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Printed June 1994

LOW-ENERGY BETA SPECTROSCOPY USING PIN DIODES TO MONITOR TRITIUM SURFACE CONTAMINATION

W. R. Wampler and B. L. Doyle
Ion Solid Interactions and Defect Physics Department
Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

We show that tritium betas emitted from a surface can be counted using a pin photodiode as a solid state charged particle detector. Furthermore, we show that the range of tritium betas through air is sufficient to allow measurement of tritium on samples in air by this method. These two findings make possible a new method to survey tritium surface contamination which has advantages over existing methods. We have built and tested several prototype instruments which use this method to measure tritium surface contamination, including a compact portable unit. The design of these instruments and results from tests and calibrations are described. Potential applications of this new method to monitor tritium are discussed.

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1. Introduction

The first experiments in which fusion plasmas were fueled with tritium were recently conducted at the JET and TFTR tokamaks [1,2]. Several megawatts of fusion power have already been produced and a few grams of tritium will be used in the course of the experiments. The proposed International Thermonuclear Experimental Reactor [3], now being designed, is expected to use kilograms of tritium and produce more than a gigawatt of fusion power. Radiological safety and environmental protection require that these projects carefully monitor tritium contamination during operation and decommissioning. Tritium monitoring is also an important issue in the production, storage and dismantling of nuclear weapons. The need for improved methods to monitor tritium for these programs motivated the development of a new tritium monitor which is described in this paper.

Most methods used to detect tritium are based on counting betas emitted when tritium decays [4]. The low energy of the betas makes tritium more difficult to detect than most other radioisotopes. The range of tritium betas through matter is on the order of 10^{-4} gm/cm² which corresponds to a distance of about 1 mm in air or about 1 μ m or less in solids and liquids. Betas from tritium at depths greater than a few microns beneath the surface are absorbed before reaching the surface. Deep tritium can be measured by liquid scintillation after dissolution of the sample. This procedure destroys the sample and produces mixed waste. Some materials can be heated to high temperatures to thermally desorb deep tritium which can then be measured with an ionization chamber. Removable tritium surface contamination is often measured using swipes, but this method gives no indication of the amount of nonremovable or fixed tritium present.

Tritium on or near a surface can be measured directly by counting the betas emitted from its surface. A windowless gas proportional counter is commercially available for this purpose [5]. Tritium betas can also be detected using solid state devices [6,7], which have the advantage of being more compact and rugged. Here we demonstrate that tritium on and near surfaces can be quantitatively measured using a pin photodiode as a solid state charged particle detector to count the betas emitted from a surface. We examine the design considerations for a surface tritium monitor based on a pin diode. Several prototype tritium monitors were built, including a compact portable battery powered unit. Tests of these tritium monitors, using a calibrated tritium beta reference source, are described and the limits of detection are discussed. Finally, we present results from recent measurements of tritium on a component from the JET tokamak, which were made using our pin diode tritium monitor.

2. Design considerations for a tritium monitor

Figure 1 shows a block schematic of the circuit we have used for our tritium monitor. This configuration is widely used for charged particle energy spectroscopy [8]. Betas emitted from a sample strike a pin photodiode where they generate a current pulse which is converted to a voltage pulse by a charge sensitive preamplifier. The signal is then amplified by a pulse shaping spectroscopy amplifier which produces a pulse whose amplitude is proportional to the energy of the particle. The energy spectrum of the particles can be recorded using a multichannel analyzer. A pulse amplitude discriminator and counter can also be used to count particles with energies in a selected range. An oscilloscope is useful to insure that no spurious interfering signals are present.

Due to their low energy, detection of tritium betas using a solid state detector requires that the detector and first stage of signal processing be selected to give a very low noise threshold. Since tritium betas have an average energy of 5.7 keV, the system noise threshold should be less than about 5 keV, which corresponds to a noise amplitude of about 2 keV (FWHM) or 0.85 keV rms.

