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## ABSTRACT

The instrumentation for processing data from an $(\alpha, 2\alpha)$ experiment is described. System requirements are set forth and the instruments for fulfilling them are discussed. Special attention is directed to fast linear gates, the stretching of narrow pulses, and a basic transistor amplifier used in the system. Additionally, gain stablization from the photocathodes of photomultipliers to the input of a four-dimensional analyzer is discussed.

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## 1. Introduction

In this experiment, various targets were bombarded with 910 MeV alpha particles; the resulting (alpha, 2 alpha) reactions were investigated. It was anticipated that this experiment would enable us to measure the cross-section for elastic collisions between the bombarding alpha particles and alpha-particle clusters on the surface of the nuclei. The results of the experiment are given in another paper.[1] This paper describes the instrumentation which was required to analyze and process the data.

The system was designed to accept events in which coincidences occured between alpha particles scattered out of the beam and alpha-particle clusters knocked out of the nuclei. The $He^3$ particles, tritons, deuterons, and protons were rejected. The detectors were scintillation counters which measured the specific ionization and energies of the coincident alpha particles. The output of the counters was digitized and stored on magnetic tape. The magnetic tape was then processed in an IBM 7090 computer.

## 2. General Description of System

As we see from fig. 1, the 910 MeV alpha beam, generated by the 184-inch cyclotron, is incident on a target. Assume at this instant that two alpha particles, $a_1$ and $a_2$, are emitted. Both alpha particles pass thru collimator counters (or anti-coincidence counters) and dE/dx counters, and are stopped in E counters. The two dE/dx pulses, henceforth referred to as $\Delta E_1$ and $\Delta E_2$,

pass through delay boxes, amplifiers, splitters (emitter followers with a common input), and then into a fast coincidence unit (resolving time 10 nsec). The output of the fast coincidence unit opens four linear gates. At this instant, the pulses $E_1$, $\Delta E_1$, $E_2$, and $\Delta E_2$ are incident upon the linear gates.

These pulses pass through the gates, are amplified, and directed into six-way splitters. The outputs of these splitters are processed in two ways:

(a) All four pulses are passed through linear amplifiers into a four-dimensional analyzer consisting of four analog-digital converters (ADC's), a buffer magnetic-core storage, and a magnetic-tape transport.

(b) All four pulses are sent into an amplitude selection and slow-coincidence (resolving time $5\,\mu$sec) system that separates the alpha particles from tritons, deuterons, and protons ($He^3$ particles are separated by the IBM program). This part of the system uses the Del-a-gate and Tranco units described later. The output of this system generates an $a_1 \cdot a_2$ gate which gives a store command to the four-dimensional analyzer.

Also shown on the block diagram are other gating units which are synchronized with the beginning of the cyclotron-beam burst. Their function is to reduce accidental coincidences and to provide the timing for light-flasher pulses between beam bursts. Light flashers on the E and $\Delta E$ counters generate artificial pulses which pass through the system in the same manner as alpha pulses. These pulses are directed into feed-back stabilizers that control the high voltage on the photomultipliers to stabilize the overall system gain. The pulses are prevented from entering the four-dimensional analyzer by anti-coincident circuits.

3. Requirements of the System

The requirements of the system are as follows:

(a) Stability (24h), 2%

(b) Linearity, 2% (excluding scintillators)

(c) Resolution, 1% (excluding scintillators)

(d) Speed, $5 \times 10^6$ counts/min (from photomultipliers)

(e) Flexibility, ability to add gating units, coincidence units, etc., as the course of the experiment dictated.

(f) Reliability, minimum down time of equipment during the experimental run.

The ways in which we meet each of these requirements are as follows:

## 3.1 STABILITY

Each of the individual units are designed to be stable to better than 1% over a 24-h period. The usual stabilizing methods are employed, such as feedback in amplifiers, controlled voltages and component tolerances in open-loop linear circuits.

The major problem with stability, however, occurred in the gain change of photomultipliers at high count rates. This shift occurs at constant dynode voltages and may be as much as 30%. A separate-feedback stabilizing system using a light flasher as the reference pulse overcame this problem.

