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Abstract

A lithium-drifted silicon detector used as a pulse radiation dosimeter is described. It is used to measure the depth-dose distribution of pion beams in water. The fractional dose due to energy depositions above a particular energy in the detector can also be measured. Such measurements yield information on the distribution of ionization density. Preliminary results of the pion-beam dosimetry using this pulse dosimeter are given.

Introduction

There has been a growing interest in the use of negative pions for therapeutic applications.[1,2] When a negative pion is brought to rest in a medium, say tissue, it is captured by a constituent nucleus, which explodes into a "star" consisting of short-range and heavily ionizing fragments capable of delivering a large localized radiation dose. One can cause this capture to take place in the region of interest by selecting the energy of the pion beam. The use of a lithium-drifted silicon detector as a pulse dosimeter is motivated by some of the dosimetry problems encountered in studying the pion beam for biomedical applications.

The characteristics of the pion-beam as it passes through an absorbing medium of Lucite, and the energy distribution of negative-pion stars in silicon, determined by using lithium-drifted silicon detectors, have been reported.[3] In order to assess the possible uses of negative pions for biomedical applications, one of the important dosimetric measurements is the depth-dose distribution of such beams. This is normally measured by using ion chambers. There are some doubts, however, regarding the validity of the Bragg-Gray principle in the region where pions stop and produce stars. In addition, ionization chambers have rather low sensitivity. The use of a solid detector is very attractive because of its high stopping power. Another advantage is the low energy used to produce one hole-electron pair (3.6 eV in silicon). For a given energy loss, nearly ten times as much charge is produced in silicon as in a gas. The energies deposited in the detector in the region where pions produce stars have been found to extend beyond 50 MeV.[3] Still another advantage of using a semiconductor detector is its linear response with energy deposited in it.

One difficulty in using these detectors as dosimeters which operate by integration of the charge induced by the ionizing radiation is the leakage current of the detector. This leakage can be annuled by using a balancing circuit, and the detector can still be used as a dosimeter for x and γ radiation if the radiation-induced charge is large compared to the contribution from the leakage current.[4] In the case of heavy-charged-particle beams, however, radiation damage prevents their use at levels above that produced by the leakage current. In the present application, these difficulties are alleviated by accepting only the ac pulses and by operating at low beam intensity.

Method

The charge liberated in the lithium-drifted silicon detector is directly proportional to the energy deposited in it. A charge-sensitive preamplifier yields a voltage pulse proportional to the energy deposited in the detector. The detector used in this investigation is a 3-mm-thick lithium-drifted silicon detector with a sensitive diameter 1.5 cm. At room temperature, the leakage current is 3 μA; and this current is quite comparable to the current generated in the detector due to pions passing through it. (The total pion intensity seen by the detector is about 5×10^4 sec.) The detector leakage current has been blocked by ac amplification used in the system, as shown in the block diagram in Fig. 1. Simple capacity coupling is not adequate because of cancellation of the positive signal by the negative overshoot. This cancellation necessitates a polarity-clipping circuit to eliminate the overshoot contribution to the subsequent integration. The circuit diagram of the polarity-clipping circuit is shown in Fig. 2. If, as shown in the figure, the capacitor's output is fed through a diode, the load seen by the capacitor changes so as to suppress the undesirable overshoot. However, this diode clipping circuit introduces a nonlinearity in the positive portion of the signal. The linearity can be optimized by judicious circuit analysis. The pulses from the polarity clipping circuit are then integrated. The integrator consists of a standard operational amplifier with feed-back capacitor.[5] It is electronically reset by a diode pump that furnishes an accurate amount of charge to the capacitor. The overall system is shown in Fig. 1.

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The integrator and polarity-clipping circuit have somewhat contradictory conditions for best operation. Most integrators impose some limitation on the instantaneous input current. On the other hand, the linearity of the polarity-clipping circuit is improved by increasing the magnitude of the signals. A satisfactory compromise using a second amplifier was reached which yielded good integrator efficiency for energy deposition of 0.5 to 50 MeV in the detector and satisfactory operation of the polarity-clipping circuit over a similar range. To measure the dose due to pulses corresponding to the energy deposition greater than a particular value or over a particular range of energies, we used a single-channel pulse-height analyser (or discriminator), gated linear amplifier, and a delayed amplifier. Such threshold measurements yield information on the distribution of ionization density at the measured position.