An example of a suitable preamplifier circuit is shown in figure 2. A field effect transistor (FET) is used for the first stage of amplification. The noise is mainly determined by the detector and the input FET. The two main noise components are; 1) delta noise due to fluctuations in the FET channel current, and 2) step noise from the feedback resistor and from leakage currents through the detector and FET gate [8]. The rms delta noise E_d is proportional to the total input capacitance (C) from the detector, the FET gate and their interconnection. Expressed as an equivalent particle energy

$$E_d \cong 2 \left(\frac{kT}{g_m \tau} \right)^{\frac{1}{2}} \frac{\varepsilon}{q} C \quad (1)$$

where k is Boltzmann's constant, T is the temperature (°K) of the FET, ε is the energy absorbed per electron-hole pair produced ($\varepsilon = 3.64$ eV for silicon), q is the electron charge and g_m is the FET transconductance. The rms step noise is

$$E_s \cong \varepsilon \sqrt{\frac{\tau I}{q}}, \quad (2)$$

where

$$I = [|I_d| + |I_f| + I_s], \quad (3)$$

I_d and I_f are the leakage currents through the detector and FET gate and $I_s = (2kT/qR)$ is an equivalent noise current due to shunt resistance R, mainly from the feedback resistor R_f . I_s can be made smaller than the leakage currents by choosing a sufficiently large value for R_f . The noise depends on the type of pulse shaping which is used [8]. The above expressions

assume a Gaussian pulse shape, which is often used for pulse height analysis and is what we used, where τ is the shaping time constant or peaking time. The combined rms noise from these two contributions is given by

$$E_n = \sqrt{E_s^2 + E_d^2}. \quad (4)$$

The above expressions can be used to model the noise performance of the system and guide the selection of an appropriate detector/FET combination.

Commercially available preamplifiers which we have tested and found to be suitable for detecting tritium betas include the eV550-5093 from eV Products [9], the 2001A from Canberra [10] and the A250 from AMPTEK [11]. The eV550-5093 and Canberra 2001A preamps are enclosed units designed to connect to and receive power from a spectroscopy amplifier. The AMPTEK A250 is supplied as a hybrid microcircuit in a 14 pin hybrid DIP along with a SK152 input FET and a circuit board assembly (AMPTEK model PC-250). The noise figures for the three preamps listed above, with no detector connected to the input, are around 100 electrons (RMS) corresponding to an energy resolution for a silicon detector of about 1 keV FWHM. This appears to be about the current state of the art for preamplifiers operating at room temperature. System noise can be reduced significantly by cooling the input FET and detector, however we did not use cooling so that measurements could be made in air without interference from water condensation.

The capacitance and leakage current of the detector increase the noise. Equations 1 to 4 can be used to estimate the maximum allowable detector capacitance and leakage current to keep the system noise below the level required for tritium beta detection of 2 keV FWHM. For example, with a FET transconductance of 20 mS (for the SK152 which we used), and with a pulse shaping time constant $\tau=1 \mu\text{s}$, the maximum capacitance and leakage current to keep the delta and step noise each below 1.4 keV FWHM are 30 pF and 5 nA. Most detectors used for charged particle energy spectroscopy do not meet these requirements and are thus too noisy for detection of tritium betas. However, we have found that pin photodiodes, manufactured by Hamamatsu [12], do meet these constraints and work well for detection of tritium betas.

Table 1 lists values for the capacitance, leakage current and area for the two Hamamatsu pin diodes we have used for tritium detection. These devices have a p doped layer less than $1 \mu\text{m}$ thick on the front and an n^+ doped layer on the back of a high resistance silicon wafer leaving a thick region of high purity silicon (i layer) in between. Under reverse bias a depletion layer extends from the p layer into the i layer to a depth (w) which depends on the bias voltage (V_b) and the resistivity of the i layer material [13]. The thickness of the depletion

layer can be calculated from the capacitance (C_d) and area (a) using $C = \epsilon a/w$, where $\epsilon = 1.05$ pF/cm is the dielectric constant of silicon. The depletion layer thickness for the two Hamamatsu pin diodes we used, reverse biased at 50 volts, was about 90 μm , which is thick enough to absorb betas with energies up to about 150 keV [14], and alpha particles with energies up to 12 MeV [15]. Pin diodes can be made with greater depletion depths and therefore lower capacitance (and thus lower delta noise) per unit area. However the detector leakage current (and step noise) tends to be higher for diodes with greater depletion depths.