## 3.2 LINEARITY

The response of plastic scintillators to alpha particles is not linear; consequently, the system is inherently not linear. However, we calibrate the system using various absorbers in the direct alpha beam, and the corrections for non-linearity were made part of the programming in order to reduce the data. Despite the non-linearity of scintillators, the individual units are expected to have 1% linearity, and the overall system (less the scintillators) has better than 2% linearity.

### 3.3 RESOLUTION

The electronics are designed not to broaden the inherent resolution of the scintillation counters. This requirement set an upper limit of 1% resolution on the electronics. The amplifiers after the linear gates are the chief source of noise and loss of resolution. Their design is discussed in the following sections.

### 3.4 SPEED

The expected count rate at the output of the photomultipliers was to be in excess of $5 \times 10^6$ counts/min. The pulse widths at half amplitude were approx. 30 nsec. The requirements on the front end of the system at this speed are minimal base-line shift, fast overload recovery, and short coincidence-resolving time.

### 3.5 FLEXIBILITY

In so far as it is impossible to predict all variables in a cyclotron experiment--and preliminary results often dictate changes in the equipment--the addition or replacement of equipment must be accomplished quickly and easily. To this end, it is desirable that the equipment have self-contained power supplies, be rack mountable, and the input and output connectors be easily accessible.

### 3.6 RELIABILITY

While reliability is the last item on the list of requirements, it is probably the most important. Sometimes overlooked is the costliness of an experiment of this nature. Cyclotron time (valuated at $100/h) alone cost $16,000; engineering and shop time about $25,000; equipment depreciation and materials about $5,000; physicist's salaries and over-head about $10,000; and other expenses bring the total to at least $60,000.

Because of the limited cyclotron time scheduled, proven equipment was

used whenever possible. Where new equipment was required, stringent tests as described below, were preformed. As further insurance, all specially designed units were backed up by spare units connected in the racks. While the goal of zero down time was not achieved, most of the cyclotron time was available for receiving data.

4. Equipment

In this section the details of equipment used in the experiment will be discussed. Emphasis will be on circuit design of new equipment. However, for completeness, the present applications of standard equipment will also be mentioned.

### 4.1 PHOTOMULTIPLIERS

The E counters used RCA 7046 tubes; the $\Delta E$ counters used RCA 6810A; and the collimator counters used RCA 7264. The scintillators were plastic (terphenyl). At high count rates the dynode voltage may sag depending upon the amount of bleeder current available. To guard against this, voltage stabilizer units were connected to the dynodes. These units consist of stacked cathode followers which are capable of supplying high currents at a constant voltage.

The lower end of the dynode-bleeder string was connected to a BNC connector instead of, as usual, ground. This connector was fed from the output of the previously mentioned feedback stabilizer to compensate for overall system gain shifts. The feedback stabilizer is discussed in a later section.

For fast timing, tunnel diode (TD) discriminators[2] were used in the base of the collimator counters. Other problems prevented their use in the $\Delta E$ counters, even though, theoretically, they should provide the fastest timing.

## 4.2  FAST CIRCUITRY

The signal paths from the photomultipliers to the fast coincidence units and linear gates are standard. The delay boxes and coax cables are 125Ω; the input and outputs of the H-P 460A amplifiers have 125 to 200 Ω transformers. The OR boxes are resistive mixers consisting of three 43 Ω resistors connected in a Y. The four channel splitter consists of 2N1143 emitter followers with 4 nsec rise time. The fast coincidence unit has been described elsewhere.[3]

## 4.3  LINEAR GATES

The high count rate from the H-P amplifiers would jam the subsequent slow electronics, if it were not for the linear gates. Less than 3% of the events are in coincidence, and it is the function of the fast-coincidence unit and of the linear gates to select and transmit them. The pulses are 30 nsec wide and if we allow for some time jitter, the gates need not be more than 50 nsec wide to keep out accidental events. The main problem with a fast linear gate is that the feed-thru of the gate and signals must be reduced enough so that they are not mistaken for coincidence events. In addition, the problem of linearly stretching the pulses (for pulse height analysis) after they pass thru the linear gate must be resolved.

A linear gate developed by Barna and Marshall[4] proved satisfactory for our purposes. The circuitry employs non-saturating current switches in a series-parallel gate. The unit was modified to accomodate different transistors and supply voltages while the essential concept was retained. Final versions of this circuit are presently being worked on.