Results and Discussion

This dosimetric system is used to measure the depth-dose distribution in water of a 190-MeV/c pion beam. Pion beams are always produced with muon and electron contamination. Our beam is contaminated with 25% electrons and 10% muons. For our incident beam, the most probable energy losses in the 3-mm detector used in this investigation are 1 MeV by the electrons and 1.2 MeV by the pions, while the energy lost by the muons is intermediate between these values. The spread of the energy-loss distribution about these values is around 30% due to Landau fluctuations.[6,7] As the pions pass through water, the energy of the pions decreases, and hence the energy deposited in the detector increases. At the end of the range the pions stop and produce stars, thereby depositing in the detector energies at times exceeding 50 MeV.[3] Hence the system should be linear at least from 0.5 to 50 MeV. When checked out by using a calibrated pulser, the system was found to be linear to within 5% over the energy region from 0.5 to 50 MeV.

The cyclotron pulses 64 times per second, thus giving 64 coarse groups of pions per second. The mode of operation can be controlled so that these groups of pions are spread out over either of two periods. The "short-spill" mode spills the beam over a period of approximately 400 μsec. The auxiliary dee mechanism of the cyclotron makes it possible to spread each group of pions over a longer period of 8 to 10 msec. Even in this mode, roughly half of the total beam arrives during the first 400 μsec (called the spike), and the other half is stretched over 8 to 10 msec.[8] To prevent overloading of the electronics in these investigations, we use a stretched beam with its spikes gated off.

Because of beam-intensity fluctuations, two plastic scintillators connected in coincidence are used to monitor the beam. The lithium-drifted silicon detector is housed in a small waterproof Lucite box and can be remotely moved in a water phantom. The integrated charge from the lithium-drifted silicon detector is measured during the time it takes the monitor scintillator systems to accumulate a fixed number of counts. This procedure is repeated for each position of the detector in the water phantom. Measurements are also made in a positive-pion beam for comparison. The characteristic difference in interaction between positive and negative pions is at the end of their range. When the positive pion comes to rest in a medium, the Coulomb repulsion between the positive charges keeps it from interacting with a nucleus. Instead, it decays into a muon with an energy of 4 MeV, which then decays to a positron with an energy distribution peaking around 30 MeV and a maximum around 54 MeV.[2] Depth-dose distributions as measured by the silicon detector in a water phantom are shown in Fig. 3 for both positive and negative pion beams. As can be seen from the figure, the negative pion beam gives rise to a much higher dose than that of the positive pion beam near the end of the range.

The integrated output of the lithium-drifted silicon detector is measured as a function of the discriminator setting (energy threshold) for positions designated 1, 2, 3, and 4 in Fig. 3. For comparison purposes, the integrated output of the detector at zero threshold setting of the discriminator at the above-mentioned positions is normalized to unity. The resulting curves are shown in Fig. 4.

It can be seen that the two curves for the negative-pion beam at positions 1 and 2 corresponding to the peak and halfway down the falling portion of the depth-dose distribution curve are similar, thereby suggesting that the ionization-density distributions at and beyond the peak of the negative-pion depth-dose curve may be similar. On the other hand, the curve corresponding to position 3 halfway up the rising slope of the depth-dose curve falls below curves 1 and 2 with increasing threshold setting, thereby suggesting that the ionization-density distribution at that point is considerably less that at the other two points. As expected, the fractional dose for threshold settings greater than 10 MeV at position 4 in the case of the positive-pion peak falls to zero quickly as there are no stars contributing here. It should be mentioned that for the detector thickness used (3 mm), pulses greater than around 9 MeV cannot be due to the passage of pions through the detector. In the case of negative pions, pulses greater than 9 MeV are definitely due to star formation.

The gain settings of the amplifiers are very critical in the measurement of the depth-dose distribution, as they determine the energy range over which the system is linear. For example, by increasing the gain, the lower-energy threshold can be lowered, but this can create a saturation at higher energies which depresses the dose reading at the peak region. Conversely, lowering the gain raises the lower-energy threshold, thereby decreasing the measured dose at the entrance. It would be better to use thin detectors for measuring the depth-dose distribution because of narrow width of the region where negative pions produce stars (~4 cm). However, we have found that the range of energies deposited in the detector in the region where pions produce stars is roughly independent of the detector thickness. Since the energy deposited by a pion in traversing the detector is roughly proportional to the thickness of the detector, linearity is required over a larger range of energies for thinner detectors. Results reported in this paper are preliminary and more work is being done to confirm our initial measurements. The depth-dose curve for a pure pion beam can be measured by using a threshold Cherenkov counter in anticoincidence with the semiconductor detector such that the particles with velocities greater than pions (i.e., muons and electrons) will not be counted. Work in this direction is in progress.