Other factors affecting the performance of pin diodes for charged particle energy spectroscopy are the thickness of the dead layer at the entry surface, and the charge collection efficiency, which depends on the lifetime for electron-hole recombination. Photodiodes and charged particle detectors both have similar requirements for efficient charge collection. Of particular importance for detecting tritium betas is the collection efficiency for charge produced very near the front surface. Maximization of photodiode response to ultraviolet light also requires efficient charge collection for carriers produced near the front surface. Both applications require low bulk recombination of carriers in the p layer and a low recombination rate at the surface, so that carriers produced in the p layer can diffuse out and be collected before they recombine. Similar considerations affect the design of solar cells with high UV efficiency for use in space [16]. The fact that the spectral response of Hamamatsu pin diodes extends below 300 nm where the absorption length of light in silicon becomes less than 0.1 μm [13,16] indicates that charge carriers produced by tritium betas, at depths up to 1 or 2 μm , should also be collected.

The Hamamatsu pin diodes have a surface coating of silicon dioxide which serves several purposes. The oxide layer passivates surface states thereby reducing leakage current and reducing carrier recombination at the surface. The oxide layer also protects the silicon surface from contaminants which can cause leakage and carrier recombination to increase. These features of the oxide layer are also beneficial for detecting tritium betas. The thickness of the silicon dioxide coating is 0.10 μm as determined by Rutherford backscattering spectroscopy using 2 MeV $^4\text{He}^+$ ions. An SiO_2 layer of this thickness acts as an antireflection coating at visible wavelengths thereby enhancing the detection efficiency for visible light. For charged particle energy spectroscopy the SiO_2 is a dead layer in which particles lose energy without contributing to the measured charge pulse. On the Hamamatsu diodes the SiO_2 layer is thin enough that it does not seriously interfere with detection of tritium betas.

We tested several prototypes of the tritium monitor. The first prototype used an eV550 or Canberra 2001A preamplifier with an Ortec spectroscopy amplifier. A pulse shaping time constant of 1 μsec was used. A second prototype was a compact battery powered unit

designed for portable benchtop operation which used components from AMPTEK, including the A250 preamp. Figure 2 shows a diagram of the AMPTEK preamp circuit. Following the preamp in the benchtop unit is a pulse shaping amplifier consisting of the AMPTEK PC250 amplifier circuit board assembly with three A275 amplifier modules. The benchtop unit also contains a pulse amplitude discriminator (AMPTEK model A150) which generates a logic pulse for each detected particle whose energy exceeds a lower limit set by a potentiometer on the front panel of the unit. The benchtop and rack mounted versions each provide an analog output signal from the spectroscopy amplifier, which can be connected to an oscilloscope and a multichannel analyzer, and a digital output signal from the pulse amplitude discriminator which can be connected to a counter. Both versions have provision for injection of a test pulse through a 1 pf capacitor into the preamplifier input for calibration and testing. Energy spectra were acquired and stored using a personal computer with a multichannel analyzer board. The noise performance was determined by observing the noise threshold and the width of the peak from a test pulser signal.

In our studies, the photodiodes were mounted in a fixture which was pressed against the sample surface during measurements. This arrangement meets several requirements. First, it provides an accurate and reproducible spacing between the sample and detector. Secondly it prevents ambient light from reaching the diode. Thirdly, helium can be used to reduce beta attenuation as described below in section 3.2. Finally, it electrically shields the diode from spurious signals. The sample and detector should have a common ground to prevent capacitive coupling of spurious signals to the input. Ground loops can also be a source of spurious signals and should be avoided.

3. Test Results

3.1 Detector response to betas from tritium and ^{63}Ni

The output pulse amplitude and corresponding MCA channel number are proportional to the particle energy. The energy calibration factor (keV/channel) was determined from the measured spectrum of particles with known energy. Spectra were recorded using reference sources of ^{63}Ni , which emits betas with an end point energy of 66 keV, and ^{241}Am , which emits alphas with an energy of 5.486 MeV. These two methods gave the same value for the energy calibration factor. Fig. 3 shows a typical spectrum measured with the ^{63}Ni reference source.

Figure 4 shows spectra for tritium betas measured using a S1223 diode with the Canberra 2001A preamp and Ortec spectroscopy amplifier. The tritium beta source used for these

measurements was a planchet reference source from Amersham [17]. Spectra taken using the portable benchtop version of the tritium monitor were similar to those shown in figure 4.