The stretching of pulses after they pass through the gate may be achieved in two ways, by diode stretching or by integration. Diode stretching is simply non-linear charging of a capacitor. The diode is in series with the

signal, and the capacitor is across the output of the diode to ground. While

this method works well with microsecond pulses, diode storage-time effects

cause non-linearities with short pulses. In addition, this method provides a

limited dynamic range: small signals are distorted by the knee of the diode.

Straight RC integration of a short pulse avoids the above problems but

has some of its own: pulse-width sensitivity and severe reduction of signal

level. To use this method one must be assured that the pulse width (FWHM)

does not vary with amplitude. (This is not always the case since rise times

will depend upon the $f_t$ of transistors which are further dependent upon collector

current). Furthermore, integrating x μsec pulses to y μsec causes an

approximate y/x reduction in amplitude. With small pulses this may cause

loss of resolution as a result of the noise in the subsequent high-gain amplifiers.

Perhaps the severest limitation on the integration method is that if the

gate is not open long enough, some of the charge from the tail of the pulse

will not appear on the integrating capacitor. If the gate is open too long, any

undershoot on the pulse subtracts from the net charge on the integrating capac-

itor; additionally, accidentals are increased.

We used the integration method of stretching, despite its pitfalls, because

the pulse shape and timing of the gate were variables that could be controlled.

Storage-time effects of even the fastest diodes presented more of a problem.

### 4.4 AMPLIFIERS

The outputs of the linear gates are RC integrated and

amplified in units called integrator-amplifiers. The signals then pass into

adders and splitters. All these units employ the basic circuit shown in Fig. 2.

This circuit allows for easy design of input impedance, bias stability,

gain, and provides positive and negative outputs. The circuit has previously

been dealt with in the literature[5]).  The low frequency and biasing design may

be simplified when it is recognized as a familiar operational amplifier shown

in fig. 3.  The gain of the operational amplifiers is:

$$\frac{e_1}{e_{in}} = \frac{-R_{fb}}{R_{in}} \tag{1}$$

Note that $R_{in}$ of fig. 3 may be recognized as being $R_1$ or $R_2$ of fig. 2.
Then if the open loop gain of fig. 2 is large, the signal gain is

$$\frac{e_1}{e_{in}} \approx \frac{-R_3}{R_1} \tag{2}$$

The dc biasing conditions are set by

$$\frac{E_1}{B_+} = \frac{-R_3}{R_2} \tag{3}$$

The base of $Q_2$ is nearly $E_1$ volts, while the base of $Q_1$ is nearly ground.
Now the currents through $R_3$ and $R_4$ may be determined.  The sum of these
currents is nearly the current through $R_6$.  All currents are now known, which
sets all voltages.

Eq. (1) gives the signal gain to the emitter.  The gain to the collector is:

$$\frac{e_2}{e_{in}} \approx \frac{R_3}{R_1} \cdot \frac{R_6}{R_4} \tag{4}$$

Two convenient ways to change the signal gain at the collector are (1) to tap off different points on $R_4$ with a capacitor to ground, and (2) to capacitively connect a potentiometer from the emitter of $Q_2$ to ground. These changes of $R_4$ in eq. (4) do not effect the dc bias conditions. Method (1) is used in the integrator-amplifiers and method (2) in the splitters and adders.

A schematic and specifications of the integrator-amplifier are shown on fig. 4. The input signal is RC integrated and passes through an emitter follower into three cascaded amplifiers. Positive and negative pulses are available from output-emitter followers.

If small signals appear at the input the gain required may introduce noise problems. In the present case, we find that the minimum input signal $E_{in}$ = 0.2 V, its width t = 30 nsec, and the integrating time constant T = 2 μsec. Then the output voltage of the integrator is

$$E_o = E_{in} \frac{t}{T} = 3 \text{ mV}. \tag{5}$$

If a 3-V output signal is required, the gain must be 1000. For 1% resolution (FWHM), the noise at the output must be less than 0.03 V/2.3 = 13 mV RMS. This condition is met in this amplifier by choice of transistors (2N502's), and by use of small currents and voltages for $Q_1$, $Q_2$, and $Q_3$.

### 4.5 SPLITTERS AND ADDERS

The schematic of the six-channel splitter is shown on fig. 5. The adder is shown on fig. 6. A fine gain control on these units compensates for any output loading.