Acknowledgments

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Figure Legends

Fig. 1. Block diagram of the experimental setup.

Fig. 2. Polarity clipping circuit.

Fig. 3. Depth-dose distribution of 190-MeV/c π^+ and π^-.

Fig. 4. Fraction of dose due to particles depositing energies higher than the threshold-energy setting, as a function threshold energy.

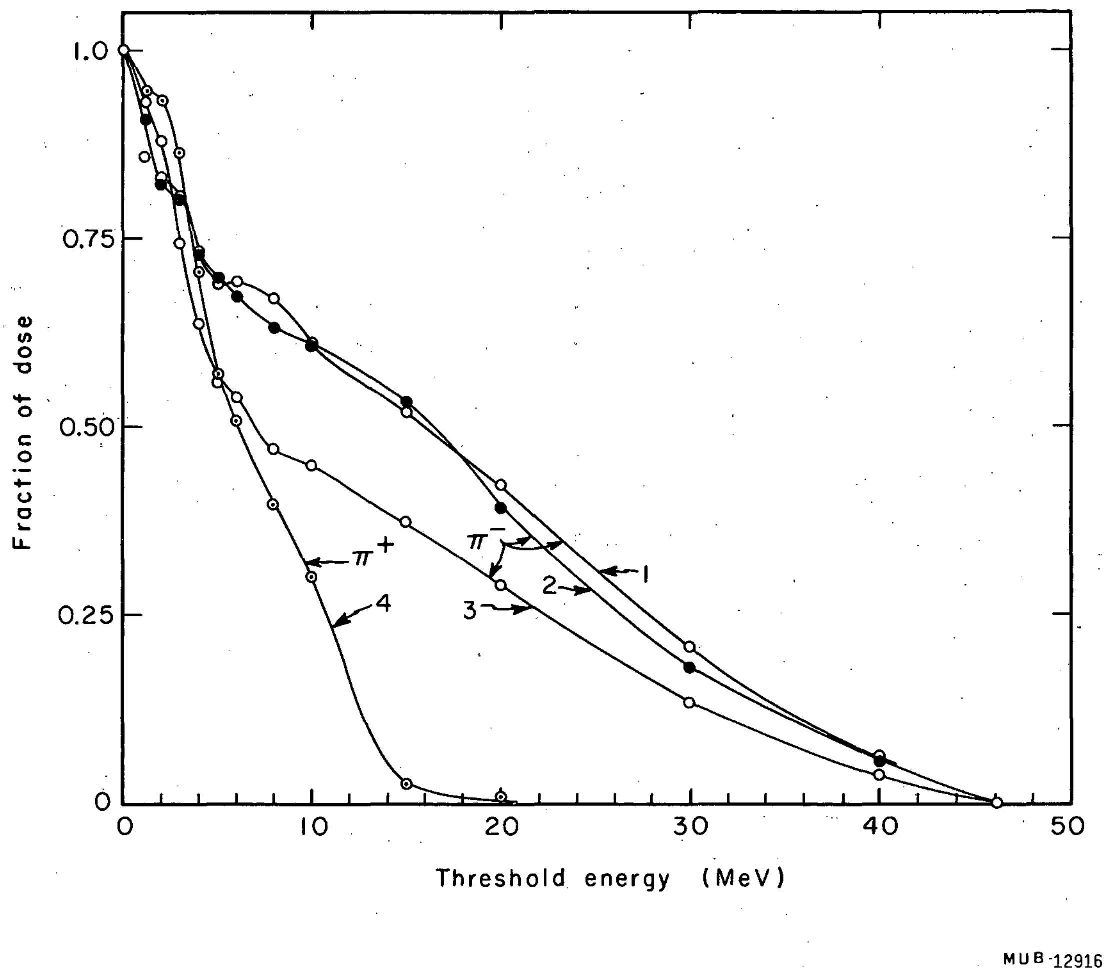
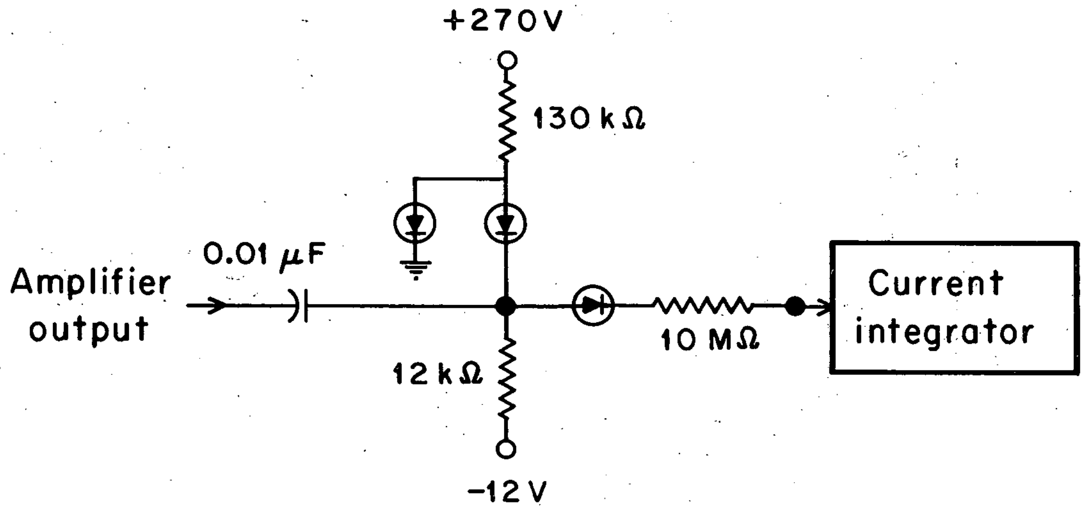

