As recently reported, we have successfully measured the branching ratio for the radiative decay mode of the neutron with a relative standard uncertainty of 11 %. We are constructing a 12-element detector to substantially increase the event rate for a new experiment. With this detector, as well as other improvements to the apparatus and the analysis, we expect to perform a precision measurement of the branching ratio and the spectrum for neutron radiative decay. A new experiment is planned for 2008.

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