The basic circuit of fig. 2 is particularly useful for the adder since the base of $Q_1$ is a virtual ground and the adding currents sum at that point without loading one another.

## 4.6 DEL-A-GATE AND TRANCO UNITS

The Del-a-gate[6]) is a unit which consists of a tunnel diode discriminator (0.3 to 6V, adjustable) followed by a delay and gate one shot. The Tranco is a multiple-input diode-coincidence unit followed by a one shot. Together, these two units perform the amplitude selection, timing, and coincidence function necessary to separate the desired alpha events from others that pass through the linear gates.

Additionally, as shown on the block diagram fig. 1, Del-a-gates are used for triggering the light flasher during beam-off time, and for opening the linear gates after a prescribed delay.

## 4.7 FEED-BACK STABILIZERS

High-intensity beams, such as in the cyclotron, cause photomultiplier gain shifts which are unrelated to dynode voltages. This effect has been attributed to cesium migration "dynode fatigue," and other causes. Usually local feedback, as in amplifiers, keeps the gain constant in what may be thought of as an open-loop system from the detectors to the analyzer. However, the need still exists for a closed-loop from the photocathode of the photomultiplier to the analyzer (and preferably into the storage system of the analyzer). The present feed-back stabilizer performed this function.[7])

The stabilizer unit employs a single-channel analyzer (SCA) whose base line is shifted from one level to another at a 60-cycle rate. In effect, this is the same as having two SCA's set at the two levels, except, in this case, drift will be the same for both windows. The two windows overlap each other by a fraction of a volt and a stable, high-resolution pulse is set in the overlap region. The pulse is generated by a gaseous-discharge light flasher fixed to the scintillator of the photomultipler. As long as the light-flasher pulse remains

in the overlap region, each SCA produces output pulses opposite in polarity. These are fed into an operational amplifier which integrates them. The output of the amplifier, normally zero volts, is connected to the bottom of the bleeder string of the photomultiplier as discussed before.

However, if the light-flasher pulse drifts out of the overlap region, one or another of the SCA's cease giving an output, the amplifier receives only one polarity pulse, and dc level of its output shifts. This shift is in a direction to change the photomultiplier gain so the light-flasher pulse reappears in the overlap region.

The light flasher has a stability greater than 1% for 24 h and resolution less than 0.5%.[8])

## 4.8 OTHER EQUIPMENT

The scaler-gater is a standard Lawrence Radiation Laboratory (LRL) delay and gate unit for msec pulses. The ADC's are vacuum-tube units requiring up to 100 V input. Hence four linear amplifiers came after the splitters for this purpose. The scalers are standard LRL 5-Mc decades.

A report on the four-dimensional analyzer is presently not available. It is not strictly a four-dimensional analyzer in so far as two of the inputs have only 15 channels available (LRL ECHO ADC), while the other two have 100 channels (PENCO ADC).

## 5. Tests for Reliability

All of the newly designed equipment was subjected to various tests during the bread-board stages as well as after prototype completion. These units included the linear gates, integrator-amplifiers, adders, splitters and Del-a-gates. No failure occurred in any of the equipment subjected to these tests during a 3 month operating period.

The tests were:

(a) Marginal voltage tests: all positive and negative supplies varied independently and simultaneously over a ±15% range. All units continued to function (though not necessarily with original specification).

(b) Heat test: units were subjected to 3 cycles of temperature rise to $65^{\circ}$C and continued to function at this temperature (though not necessarily with original specification).

(c) Triggering levels: all circuits were checked to have at least a safety factor of two in triggering level.

(d) Marginal allowance: substitution of transistors with different $f_t$, power ratings and $\beta$'s to find the marginal allowance in these characteristics.

## 6. Acknowledgment

The instrumentation was developed for Dr. Luisa F. Hansen, Dr. Terence J. Gooding, and Dr. George Igo. I would like to thank them for their cooperation and assistance in all phases of this work.

Thanks are also due to Elwood C. Douglas for his modification of the two-dimensional analyzer to four-dimensions, and for his other assistance with the electronics.

## References

[1] Terence J. Gooding, Luisa F. Hansen, and George Igo, Lawrence Radiation Laboratory, Berkeley, California (private communication).

