Pulsed-Beam Neutron-Lifetime Measurement

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We have measured the neutron lifetime using a superconducting electron spectrometer and a pulsed beam of cold neutrons. Spatially defined neutron bunches are completely contained within the spectrometer's active volume while the β-decay rate is measured. The flux is determined from the radioactivity of nearly totally absorbing thick samples of cobalt and gold exposed to the neutron beam. We obtain $\tau_n = 876 \pm 21$ sec.

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The measured neutron lifetime provides information about fundamental parameters, in particular the vector and axial-vector weak-coupling constants, G_V and G_A. Knowing these quantities is crucial for an understanding of the weak interaction and there are important consequences for cosmology and astrophysics.[1] At present G_V is best determined from nuclear β-decay experiments and the experimentally determined neutron lifetime is used to infer G_A/G_V.

In previous experiments electrons or protons were detected from neutrons decaying in continuous thermal or cold beams. Published lifetimes[2] vary between 877 and 937 sec, with errors between 8 and 18 sec. The discrepancies are much larger than the stated errors. Until recently, precise values for G_A/G_V came only from the experimental lifetime, but the inconsistencies introduce a large systematic uncertainty. Fortunately, a recent measurement of the neutron β asymmetry determines G_A/G_V better than the lifetime measurements, mitigating the difficult choice between inconsistent lifetimes.[3] Nevertheless, it is important to resolve the lifetime discrepancies. The combination of very precise neutron-decay experiments will eventually allow us to determine both G_A and G_V without resorting to more complex nuclear systems.

We measured the neutron lifetime with a new method using a pulsed neutron beam. This pulsed beam passes through an "in-beam" electron spectrometer with large active volume. We detect decay electrons during short time intervals of length $\Delta t \approx 0.5$ msec, when neutron bunches are fully contained within the spectrometer and all neutron decays with electron energies above threshold have the same detection probability. The neutron lifetime τ_n is obtained from the decay law $\Delta N_n/\Delta t = -N_n/\tau_n$. The integrated number of neutrons N_n comes from measurements of the γ activity, $n_\gamma = N_n/\tau_\gamma$, of thick samples of high-purity ^{59}Co and ^{197}Au exposed to the beam. The neutron-decay rate $\Delta N_n/\Delta t$ is obtained from the measured β rate $n_\beta = N_\beta/\Delta t$. Thus the experimental method is summarized by the simple relation $\tau_n = \tau_\gamma(n_\gamma/n_\beta)$ which relates the neutron lifetime to the well-known nuclear lifetimes τ_γ.

Compared to continuous-beam lifetime measurements our method does not require precise knowledge of the effective length of the spectrometer or the neutron velocity distribution. In many previous experiments sensitivity to the neutron velocity spectrum is avoided by the measurement of the neutron-capture flux directly with thin detectors containing ^{3}He or ^{10}B. However, this procedure relies on the exactness of the $1/v$ dependence of the capture cross section. These experiments are also sensitive to the exact length of the proton or electron detector and to many details of the capture-flux detector. The present pulsed-beam method avoids serious sources of systematic error but the counting rate is low since only a small fraction of the available beam is utilized.

The experiment, located at a cold-beam position of the Institut Laue-Langevin's 57-MW reactor in Grenoble, is shown schematically in Fig. 1. Cold neutrons from a 23-K deuterium moderator near the reactor core are transported through a 120-m-long totally reflecting neutron guide. A turbine velocity selector confines the spectrum to between 450 and 750 m sec^{-1}, reducing the spatial dispersion of the bunches. The velocity distribution is roughly a triangle with a maximum at about 580 m sec^{-1}.

The β spectrometer, PERKEO, was originally designed to study the decay of free polarized neutrons, and to measure the β-decay asymmetry. The principal component is a 1.7-m-long, 20-cm-diam, superconducting solenoid wound with niobium wire in a copper matrix. The solenoid is operated in the "persistence mode." At

