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USE OF A HIGH REPETITION RATE NEUTRON GENERATOR FOR IN VIVO BODY COMPOSITION MEASUREMENTS VIA NEUTRON INELASTIC SCATTERING*

J.J. KEHAYIAS, K.J. ELLIS and S.H. COHN
Medical Research Center, Brookhaven National Laboratory, Upton, New York 11973, USA

J.H. WEINLEIN, Sandia National Laboratories, Albuquerque, New Mexico 87185, USA

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Abstract

A small D-T neutron generator with a high pulse rate is used for the in vivo measurement of body carbon, oxygen and hydrogen. The core of the neutron generator is a 13 cm-long Zetatron tube pulsed at a rate of 10 kHz delivering 10^3-10^4 neutrons per pulse. A target-current feedback system regulates the source of the accelerator to assure constant neutron output. Carbon is measured by detecting the 4.44 MeV γ-rays from inelastic scattering. The short half-life of the 4.44 MeV state of carbon requires detection of the γ-rays during the 10 μs neutron pulse. Generators with low pulsing rate were found inappropriate for carbon measurements because of their low duty-cycle (high neutron output during the pulse). In vivo measurements were performed with normal volunteers using a scanning bed facility for a dose less than 25 mrem. This technique offers medical as well as general bulk analysis applications.

1. Introduction

The in vivo measurement of the body's major elements is essential for a variety of medical studies requiring the determination of the body's compartments (protein, water, fat, bone). Total body protein is being determined at Brookhaven National Laboratory using in vivo nitrogen measurements, based on a prompt γ neutron activation analysis technique (1). Total body calcium (used to determine the bone mineral mass) and total body chloride (a measure of extracellular water) are measured by delayed neutron activation analysis (2,3). The natural activity of body potassium is measured by whole body counting and serves as an index of body cell mass (4). Total body water is evaluated by a tritium dilution technique (5). There is no direct method available, however, for the in vivo measurement of body fat, the principal energy store of the body. Total body carbon measurements can provide a direct evaluation of body fat (and energy store) both in normal subjects and in patients.

Carbon can be measured in vivo through the reaction $^{12}C(n,n')^{12}C^*$ by detecting the 4.44 MeV γ-rays from inelastic scattering of fast neutrons by the body's carbon nuclei. The reaction has an energy threshold of 4.8 MeV and therefore cannot be performed with the use of neutron sources. Kyere et al. (6) have investigated the use of a D-T neutron generator as a source of fast neutrons for the measurement of body carbon. We present here a facility for carbon measurements without the use of a major accelerator. The same facility can be used for the measurement of other major body elements (K,O,N,H) and thus for the evaluation of the body's compartments.

2. Experimental apparatus and technique

2.1 The high repetition-rate neutron generator

A 10 KHz repetition rate D-T neutron generator system was developed at Sandia National Laboratories. This generator delivers 10^3-10^4 neutrons per pulse. The core of the system is a Zetatron neutron tube (7,8), a cross section of which is shown on figure 1. The Zetatron tube consists of an ion source, an ion accelerator and a metal target which is loaded with deuterium and tritium. A mixture of deuterium and tritium ions (D/T) is accelerated between 25 and 60 KeV into the target. The resulting fusion reaction produces fast neutrons which have an energy of 14 MeV.

Figure 2 shows a schematic representation of the neutron tube and the control circuits for the present 10 kHz application. The reservoir drive circuit supplies a controlled dc current (3-5 A) to the heater in the D/T loaded reservoir. The current heats the small cylindrical reservoir which contains a metal hydride powder, releasing a 50/50 mixture of D/T gas. To ionize the gas, a 2.5 kV, 1 μs pulse is applied to the ion source ring by the source drive circuit. A glow discharge is produced and an external permanent magnet causes a penning discharge which in turn produces ions. Simultaneously with the 2.5 kV pulse applied to the ion source ring, a trigger pulse is generated to synchronize the detector instrumentation. A negative dc high-voltage (HV) accelerating potential of -30 to -60 kV is applied to the target and an ion beam current (I_t) is produced as the ions are accelerated to the target. By monitoring the average I_t and feeding

it back to the reservoir drive circuit, the amount of gas pressure in the neutron tube during operation can be controlled.