[2] A. E. Bjerke, Q. A. Kerns, and T. A. Nunamaker, Pulse Shaping and Standardizing of Photomultiplier Signals for Optimum Timing Information Using Tunnel Diodes, Lawrence Radiation Laboratory UCRL-9838, (August 30, 1961) (unpublished).

[3] S. C. Baker, H. G. Jackson, and D. A. Mack, Transistor Counting Systems for Scintillation Detectors, IRE Trans. on Nuclear Science, NS-7, No. 2-3, (June-Sept. 1960) 89.

[4] Arpad Barna and J. Howard Marshall, A 50 Nanosecond Linear Gate Using Transistors, Calif. Inst. of Tech., CTSL-18 (February 1961).

[5] Chaplin, Candy, and Cole, Transistor Stages for Wide-Band Amplifiers, Proc. Inst. Elec. Engrs. (London), No. 2892 E (May 1959).

[6] Melvin Brown, UCRL Counting Handbook, Lawrence Radiation Laboratory, UCRL-3307, No. CC10-5, (June 20, 1962).

[7] No published report is available on the stabilizer. The basic principles, however, have been discussed by H. deWaard, Stabilizing Scintillation Spectrometers with Counting Rate Difference Feedback, Nucleonics 13, No. 7, (July, 1955) 36. A more recent addition to the subject is J. A. Ladd and J. M. Kennedy, A Digital Spectrum Stabilizer for Pulse Analyzing Systems, Atomic Energy Commission of Canada, Chalk River, Report CREL-1063, (December, 1961).

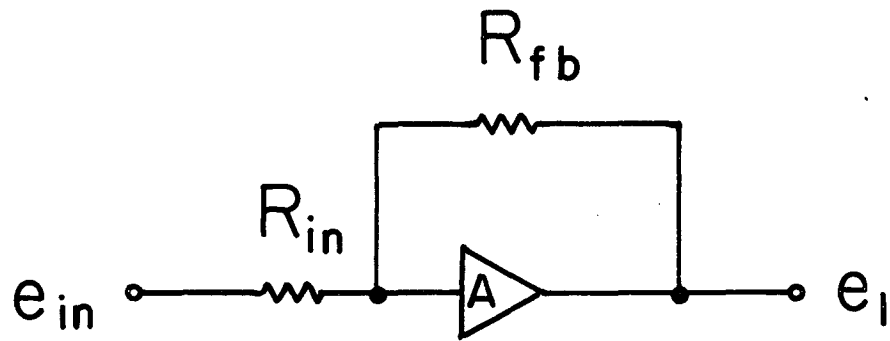[8] Quentin A. Kerns and Robert Tusting, Lawrence Radiation Laboratory (private communication).

FIGURE LEGENDS

Fig. 1.  Block diagram of experiment.

Fig. 2.  Basic circuit of amplifier.

Fig. 3.  Operational amplifier schematic.

Fig. 4.  Schematic of integrator amplifier.

