Notes on Experiment N-15

The decay rate of cosmic-ray μ (muons) [redacted] is studied by detecting those muons that stop in a scintillation counter and by requiring a delayed pulse that signals the decay of the muon into an electron and neutrinos. e.g. ($\mu \rightarrow e + \nu_\mu + \nu_e$).

Most cosmic-ray muons have enough energy to pass right through the scintillator without stopping, but those having a kinetic energy less than ~ 100 MeV are stopped. The stopping of a μ [redacted] and its subsequent decay into an electron (and neutrinos) is signaled by a **double-pulse** from a photo multiplier viewing the scintillator. The time lapse between stopping and decay pulses is sorted in discrete "bins" by the electronic logic circuitry. The bins formed by the electronics are all started at the same time and have widths which are roughly multiples of 1 µsec. From the electronic bins one can determine the number of decays in consecutive time intervals. A rough measure of the decay lifetime is then obtained by plotting the number of decays observed in consecutive time bins. The overall shape of the decay curve will be found to be a simple exponential, i.e., if plotted on semi-log paper, the points will fall on a straight line. The slope of the line then represents the mean lifetime.

A more accurate determination of the mean lifetime requires accounting for the bin overlaps and widths. A least-squares fitting procedure should be used. A further correction to the observed lifetime is required, to extract the actual decay lifetime in vacuum. This is because although μ^+ mesons decay away with the characteristic "decay" lifetime, stopped μ^- [redacted] disappear slightly more rapidly due to the competing process of nuclear capture in the surrounding matter (in this case, the scintillator). The ratio of μ^+/μ^- [redacted] in the cosmic rays has been measured. It should thus be possible to obtain the true decay lifetime of muons from your measurements, using known capture rates in carbon.

Description of the Electronics

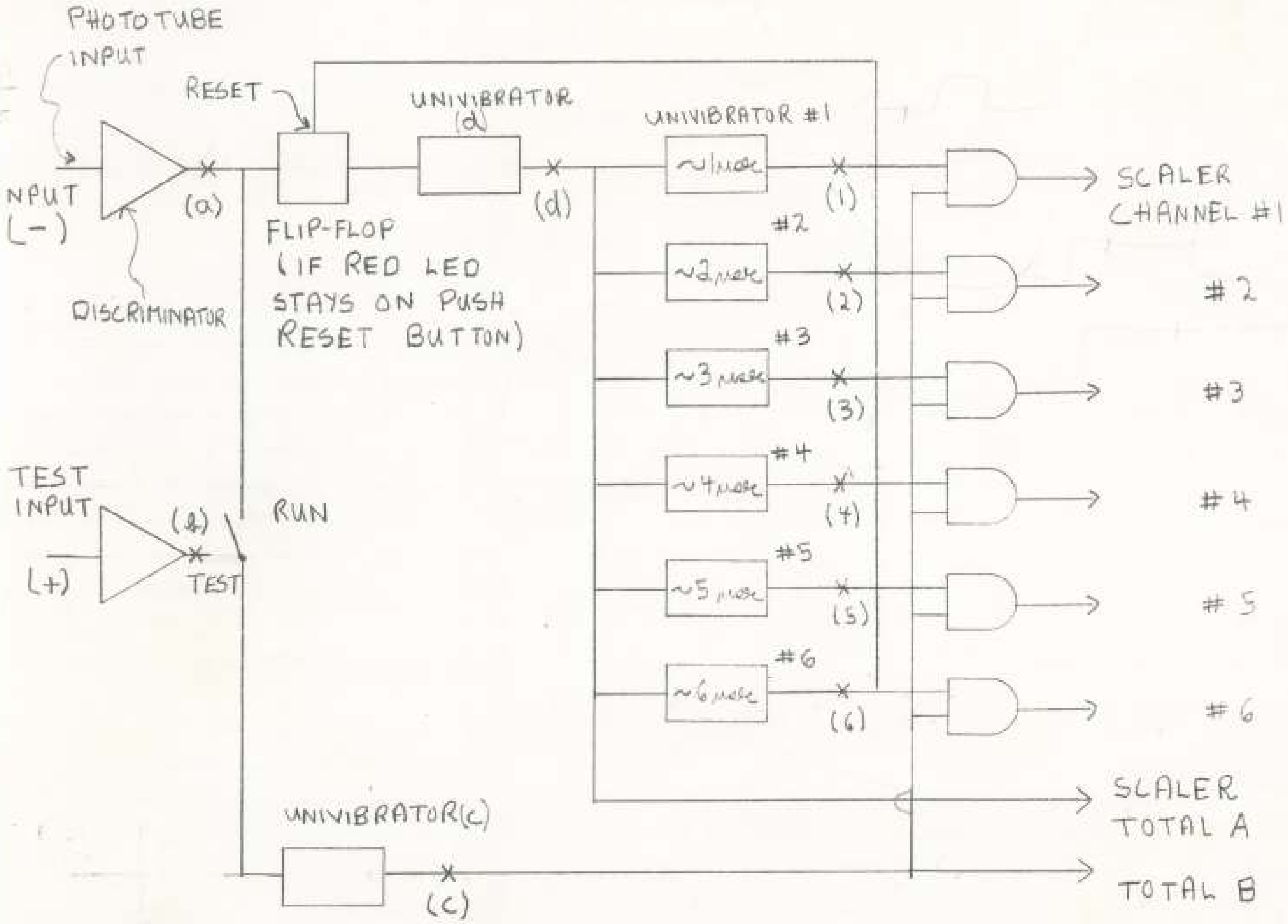
A block diagram of the logic is shown in fig. 1 and a detailed drawing in fig. 2. The data sheets for some of the circuits are also included. Refer to fig. 1 when reading the description below.