2.2 Operation

The neutron generator is operated at a repetition rate of 10 kHz. More than 90% of the neutrons are emitted during a time period of 10 μs starting about 3 μs after the trigger pulse. This is demonstrated by the measurements presented in figure 3. A NaI detector was used to monitor the 846 KeV gamma rays resulting from the inelastic reaction $^{56}Fe(n,n')^{56}Fe^*$. The detector was gated to collect data for a 2 μs time period. A delay D between the trigger pulse and the beginning of the gate was adjusted for each measurement. Because of the short halflife of the 846 KeV state of $^{56}Fe^*$, the measurement of these gamma rays serves as a good monitor of the fast neutron flux.

2.3 The gamma ray detection system.

The short half-life of the 4.44 MeV state of carbon requires detection of the gamma rays simultaneously with the 10 μs neutron pulse. The detection system is shown in figure 4. A fast ADC (Nuclear Data 582) is used for the during-neutron-burst counting; it has 1.5 μs fixed conversion time. A second ADC (Nuclear Data 575) is used for between-pulse counting. A 15.2 x 15.2 cm cylindrical NaI(Tl) detector shielded with lead and boron is used. The signal from the photomultiplier is amplified without the use of preamplifier to minimize pile-up. The neutron generator pulsing circuit provides an external trigger pulse at the beginning of each neutron burst which is

used to generate two gates: one of 12 μs for the fast ADC for pulse height analysis of the inelastic events and a second one of 90 μs for the second ADC which monitors the delayed activation analysis mainly due to reactions induced by thermal neutrons. For the data acquisition, a buffer-based, micro-multichannel analyzer is used, designed for maximum data throughput.

3. Results and discussion

Preliminary measurements have been performed with anthropomorphic phantoms and normal volunteers using a scanning bed, for a dose less than 25 mrem. Figure 5 shows the gamma ray spectrum from a normal volunteer acquired during the neutron burst (inelastic scattering interval). There are several elements which can be quantified by neutron inelastic scattering. There is small variation of inelastic cross sections, for the first excited states, throughout the periodic table (typically 400-800 mb). Detection of the gamma rays must be performed simultaneously with the neutron burst because, in most cases, the excited nucleus will decay to the ground state within a picosecond. Although these measurements are feasible with a fast data acquisition system, the intensity of the neutron flux at the detector area remains the limiting factor. The high repetition-rate neutron generator makes possible elemental analysis of bulk materials by inelastic neutron scattering reactions. In a large target such as the human body, neutron thermalization provides enough thermal neutron flux for the detection of bulk elements by counting between neutron bursts. For our medical applications, we take advantage of this feature for the in vivo quantification of body hydrogen.

REFERENCES

1. Vartsky D, Ellis KJ, Cohn SH. J Nucl Med 20:1158 (1979)

2. Cohn SH, Ellis KJ, Wallach S. Amer J Med 57:683-686 (1974)

3. Ellis KJ, Vaswani AN, Zanzi I, Cohn SH Metabolism 25:645-654 (1976).

4. Cohn SH, Dombrowski CS. J Nucl Med 11:239 (1970)

5. Vaugh BE, Boling EA. J Lab Clin Med 57:159 (1961)

6. Kyere K, Oldroyd B, Oxby CB, Burkinshaw L, Ellis RE, Hill GL. Phys Med Biol 27:805 (1982)

7. The Zetatron tube was assembled by the General Electric Neutron Devices Department, an integrated contractor for the Department of Energy.

8. Shope LA, Berg RS, O'Neal ML, Barnaby BE. IEEE Trans. Nucl. Sci. NS-28 (1981) 1696.

Figure Captions

Fig. 1 Cross section of the Zetatron tube.

Fig. 2 Schematic diagram of the neutron tube with the supporting circuits.

Fig. 3 Number of 847 KeV inelastic scattering gamma rays of Fe collected during a 2 μs long gate plotted vs delay D from the beginning of the trigger pulse (see text).

Fig. 4 Electronics block diagram. ADC 1 is used for during-pulse counting; it has a fixed 1.5 μs conversion time. ADC 2 is used for between-pulses counting. A buffer-based micro-multichannel analyzer is used for maximum data throughput.