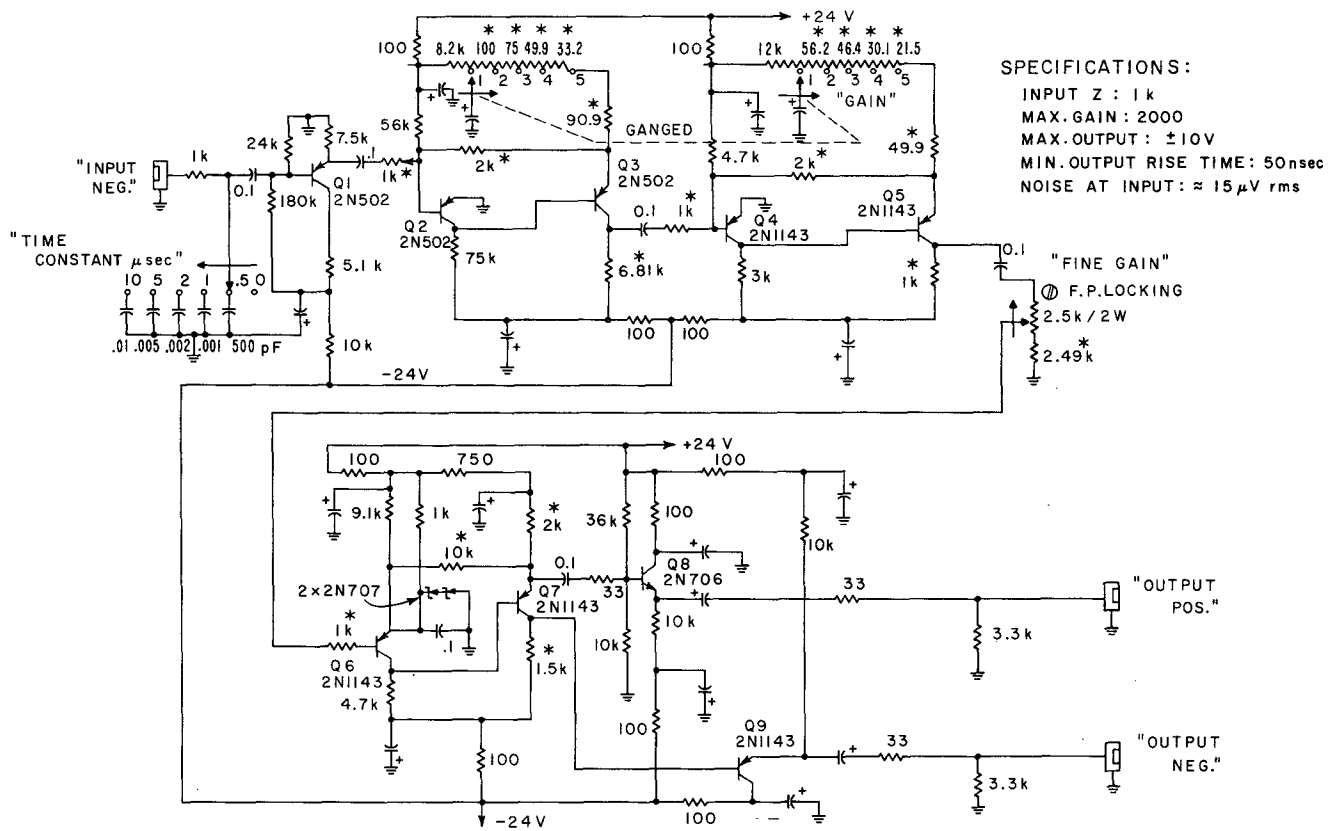Fig. 5.  Schematic of six-channel splitter.