Pulses from a photo multiplier tube are fed into the negative input connector. These pulses are discriminated by using a comparator; if the pulse amplitude exceeds a present amount the discriminator makes a standard width and amplitude pulse. This pulse can be seen at test point (a). The output from (a) is used to set a flip-flop such that no other pulses can be accepted until the flip-flop is reset by the trailing edge of the last bin (univibrator #6). The flip-flop is followed by univibrator (d) which serves to delay the gate starting time by a fraction of a microsecond. This prevents the stopping-μ pulse from counting in the gates. Univibrator (d) is followed by the gate-forming univibrators #1 to #6.

The "gates" generated by the univibrators form one set of inputs to the six coincidence circuits, the other input to each two-fold coincidence is the input line (through the TEST/RUN switch and univibrator (c)). Thus, if there is a delayed pulse on the input line within the time interval of one of the gates, the corresponding coincidence will register a count.

The outputs of the coincidence gates drive scalars. In addition the total number of pulses of univibrator (d) is scaled as "TOTAL A", and those of univibrator (c) as "TOTAL B". In the run mode these two totals are roughly equal; the real utility of having two "total" scalars is in the test mode.

A pulse generator may be used to introduce a known rate of positive pulses through the TEST input (TEST/RUN switch on TEST). These make coincidences with the randomly triggered gates, triggered by μ-meson pulses. If the number of μ[redacted] triggers is known (TOTAL A counts), as well as the total number of positive test pulses (TOTAL B counts), then the number of random coincidences in each channel enables you to calculate the "width" of each channel. The resolving time of each coincidence is the sum of the pulse widths of the two pulse inputs.



X INDICATES TEST POINT

N15 FIGURE 1

Physics 410/510

Exposure to Ionizing Radiation

Several experiments in the laboratory involve the use of radioactive materials which produce ionizing radiation. It is important that any student working with these radioactive sources have a good understanding of the nature of the radiations and of the maximum exposure levels that are permissible by federal and state law. Cornell University expects us to limit exposures to 10% of the maximum permissible. In this laboratory it is possible to keep exposures well below these levels and it behooves all of us to use sources wisely to minimize exposures to ourselves. To do otherwise would be very foolish indeed. The purpose of this summary is to present basic information about exposure levels and how they can be interpreted. Reference to more detailed information will be given at the end.