The noise threshold for this system is 4 keV, as can be seen from figure 4. The energy resolution determined from the width of the peak from a test pulser signal was 1.5 keV FWHM. The dashed line in figure 4 shows the energy distribution for tritium betas predicted by the Fermi theory [14]. Formulas used to evaluate the theoretical energy distribution are given in the appendix. Previous studies have shown that the Fermi theory accurately predicts the energy distribution for tritium betas [18]. Figure 4 shows that the tritium beta spectra we measured using the pin photodiode have the correct energy distribution. The good agreement with theory can be seen even more clearly in figure 5 in which the measured spectra are plotted as Fermi plots (see appendix). This transformation maps the Fermi beta spectrum onto a straight line which intersects the energy axis at the endpoint energy. This type of plot is used to identify unknown beta emitting isotopes from their endpoint energies. The measured spectra shown in figure 5 have endpoint energies of 18 keV which is the correct value for tritium betas.

3.2 Absorption of betas by air and helium

Quantitative area surveys of tritium surface contamination requires that attenuation of the beta flux by air in the gap between the emitting surface and the detector be taken into consideration. The effect of this air attenuation on the tritium beta spectrum is shown in figures 4 and 5. These spectra were taken with the tritium reference source and detector in a small chamber which could be evacuated and backfilled with air or helium. The distance between the surface of the beta source and the detector was $0.50 \pm .05$ mm. Figure 4 shows spectra taken with the chamber evacuated (circles), and with the chamber filled with air (squares) and with helium (diamonds). The measurements in air and helium were made at a temperature of 23°C and a pressure of 625 Torr. These measurements provide two results which are important for tritium detection. The first is that the attenuation by air or helium does not significantly change the shape of the beta spectrum, but simply reduces the count rate at all energies by approximately the same factor. This can be seen in figure 4 from the fact that the three curves can be superimposed by a shift along the vertical logarithmic scale. Similarly, in figure 5 the three curves are all linear with nearly the same endpoint energy but with different slopes. This feature of beta absorption has previously been noted and discussed [14]. The second result from the data in figure 4 is the magnitude of the attenuation factor. The total count rate summed over the energy range from 4 to 18 keV is 45.1 ± 0.2 counts per minute (cpm) for vacuum, 39.3 ± 0.2 cpm for helium and 23.9 ± 0.2 cpm for air. The ratio of

the count rate in air or helium to the count rate in vacuum gives transmission factors of 0.87 for helium and 0.53 for air. The transmitted fraction of betas after passing through a thickness (x) of absorbing material of mass density ρ can be approximated by

$$F = I/I_0 = \exp(-x\rho/\lambda), \quad (5)$$

where I_0 and I are the flux before and after passing through the absorber [14]. The mass attenuation length λ depends on the beta endpoint energy but varies only slightly with the atomic number of the absorbing material [14]. Equation 5 assumes the detector-sample spacing is constant over the area of the detector and that the beta emitting surface extends well beyond the edge of the detector. Using equation 5 and transmission factors given above for the data shown in figure 4, we find the mass attenuation length λ for tritium betas to be $7.7 \pm 0.8 \times 10^{-5}$ gm/cm² for air and $4.9 \pm 0.5 \times 10^{-5}$ gm/cm² for helium. These values can be used with equation 5 to calculate the transmission factor for detector-sample spacings which differ from the value of 0.5 mm used in our measurements. Provided the detector-sample spacing is known, this correction for absorption can be applied to the measured count rate to determine the emission rate from the surface. This fact means that quantitative measurements of tritium beta surface emission rates can be made with the detector and sample in air, enabling area surveys to be made with a portable hand held instrument. The spacing between the sample and detector, and the tolerance limits on the spacing for a given measurement precision, are larger when the gap is filled with helium instead of air. We found this can be accomplished by using a collar around the photodiode which is pressed against the sample and by flowing helium through the small volume between the detector and sample. As an example, for a transmission factor of 0.5 ± 0.1 the required spacing is 2.0 ± 0.5 mm for helium and 0.4 ± 0.1 mm for air, assuming gas densities at standard temperature and pressure.