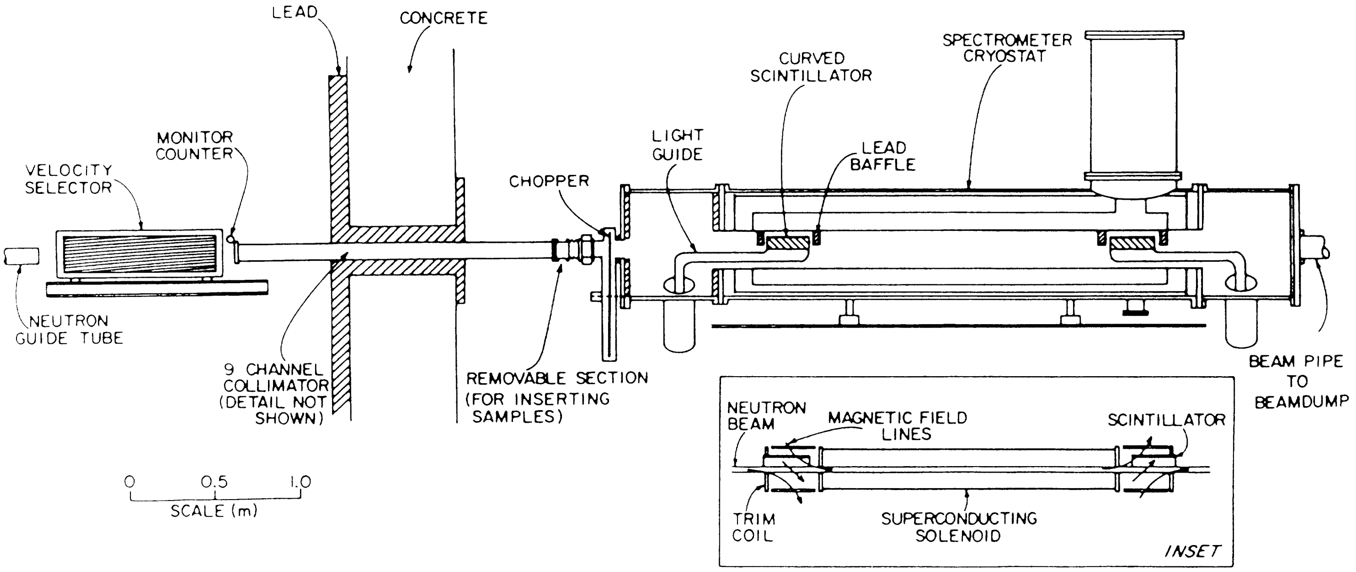

FIG. 1. Experimental arrangement at the end of the cold guide tube.

260 A, the axial magnetic field is 1.6 T. The main solenoid field is bent upwards at the ends by the arrangement of superconducting coils, as shown in the inset of Fig. 1. The helical trajectories of electrons from neutrons decaying within a 2.1-m-long active volume follow the magnetic field lines which intersect plastic scintillators. The magnetic field decreases monotonically from the center of the spectrometer towards the detectors so that electrons cannot be trapped by magnetic mirrors. An electron backscattered from one scintillator either is reflected by the now increasing magnetic field, or goes on to hit the other detector. Coincident events are reconstructed from timing information and included in the spectrum of the detector hit first.

The two 5-mm-thick plastic scintillators are curved to conform to the cylindrical geometry. Two photomultipliers are connected by acrylic light guides to each scintillator. We operate the two phototubes viewing each scintillator in coincidence to suppress dark noise. The detector sensitivity is approximately 100 photoelectrons/MeV and the effective threshold is about 20 keV with the discriminators set below the single photoelectron level. Remotely inserted conversion-line sources on 10-μg/cm^2 carbon backings calibrate the system. The sources and corresponding K energies are ^{139}Ce (126.9 keV), ^{113}Sn (363.7 keV), and ^{207}Bi (481.7 and 975.7 keV). Fits to calibration spectra take into account Auger, K, L, M, and higher-order line structure broadened by a Poissonian detector response.

A 1.7-m-long upstream collimator with nine rectangular channels constructed entirely of ^{6}LiF reduces beam spread. The collimated beam divergence is 0.19° in the vertical and 0.12° in the horizontal direction. The beam chopper, located near the entrance of PERKEO, is constructed from a 40-cm-diam ^{6}LiF disk with two symmetric slits which are shaped like 20° segments of a circle. Thus the open-to-closed ratio of 1:8 is constant over the whole chopper radius and avoids different weighting of different parts of the beam. A neutron bunch so prepared is approximately 1.5 m long just behind the chopper. After passing through the electron spectrometer neutrons are finally absorbed on a ^{6}LiF beam dump, 9 m downstream of the chopper.