A. Properties of Radiation

Radiations from radioactive isotopes were named before they were identified and even today carry these historic names -- alpha, beta, and gamma rays. Alpha rays are the nuclei of helium atoms and are characterized by their production of dense ionization over a very short path before coming to rest. Energies fall between 3 and 8 MeV, with corresponding track lengths in air of from 2 to 7 cm. A few thousandths of an inch of any solid will thus absorb alpha rays.

Beta rays are positrons or electrons, again typically having energies up to a few MeV. Electrons scatter readily in matter and as a result do not have the sharp, well defined ranges that are characteristic of alpha rays. But roughly speaking they can be stopped by modest amounts of material such as 1/8" thick aluminum.

Gamma rays are photons and so are identical to x-rays, except for their mode of production. Energies are again in the region up to a few MeV. Gamma rays penetrate sizable amounts of matter and their absorption is characterized by an exponential decrease in intensity with increasing thickness.

Measurements of the absorption of these radiations in matter are the subject of several P410/510 experiments.

The problems associated with the use of sources of these radiations in the laboratory are quite different for the three types. Alpha emitters are generally used in an unsealed condition and care must be taken to avoid contamination which could lead to inhalation or ingestion. Instruments to detect contamination by alpha emitters are very delicate and must be capable of being placed directly in contact with possibly contaminated surfaces to avoid absorption by the intervening air. On the other hand, gamma sources are generally sealed in containers and their presence can readily be detected by relatively simple equipment. Beta emitters fall somewhere in between these extremes, and one finds them being used both sealed and open. In the P410/510 lab we use only sealed sources, which are periodically checked for leaks by Cornell radiation safety personnel.

B. Units of Radiation

We are "blessed" with a set of strange units which evolved from the earliest attempts to measure radioactivity. The important units are these:

For Activity

curie - Originally defined as the number of disintergrations per second in a gram of radium. Now set equal to 3.7×10^{10} disintegrations/second and applied to any source.

$1 \text{ Ci} = 3.7 \times 10^{10}$ dis/sec

1 millicurie (mCi) = 3.7×10^{7} dis/sec

1 microcurie (μCi) = 3.7×10^{4} dis/sec

becquerel - 1 Bq = 1 disintegration/second

For Radiation Dose

roentgen - A unit of radiation dose. Originally defined as an amount of radiation that will release one electrostatic unit of charge (3.3×10^{-10} C) through ionization in one cubic centimeter of dry air at NTP (or in 1.29×10^{-3} g of air). If we use the experimental result that fast charged particles expend on the average 34 eV in producing one ion pair in air and use the equivalence $1 \text{ eV} = 1.6 \times 10^{-12} \text{ erg} = 1.6 \times 10^{-19}$ J, the roentgen becomes an energy deposition of 87 erg/g or 0.0087J/Kg.

rad - Updated version of the roentgen - defined as an energy deposition of 100 ergs per gram of matter (0.01 J/Kg).

gray - 1 Gy = 1 J/Kg = 100 rad

For Dose Equivalent

rem - (roentgen equivalent man) Unit of dose designed to be relevant to biological effects. For beta and gamma radiation 1 rem = 1 rad in tissue. For any radiation 1 rem = 1 rad x QF where QF is called the relative biological effectiveness or quality factor. The QF is a number that is used to account for the experimental fact that very dense ionization produces more biological damage per unit of absorbed energy than light ionization.

sievert - 1 Sv = 100 mrem

Some values of QF are :

Radiation	QF
Beta and Gamma rays	1
Thermal neutrons	4 to 5
Fast neutrons	10
Alpha particles	10 to 20

These units of dosage are measures of accumulated dose. We are interested in dose rates, so we will be using units such as rem/year, mrem/hour etc. Many radiation monitors are designed to read dose rated in rad/hour or mrad/hour. When we are dealing with gamma radiation in the lab such meters can be considered to read directly in rems as well as rads.