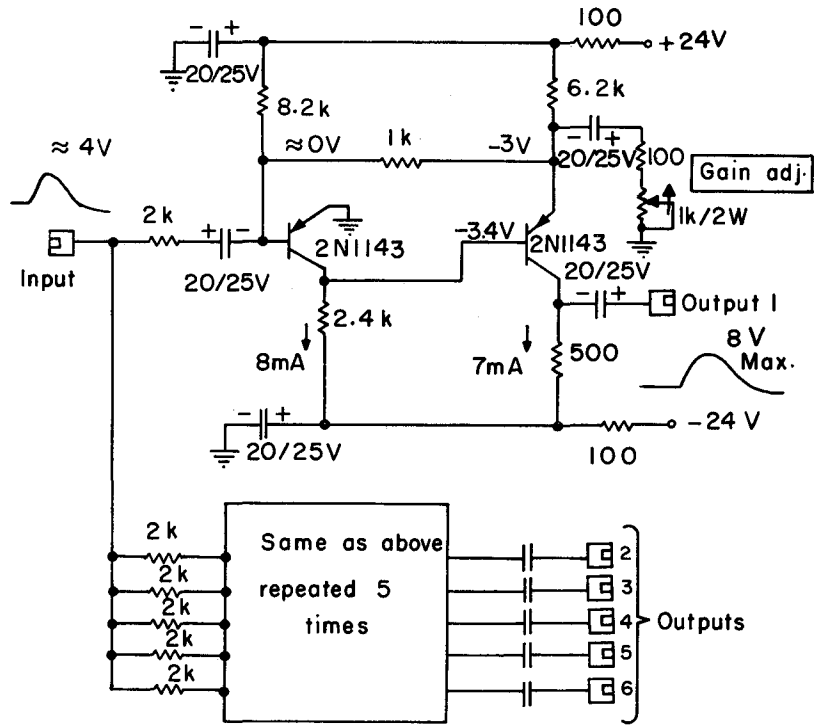Fig. 6.  Schematic of adder.
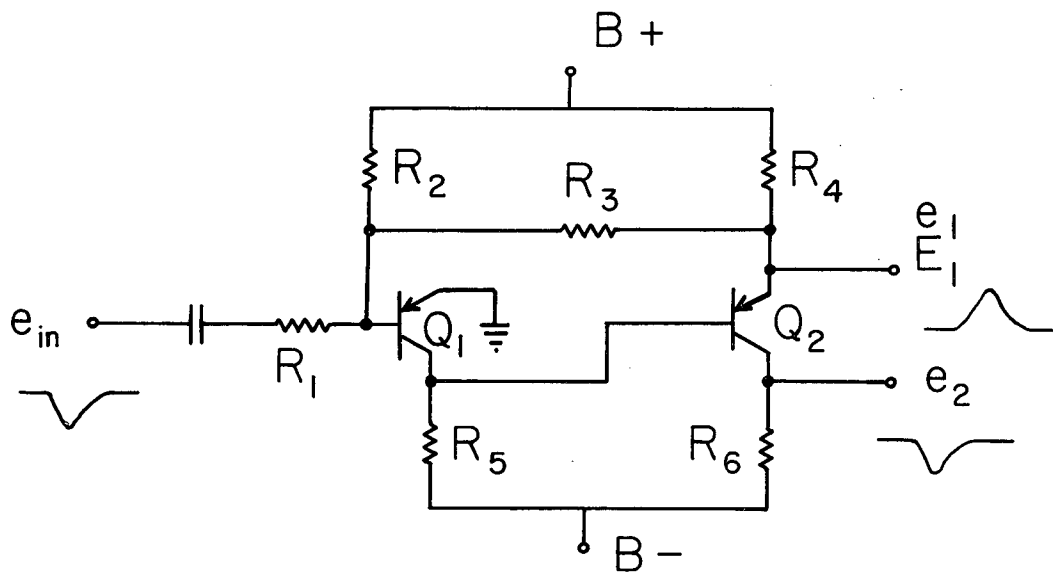
Fig. 1
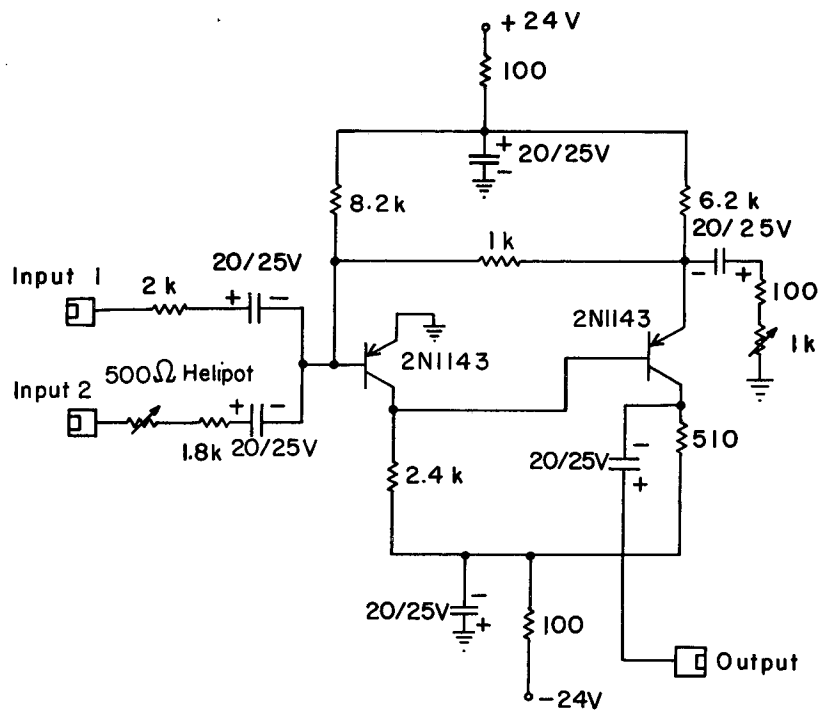
MUB-1351

Fig. 2

MU-28195

MU-28196

Fig. 3

Fig. 4

Output: 8V linear, positive
Input : positive
Gain adjust: 0.5 to 2.5

MU-28194

Fig. 5

MU-28197

Fig. 6