1.0
0.75
0.50
0.25
0
Fraction of dose
0
10
20
30
40
50
Threshold energy (MeV)
π+
π−
1
2
3
4
MUB-12916

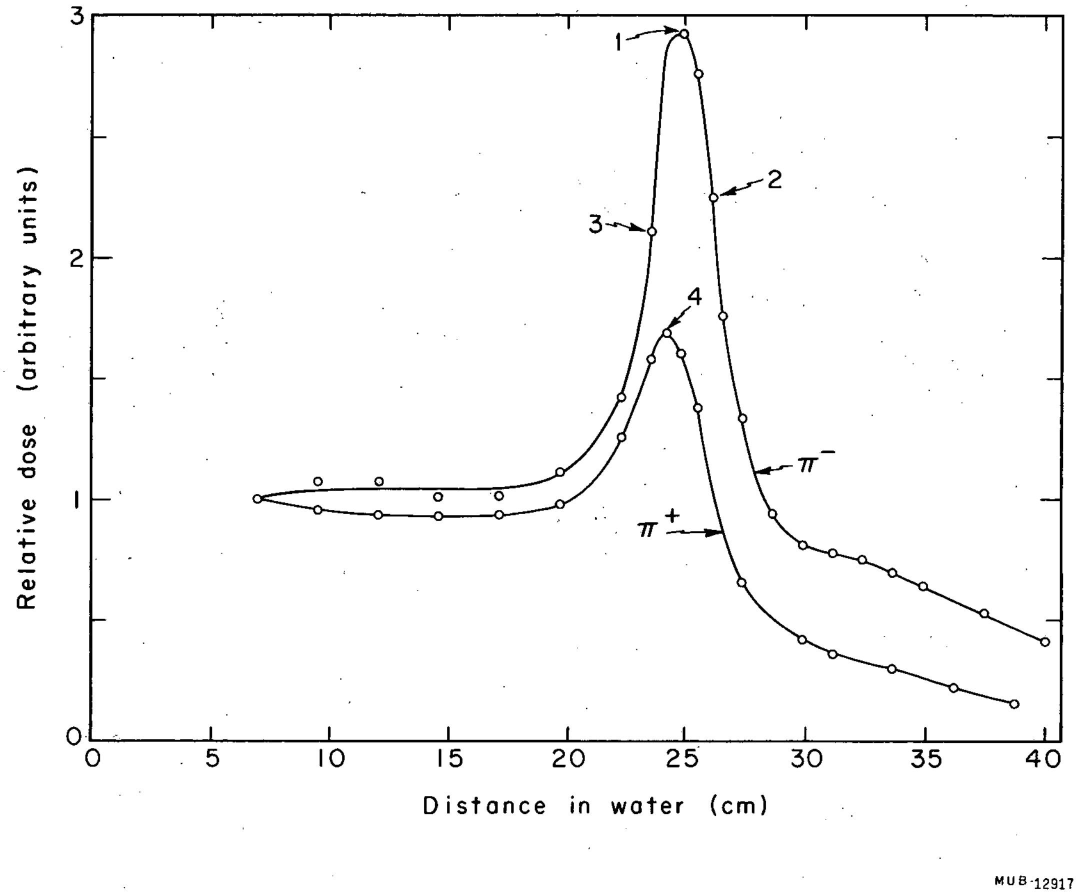
Fig. 1



(All diodes are 1N914)