C. Maximum Permissible Exposure Levels

It is impossible to fix an exposure level below which it can be absolutely guaranteed that no damage to a biological system will take place. However, from a large amount of experimental evidence obtained during the past 50 years, exposure levels which are considered to pose no health hazard to an individual have been derived. Before writing down these levels, several interesting pieces of data can be noted:

1. Background radiation. People at or near sea level are subject to a constant dose rate of about 150 mrem/year. About 25% comes from cosmic rays, about 10% is from the K-40 in our own body, the rest from radioactivity in matter. This background level can be as much as three times higher for people living at the highest elevations.
2. Lethal dose. A single, whole body, dose acquired in a short time (several hours) of 400 rem is known to have a 50 percent probability of being fatal. Known lethal doses vary from about 200 rem to 800 rem. These values show the influence of not only the state of health of the individual but also the kind of treatment given.
3. Healing. The effects of radiation are cumulative over a period of time of the order of a month, but a healing process is evident in cases where the dose has been received over longer periods.

Maximum permissible occupational exposure levels are set by the Nuclear Regulatory Commission. They have decreased about a factor of ten from the time they were first set in 1934. The present levels for persons 18 years old or older working with radioactivity are:

Whole body radiation..................................5 rem in a year
Hands or feet...75 rem in a year

The federal and state maximum permissible exposures in a 3 month period (calendar quarter) are:

Whole body; head and trunk; active blood-forming organs; lens of eyes; or gonads..1.25 rem
Hands and forearms; feet and ankles......................18.75 rem
Skin of whole body..7.50 rem

The levels in the second list may be exceeded if (1) the whole body dose does not exceed 3 rem in any calendar quarter and (2) the accumulated dose does not exceed 5(N-18) rem, where N is the person's age.

A simple interpretation of all these numbers is to say that one should not exceed a dose rate of 100 mrem per week. If you were working a 40-hour week in an establishment using radioactive sources you (and your employer) would have to be sure that you were working in an area where the average dose rate was less than 2.5 mrem/hour. Cornell University recommends that exposure be limited to 10% of this dose rate.

D. Dose Rate Produced by Gamma Source

We can calculate the dose rate produced by a given gamma source. To see what factors enter into such a calculation, let us do an example to find the dose rate at a distance of one meter from a one MeV gamma source having a strength of one millicurie. We will assume that only one photon is emitted in each decay.

We need to know the effective thickness of tissue in which the energy will be deposited. From the absorption coefficients for the light elements we can estimate that this length is 20 cm. Having this value, we can proceed:

Strength of source 1 mCi = 3.7×10^7 photons/second
At 1 m, the intensity of radiation falling on a surface is

$$3.7 \times 10^7 / 4\pi \times 10^4 = 2.9 \times 10^2 \text{ photons/cm}^2\text{-sec}$$

With 1 MeV = 1.6×10^{-6} erg, the surface energy density is $2.9 \times 10^2 \times 1.6 \times 10^{-6} = 4.6 \times 10^{-4}$ erg/cm^2 -sec and if this is absorbed in 20 cm of tissue of density 1 g/cm^3 , the volume and mass energy density becomes:

$$\frac{4.6 \times 10^{-4}}{20} = 2.3 \times 10^{-5} \text{ erg/cm}^3\text{-sec}$$

or erg/g-sec = 8.4×10^{-2} erg/g-hour.

Using 1 rad = 1 rem = 100 erg/gram we find the dose rate is:

$$\frac{8.4 \times 10^{-2}}{100} = 8.4 \times 10^{-4} \text{ rem/hour} = 0.84 \text{ mrem/hour.}$$

This quantity varies slowly with energy and since the photon energy of sources we use is not too different from one MeV we can use a rule of thumb, for a source that emits one photon per decay:

A one mCi gamma source produces one mrem/hr at one meter.

E. Significance for Physics 410/510

Before you can work safely with radioactive sources you must realize that time and distance play a dramatic role in determining the dosage. A one milliCurie source at one meter poses no threat but if you were to carry the same source in your pocket for a few days you would have severe damage to the nearby tissue. But you could pick the source up in your hand for a few seconds without adding appreciably to your accumulated dose.

The sources in Physics 410/510 are described in an attached Appendix I.