Fig. 5 Gamma ray spectrum from a normal volunteer acquired with ADC 1.

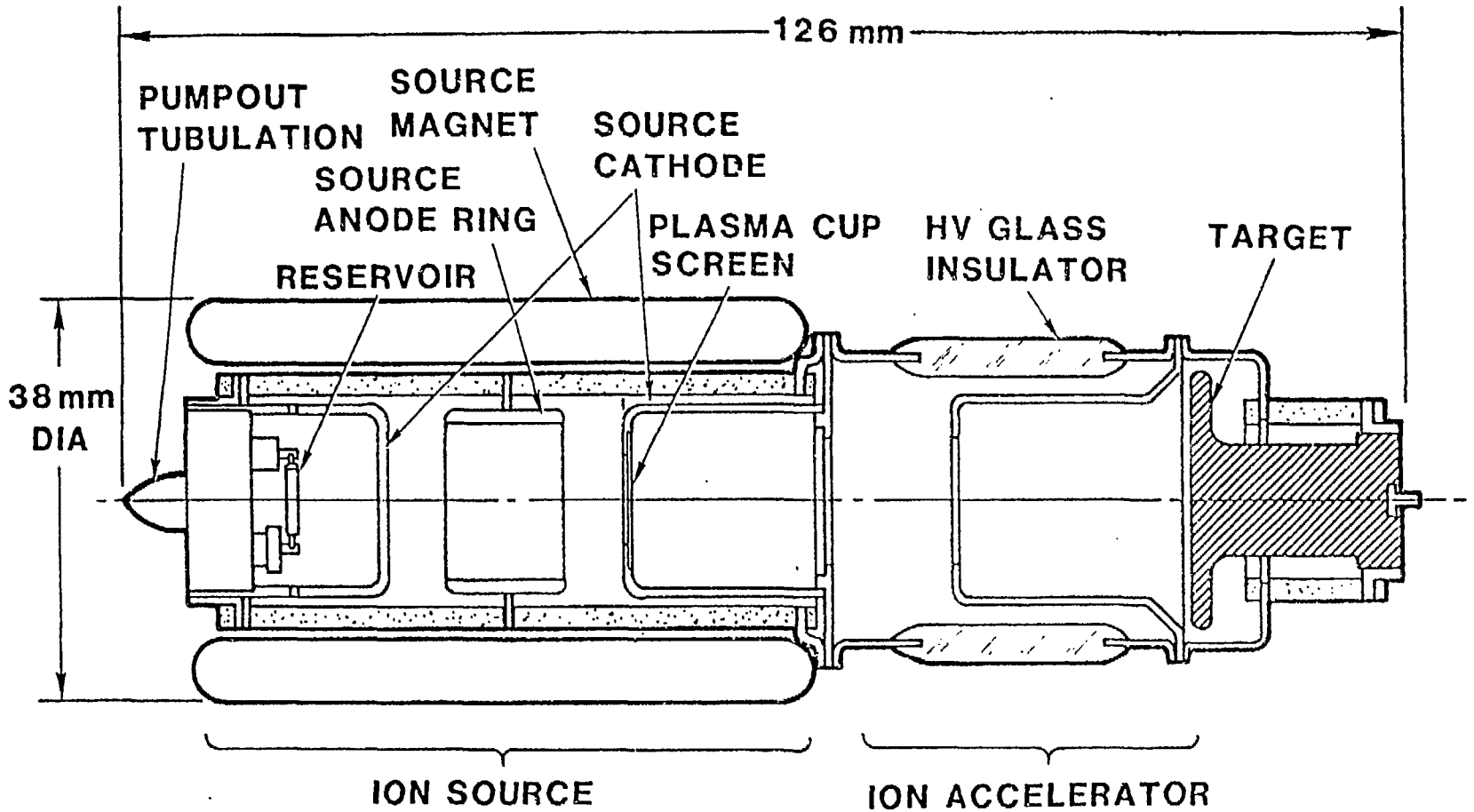

FIG. 1

ZETATRON

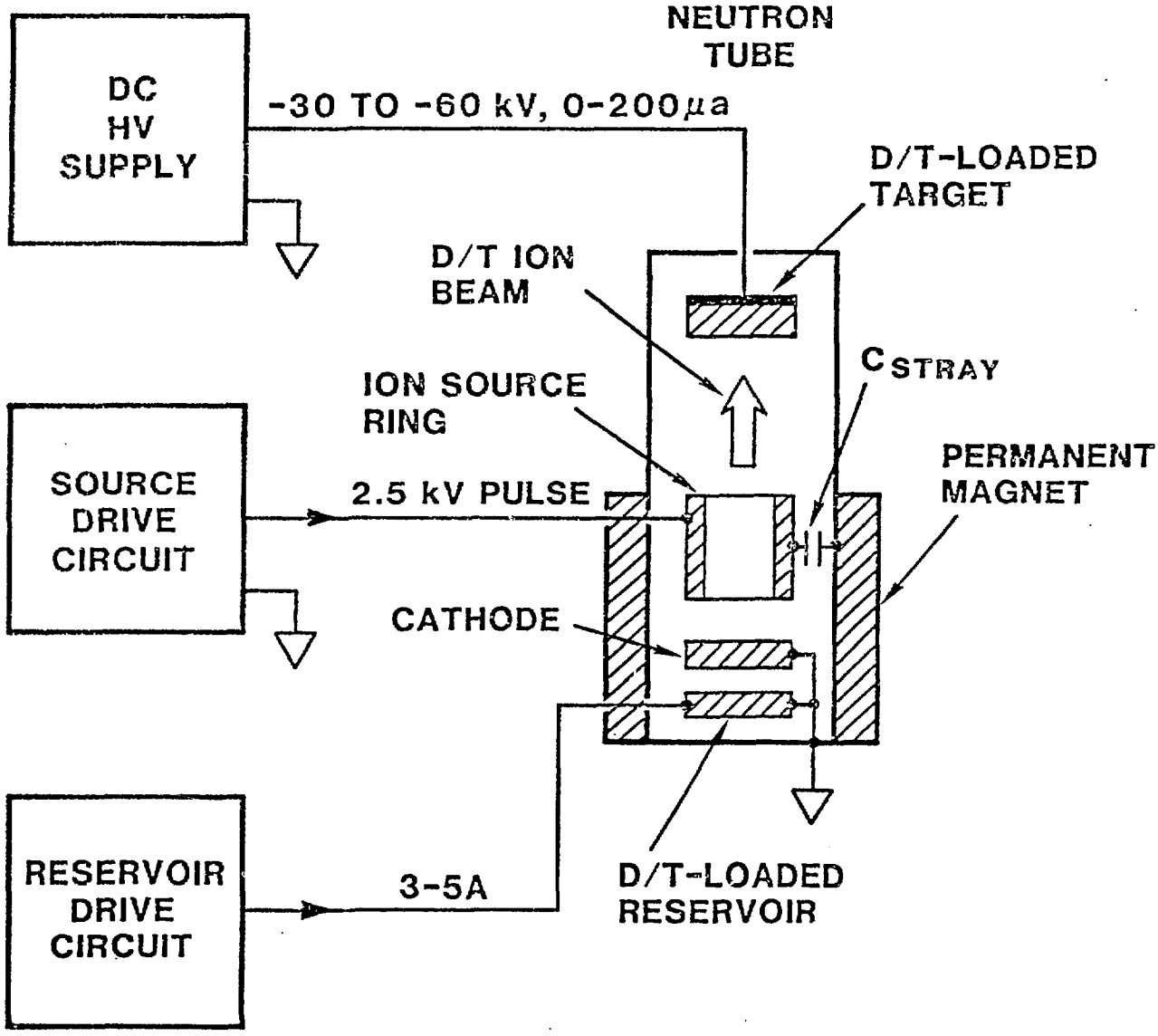
NEUTRON
TUBE
DC
HV
SUPPLY
-30 TO -60 kV, 0-200μa
D/T-LOADED
TARGET
D/T ION
BEAM
C STRAY
ION SOURCE
RING
PERMANENT
MAGNET
SOURCE
DRIVE
CIRCUIT
2.5 kV PULSE
CATHODE
RESERVOIR
DRIVE
CIRCUIT
3-5A
D/T-LOADED
RESERVOIR