3.3 Calibration of tritium surface activity measurements

The beta emission rate per unit area (Γ) from a surface can be calculated from the measured count rate (Y) using

$$\Gamma = Y/(aFG), \quad (6)$$

where F is the transmission factor discussed above, (a) is the area of the pin diode and

$$G = \frac{\int_{Eth}^{Em} n(E)dE}{Em} \quad (7)$$

is the fraction of betas which have energies above the counting threshold. E_m is the endpoint energy of the beta spectrum. This expression assumes a flat sample with uniform spacing between the sample and detector and that the sample extends well beyond the edge of the detector. The emission rate per unit area obtained from equation 6 is an average value over

an area approximately equal to the detector area. Figure 6 shows G versus the threshold energy E_{th} for the theoretical energy distribution $n(E)$ of tritium betas from the Fermi theory of beta decay (see appendix). For the spectrum taken in vacuum shown in figure 4, $Y=45.1$ counts/minute, $F=1$, $A=.066 \text{ cm}^2$ (from table 1), and $G = 0.58$ (from figure 6 with $E_{th} = 4 \text{ keV}$). These values in equation 6 give a measured emission rate of $\Gamma = 19.6 / \text{cm}^2 \text{ sec}$. Measurements at several positions showed the local emission rate was uniform over the active region of the source. This measured emission rate agrees with the quoted surface emission rate for the Amersham tritium beta reference source which was $102 \pm 10\% / \text{sec}$ into 2π steradian from an active region 2.5 cm in diameter, giving a local emission rate of $20.8 \pm 2 / \text{cm}^2 \text{ sec}$. The calibration of the Amersham source is traceable to the Physikalisch-Technische Bundesanstalt in Germany. A similar measurement using a larger area type S1223-01 diode with the Amersham source gave a measured emission rate of $22.7 / \text{cm}^2 \text{ sec}$, which is also in good agreement with the source calibration value. A calibration check was also made using a ^{63}Ni beta reference source for which the measured emission rate was $167 / \text{cm}^2 \text{ sec}$ which is 18% higher than the calibration value of $141 \pm 7 / \text{cm}^2 \text{ sec}$.

Assuming the beta emission is from tritium on the surface or at depths small compared to the linear attenuation length λ/ρ (typically $1 \mu\text{m}$ or less in solids), the areal density (N) of tritium and its disintegration rate dN/dt can be determined from the measured beta emission rate (Γ) as follows. Since the betas are emitted isotropically, half will be directed away from the surface and half will be directed into the material. A fraction of the beta flux directed into the material will scatter and contribute to the outgoing flux. A backscattering factor may be applied to correct for this effect [19], however here we neglect backscattering and simply assume that the disintegration rate or activity is twice the emission rate,

$$dN/dt = -2 \Gamma. \quad (8)$$

The areal density of tritium atoms is related to the disintegration rate by

$$dN/dt = -N \lambda_D, \quad (9)$$

where λ_D is the decay rate constant. Thus N is related to the surface emission rate by

$$N = 2 \Gamma / \lambda_D, \quad (10)$$

where $\lambda_D = 1.79 \times 10^{-9} / \text{sec}$ for tritium.

3.4 Limits of detection for tritium surface activity

The lower limit of detectable tritium activity is determined by the background count rate. A background spectrum is shown in figure 4. The count rate from this background spectrum summed over energy range of 4.5 to 18 keV is 0.16 counts/minute. The disintegration rate corresponding to this background is $0.15 / \text{cm}^2 \text{ sec}$ (880 dpm/100 cm^2 or 4.0 picoCurie/ cm^2).

Using the larger area S1223-01 diode and the eV550 preamp the background count rate, over the energy range from 6 to 18 keV, was 0.14 counts/minute corresponding to a disintegration rate of $0.090/\text{cm}^2 \text{ sec}$ ($520 \text{ dpm}/100\text{cm}^2$ or $2.4 \text{ pCi}/\text{cm}^2$). Thus the lower limit of detectable activity using our current pin diode system is around $0.1 \text{ disintegrations}/\text{cm}^2 \text{ sec}$. We made no special efforts to identify and minimize sources of background, and it seems likely that the background and minimum detectable activity could be further reduced. We note however that the minimum detectable activity for surface tritium with the current system is already well below the limit of $5000 \text{ dpm}/100\text{cm}^2$ allowed for surface contamination by beta emitters outside designated radiological areas [20].