When you do an experiment in which you use a radioactive source you should measure the dose you receive in each lab session with a survey meter and record it in your notebook. You will find that with a little bit of care and planning you can keep the exposure comparable to the dose that you receive in the course of a few days from natural background radiation, far below the legal permissible exposure level.

References
(some library locations included)

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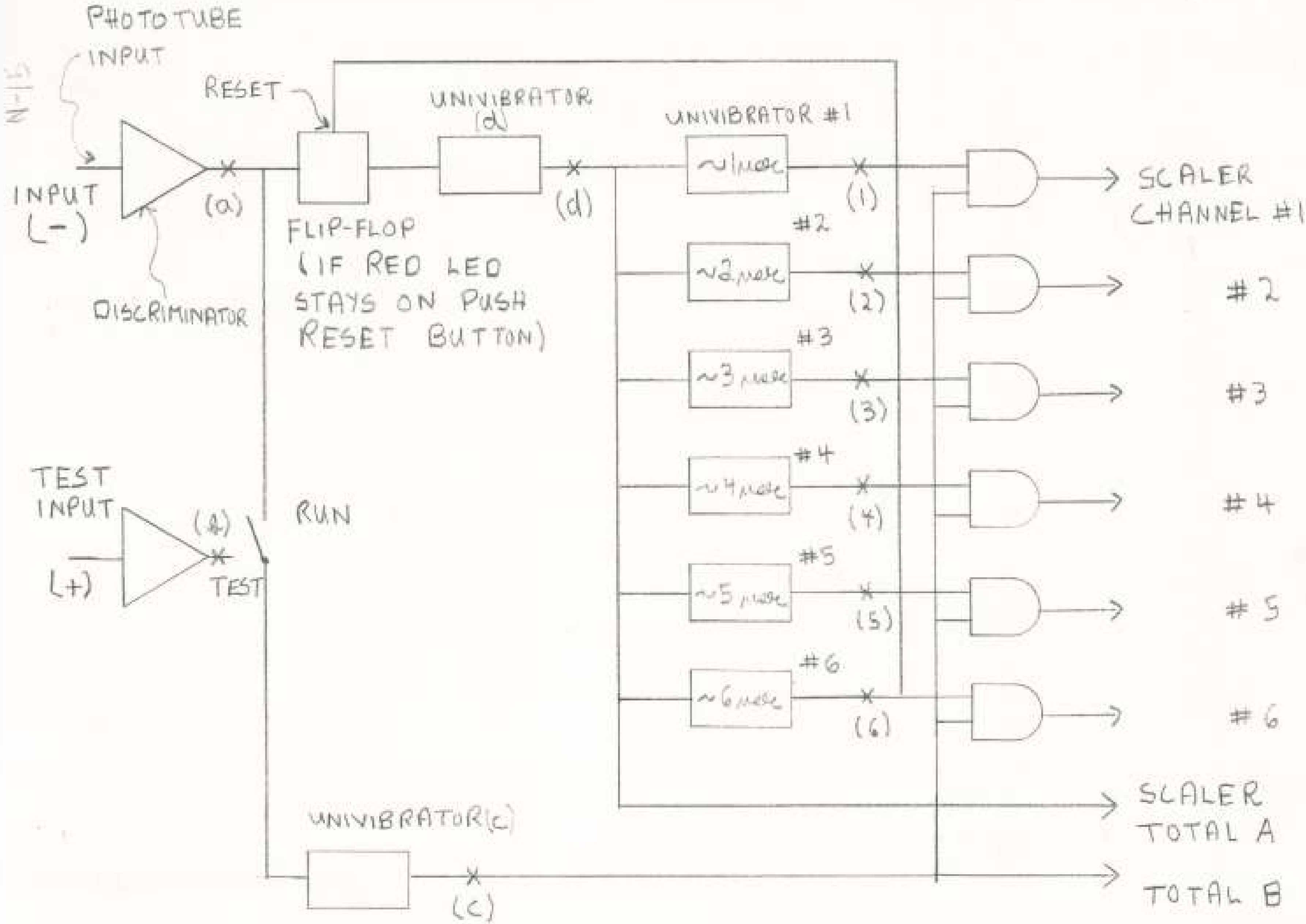