The neutron flux is continuously monitored with a small pen-shaped ^{3}He detector close to the collimator entrance window. The monitor is used to compensate for beam intensity changes. Flux-change corrections are less than 0.5%, and the variations track well with the spectrometer counting rate.

Data taking and experimental control is accomplished with a Digital Equipment Corporation LSI 11/73 computer connected through a CAMAC interface. Data are recorded event by event. The magnetic tape records include the energy from each detector as well as the sum energy, the arrival-time difference for coincidence events, and scaler readings for the ^{3}He counter and the trigger rate (used for dead-time corrections).

Typical results are shown in Figs. 2 and 3. The solid points in Fig. 2 are the β-decay rates at successive times during a cycle. The first 1.5 msec of the figure represents the background level since neutrons have not yet entered the spectrometer. After about 2 msec the fastest neutrons enter the active volume and the counting rate increases, reaching saturation when the neutron bunch is fully contained. Background is measured with better statistics in a separate run with the chopper in the closed position. The background-subtracted β spectra from the plateau region, for one run, are plotted in Fig. 3. The background is primarily from cosmic rays and from γ rays generated by upstream neutrons. Compared to pre-

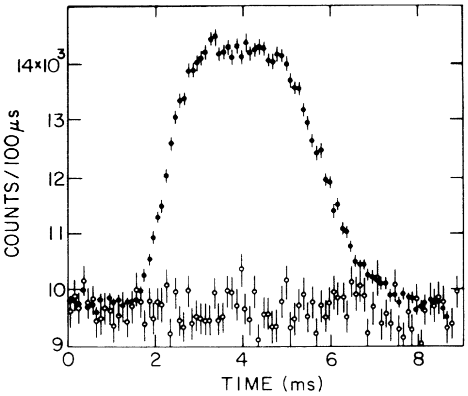

FIG. 2. Detector counting rate vs time synchronized at the beam chopper. The solid points are data with the chopper operating and the open points with the chopper turned off, in the closed position, showing the background level.

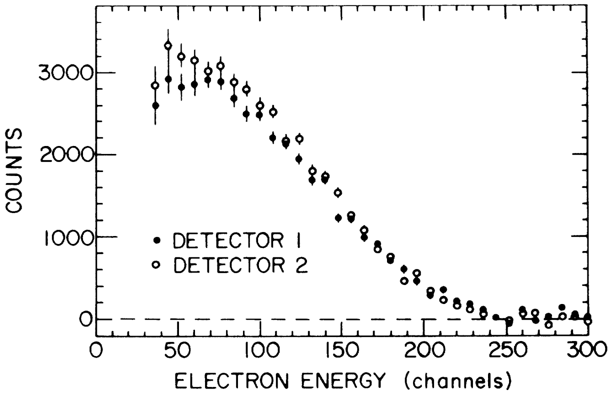

FIG. 3. Background-subtracted β spectra. The signal is obtained during a 0.5-msec period when each neutron bunch is completely within the spectrometer. The spectra are not corrected for the slight gain difference between the two detectors. The summing range is, approximately, channels 100 to 250.

vious continuous-beam lifetime experiments we measure the background and signal under more nearly identical conditions. While in both methods the background is measured with the neutron beam hitting a shutter, in our experiment the shutter is the beam chopper, which is also closed while we observe β decay.

In principle the total β-decay rate can be determined by the integration of the spectra in Fig. 3, accounting for finite detector thresholds and dead times. However, there are serious sources of systematic error in the low-energy data: Deviation from a simple Poissonian response is likely at low energies, the exact form of the effective threshold is complicated by the two-phototube coincidence requirement, and the light output of plastic scintillators is nonlinear at low particle energies. In addition, we suspect that background subtraction is not complete in the low-energy part of the β spectrum. For example, there seems to be a slight systematic difference between the two spectra in Fig. 3 below about 250 keV. Previous PERKEO experiments with β spectra with higher statistics indicate that unsubtracted background at low energies can be caused by an extremely small number of neutrons hitting the internal parts of the apparatus.