The minimum detectable surface activity can be expressed in terms of a minimum detectable bulk activity or concentration of tritium in materials. The attenuation length of tritium betas through matter is about $10^{-4} \text{ gm}/\text{cm}^2$. The above lower limit of detectable surface activity of $0.1 \text{ disintegrations}/\text{cm}^2 \text{ sec}$ thus corresponds to a bulk activity detection limit of about $10^3 \text{ disintegrations}/\text{gm sec}$ or $27 \text{ nCi}/\text{gm}$, or to a tritium concentration of $5.6 \times 10^{11} \text{ atoms}/\text{gm}$. The equivalent dose rate from decay of tritium at this concentration is $3 \text{ rem}/\text{year}$ [4] which is less than the maximum allowed occupational exposure of $5 \text{ rem}/\text{year}$. This detection limit translates to a volume activity in air of about $35 \text{ nCi}/\text{liter}$, using $1.3 \text{ gm}/\text{liter}$ for the STP density of air. This limit is comparable to the derived air concentration (DAC) for occupational exposure which is $20 \text{ nCi}/\text{liter}$ [4,20].

We have not investigated the upper limit on tritium activity measurable by our method. Electronic effects, such as baseline drift, ADC deadtime (typically a few microseconds) and pulse pile-up, impose an upper limit on the count rate which can be processed [8]. Count rates of $10^4/\text{sec}$ or higher are not uncommon in nuclear spectroscopy applications. A count rate of $10^4/\text{sec}$ with the S1223 photodiode and an energy threshold of 4 keV would correspond to a surface activity of $0.5 \times 10^6 \text{ disintegrations}/\text{cm}^2 \text{ sec}$ or $14 \text{ } \mu\text{Ci}/\text{cm}^2$. For higher levels of activity the count rate could be reduced by one or two orders of magnitude by decreasing the active area of the diode. The dynamic range of detectable surface activity thus spans more than 6 decades.

4. Applications

4.1 Tritium on plasma facing components from Tokamaks

Several large tokamaks including TFTR, JET, DIII-D and JT-60U, have been operating for several years as a part of the multinational magnetic fusion energy research program. Plasmas in these machines have been fueled mainly with deuterium (D). Improvements in plasma conditions have reached the point where tritium produced by D(d,p)T nuclear

reactions in the plasma creates a radioactive contamination problem for components removed from the vessel. In addition, experiments have begun in JET and TFTR in which plasmas are fueled with tritium [1,2]. The amount of tritium retained inside these devices, how it is distributed and methods for removing it are important issues affecting their operation and safety [21,22]. We have been studying these issues by measuring the distribution of surface tritium on tokamak components using our tritium monitor. Figure 7 shows an example of such a measurement on the plasma facing (curved) surface of a graphite tile from the belt limiter in JET. This tile (number 7165) was in JET during a series of experiments in November 1991 [1], in which 53 Curies of tritium were injected into the plasmas. The data shown in figure were taken with a counting time of 100 seconds at each position. The data show that there is much more tritium at the sides of the tile, where there is net deposition of material by the plasma, than in the center or plasma contacting region, where there is net erosion of material by the plasma. This example demonstrates that our tritium monitor provides a convenient way to measure surface tritium which is rapid, non-destructive and has high spatial resolution. We have made similar measurements, with our tritium monitor, of surface tritium on components from the TFTR, DIII-D and TEXTOR tokamaks [23].

A pin diode tritium monitor could also be used to remotely measure surface tritium inside a tokamak vacuum vessel. In TFTR the in-vessel tritium inventory is a critical issue for high power DT experiments now in progress. The amount of tritium in the TFTR vessel is not allowed to exceed 2 grams. Previously reported studies [24] of deuterium retention in TFTR show that about half of the deuterium used to fuel the plasmas remains inside the vessel. At this rate of accumulation, the 2 gram limit would be reached before experiments are finished. If this happens, tritium removal procedures will be necessary to reduce the in-vessel inventory before experiments can continue. Removal of in-vessel tritium will also be part of the decommissioning of TFTR after experiments are completed. An in-vessel tritium monitor would help to follow the build-up and clean-up of tritium in the vessel [25]. To test the feasibility of in-vessel operation, we have built a prototype tritium monitor which was designed to operate inside the TFTR vacuum vessel. This prototype was built within a stainless steel can 2.3 inches in diameter by 5 inches long, to be compatible with an existing sample insertion system on TFTR. Signal processing electronics from AMPTEK were used in this unit. Benchtop tests of this TFTR tritium monitor probe showed its performance equaled that of the other tritium monitor prototypes described above. Compatibility of this module with operation inside TFTR is under evaluation.