X INDICATES TEST POINT

N15 FIGURE 1

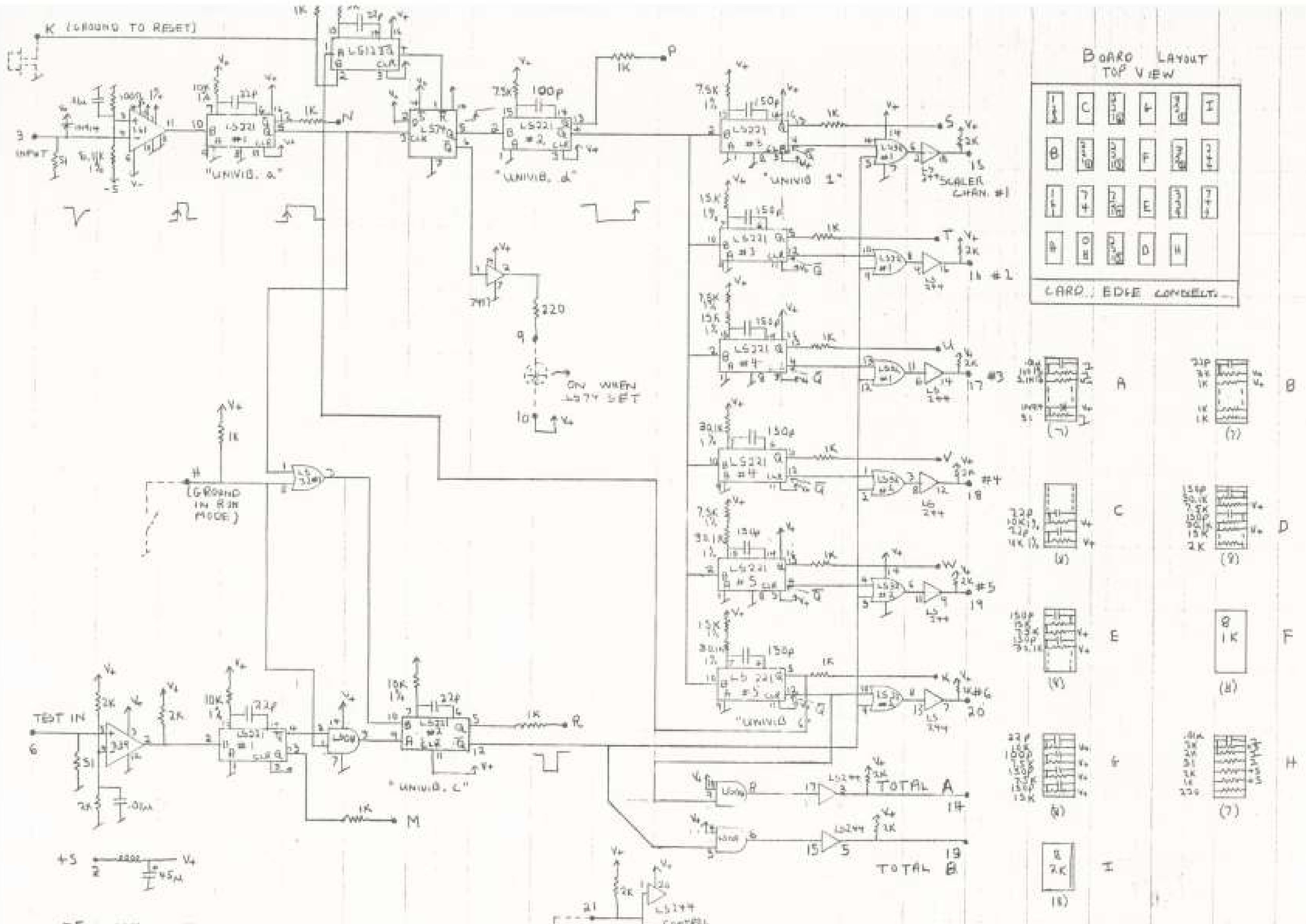

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FIGURE 2