MUB-12914

Fig. 2



Relative dose (arbitrary units)
Distance in water (cm)
0
1
2
3
0
5
10
15
20
25
30
35
40
1
2
3
4
π⁻
π⁺
MUB-12917

Fig. 3

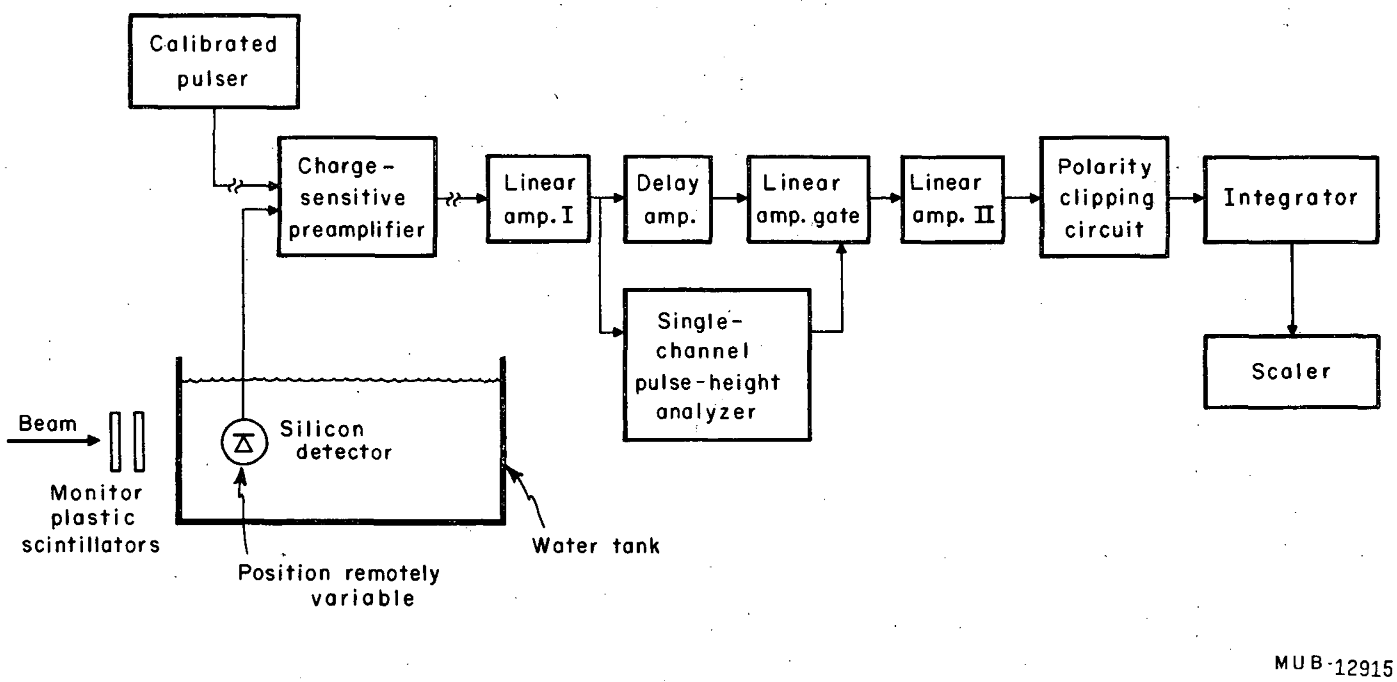

Calibrated pulser
Charge-sensitive preamplifier
Linear amp. I
Delay amp.
Linear amp. gate
Linear amp. II
Polarity clipping circuit
Integrator
Scaler
Single-channel pulse-height analyzer
Beam
Monitor plastic scintillators
Silicon detector
Position remotely variable
Water tank
MUB-12915

Fig. 4