4.2 Other Potential Applications

A pin diode tritium monitor could be used as a portable hand-held instrument for area surveys of tritium surface contamination. Such a device could measure fixed surface tritium rapidly and non-destructively. Such measurements are difficult to make by other methods. Routine analysis of tritium on swipes could also be made using a pin diode tritium monitor. Presently, swipes are analyzed by dissolution and liquid scintillation counting, a process which is costly, time consuming and which generates undesirable liquid radioactive waste. Analysis of swipes using a pin diode monitor would be quicker and produce no radioactive waste beyond the swipe itself.

Continuous real-time measurements of tritium in water, or other liquids, might be possible using a monitor based on a pin diode detector. Such a monitor could give early warning of a contamination problem in cooling water systems at facilities where tritium is present, for example at tritium production reactors or at future fusion reactors such as ITER. A monitor for tritium in water could also be used to check for tritium contamination of ground water at radioactive waste storage sites.

5. Appendix, The Fermi Theory of Beta Decay

The beta momentum distribution is given by

$$n(\eta) = n_0 \eta^2 F(W_m - W)^2 \quad (11)$$

and the energy distribution, which is the quantity we measure, is given by

$$n(E) = n(\eta) W/(\eta E_0) \quad (12)$$

where

$$\eta = p/m_0 c \quad (13)$$

and

$$W = (E/E_0 + 1) = (\eta^2 + 1)^{1/2} \quad (14)$$

are the beta momentum and total energy expressed as dimensionless quantities [12]. m_0 is the rest mass of the electron, c is the speed of light, E is the kinetic energy, p is the momentum, $E_0 = m_0 c^2$ and n_0 is a constant. W_m refers to the beta endpoint energy. We use the nonrelativistic expression

$$F(Z, \eta) = y/(1 - e^{-y}) \quad (15)$$

with

$$y = \pm Z 2\pi \alpha W/\eta \quad (16)$$

for the nuclear coulomb factor, where (+) applies to β^- decay and (-) applies to β^+ decay, Z is the nuclear charge of the decay product, and $\alpha = 1/137$ is the nuclear fine structure constant. For a Fermi plot (eg. figure 5) the quantity $[n(\eta) / \eta^2 F]^{1/2} = [n(E) E_0 / \eta W F]^{1/2}$, which is proportional to $(W_m - W) = (E_m - E)/E_0$, is plotted versus E . This gives a linear plot which intersects the horizontal axis at the endpoint energy E_m .

Acknowledgments

The authors thank Mark Adams for his assistance in constructing and testing the tritium monitors. This work was supported by the United States Department of Energy under contract DE-AC04-94AL85000.

Table 1. Area (A), capacitance (C) and leakage current (I) for the two types of pin photodiodes used. Capacitance and leakage were measured at a temperature of 23 °C with a reverse bias of 50 volts.

Type	Area (mm ²)	Capacitance (pf)	Leakage current (na)
S1223	6.6	8	0.1
S1223-01	13	15	0.2

Figure Captions

1. Schematic diagram of the tritium monitor.
2. Diagram of the charge sensitive preamplifier used in the portable tritium monitor. The feedback circuit (R_f , C_f) used a $1000\text{ M}\Omega$ resistor and the residual capacitance which was about 0.3 pF . The dashed box indicates components which were housed in a small hand held probe unit 2 cm in diameter by 10 cm long.
3. Measured energy distribution for betas from a ^{63}Ni reference source (dots) and the corresponding spectrum calculated from the Fermi theory (curve).
4. Measured beta spectra for a tritium reference source. Measurements were made with the source and detector in vacuum (dots), helium gas (diamonds) and air (squares). The triangles show a background spectrum measured with the beta source removed. The dashed line shows the spectrum predicted by the Fermi theory.
5. Fermi plots for the tritium beta spectra measured in vacuum, helium and air.
6. The fraction of betas with energies greater than the threshold energy calculated using equation 3 for tritium betas. The median energy is 5 keV .
7. Distribution of surface tritium on a graphite tile from the belt limiter in the JET tokamak, measured with our pin diode tritium monitor.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

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