For these reasons we choose an alternative procedure, avoiding these problems, but with some loss in statistical significance. We take the threshold for summing at the ^{113}Sn calibration-source K energy. The corresponding channel can be accurately determined from fits to the calibration spectrum essentially without interpolation. Using the calculated resolution-broadened allowed spectrum we determine that the region between the ^{113}Sn K energy and the end-point amounts to 34.85(5)% of the entire spectrum. The error comes from the allowance of the detector sensitivity to vary by ±20 photoelectrons about the measured value, representing a conservative estimate. After dead-time correction the total rate is obtained by our summing over this region and dividing by 0.3485. This method is quite insensitive to nonlinearities in the detector energy response. The detectors are calibrated before and after β-decay measurements, and the systematic error from gain drifts is estimated from separate studies of the gain stability.

Measurements of β decay are alternated with measurements of the neutron flux. It is preferable to measure both of these simultaneously with a downstream irradiation sample but the background from prompt neutron capture is much too large. During irradiations the sample material is installed upstream between the collimator and the chopper wheel (see Fig. 1). We use fine powders of high-purity (99.994%) gold and (99.9%) cobalt. The material is packed in rectangular aluminum forms and covered with thin aluminum windows. After exposure the samples are mixed thoroughly and small amounts are sent to various laboratories for analysis.

The capture efficiencies are calculated with a Monte Carlo simulation which accounts for neutron absorption and scattering in the sample and the aluminum window. The window transmission is 99.9(1)%. Inside the sample the capture probability for a neutron is 99.9(1)% for gold and 95.1(4)% for cobalt. In the latter case the difference from 100% comes almost completely ($>4.8\%$) from neutrons which traverse the sample without being absorbed. Less than 0.1% are backscattered. The error comes from uncertainties in the neutron velocity spectrum and the mass density per unit area.

Gold is measured at the Physikalisch-Technische-Bundesanstalt, Braunschweig, the Centre d'Etudes Nucléaires, Grenoble (CENG), the Technische Universität München, and the National Bureau of Standards, Gaithersburg, and cobalt at the CENG and by us at Heidelberg. All laboratories measure γ-ray activity with absolutely calibrated germanium detectors in well-defined geometries. The results are corrected for γ absorption

TABLE I. Summary of results from two runs.

	Run 1		Run 2
Δt (sec)	0.5×10^{-3}		0.5×10^{-3}
N_β	36609		55274
N_n	6.32×10^{10}		9.88×10^{10}
τ_n (sec)	863		894
Stat. error from N_β (sec)	±15		±13
Syst. error from N_n (sec)	±5		±13
Weighted $<\tau_n>$ (sec)		876	
Combined stat. error from N_β (sec)		±10	
Combined syst. error from N_n (sec)		±7	

Systematic errors common to all runs

Source of uncertainty	Value (sec)
Gain drifts	±17
Absorption in irradiation sample	±3
Corrections for thickness of chopper	±2
Detector resolution	±1
Energy calibration procedure	±3
Total common systematic error	±18

and finite sample size; the procedures vary. Errors take systematic uncertainties into account. The various measurements agree well and we take the error-weighted average. The final error is estimated with a standard method recommended by Aguilar-Benitez *et al.*[2] More details of the neutron flux calibration method are given by Döhner.[4]

Table I summarizes the results from two runs, detailing the components of the statistical and systematic errors. The error from N_β is statistical and comes from the summing procedure while the error from N_n primarily reflects the consistency of the various radioactivity measurements and the stated systematic errors of each. The biggest common systematic error is from detector gain drifts to which our analysis procedure is very sensitive. The experiment would thus be significantly improved by our better stabilizing the gains. Since the error from gain drifts is common to the two runs it must be applied individually when we evaluate their consistency. Finally we obtain $\tau_n = 876 \pm 10 \pm 19$ sec, where the first error is statistical and the second is systematic. The overall error is 21 sec, combining statistical and systematical uncertainties in quadrature. Results from the use of the 481.7-keV bismuth energy instead of the ^{113}Sn line are in agreement with the value given above but have significantly bigger statistical and systematical errors. Summing the spectra above the ^{139}Ce energy leads to very low lifetime values from detector 2, an effect that is due to the unsubtracted background in this detector. The neutron lifetime from detector 1 alone is well inside the quoted error bars.

Using a recent evaluation[5] of $(ft)_{0^+\to0^+}$ and the neutron Fermi function from Wilkinson,[6] we have $|G_A/G_V| = 1.277 \pm 0.018$. This is in reasonable agreement with the more precise value, $G_A/G_V = -1.262 \pm 0.005$, from measurements of the β asymmetry with PERKEO.[3]

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