FIG. 2

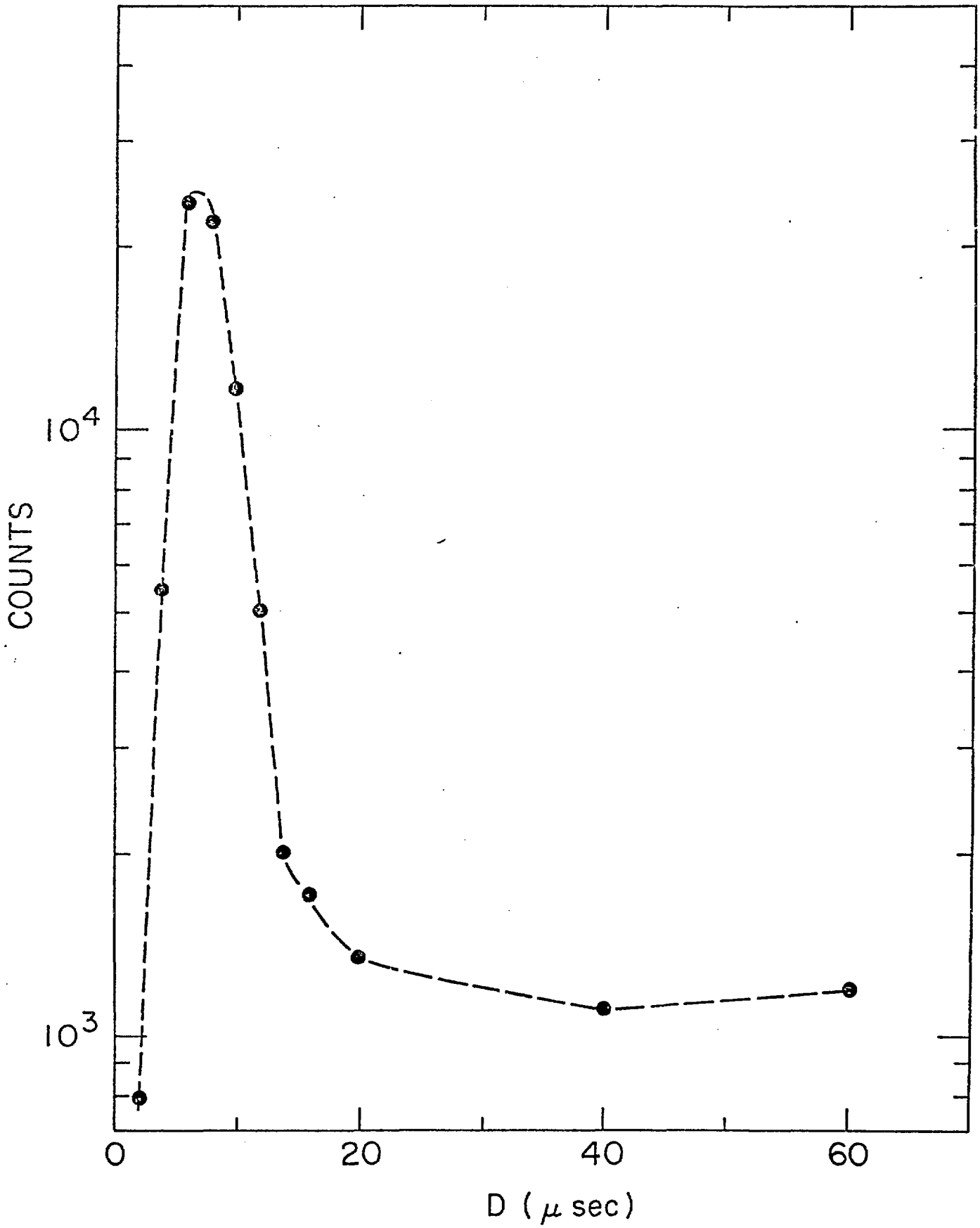

FIG. 3

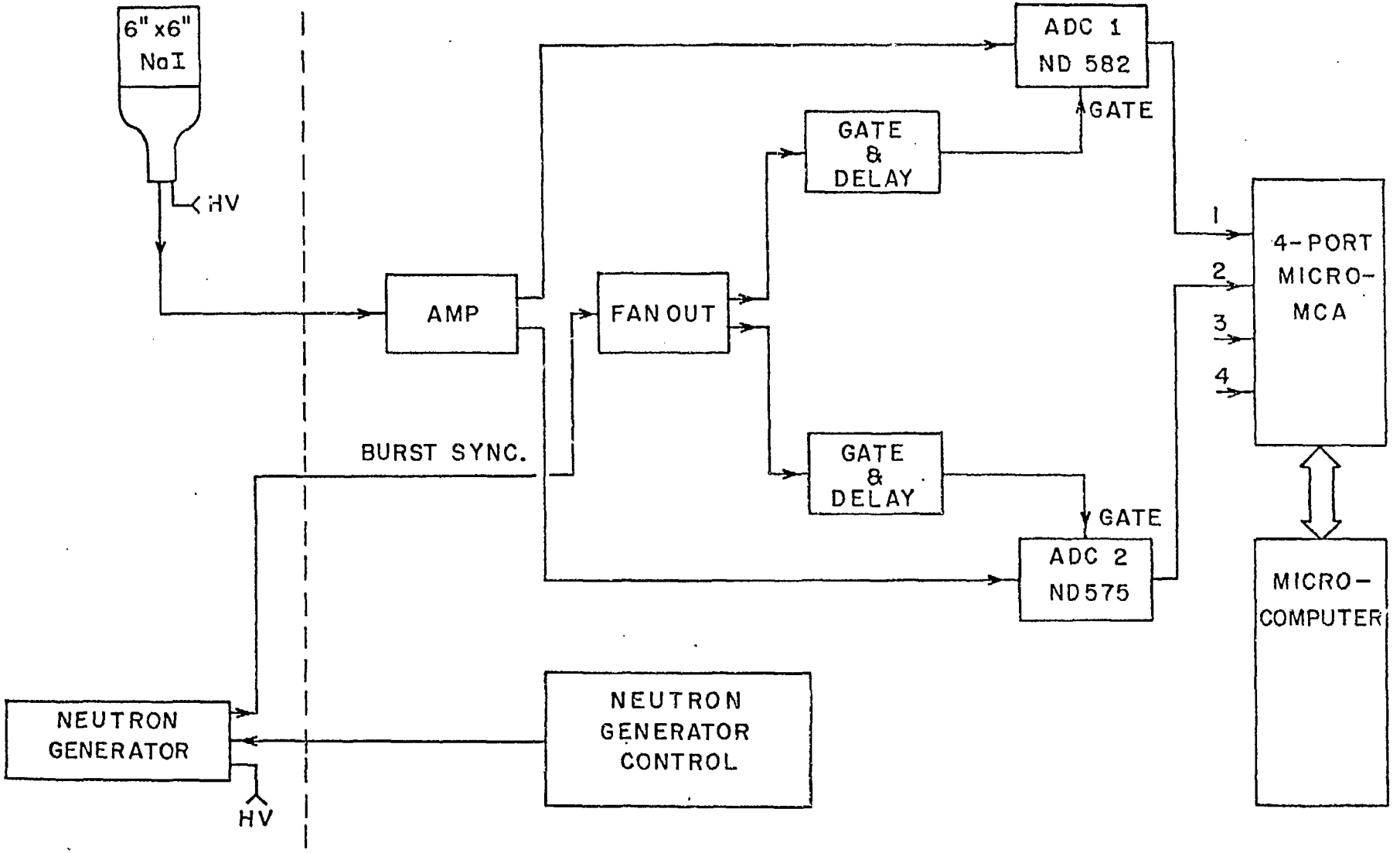
6" x6"
NaI
HV
AMP
FAN OUT
ADC 1
ND 582
GATE
GATE
&
DELAY
GATE
&
DELAY
GATE
ADC 2
ND575
1
2
3
4
4-PORT
MICRO-
MCA
MICRO-
COMPUTER
BURST SYNC.
NEUTRON
GENERATOR
HV
NEUTRON
GENERATOR
CONTROL

FIG. 4

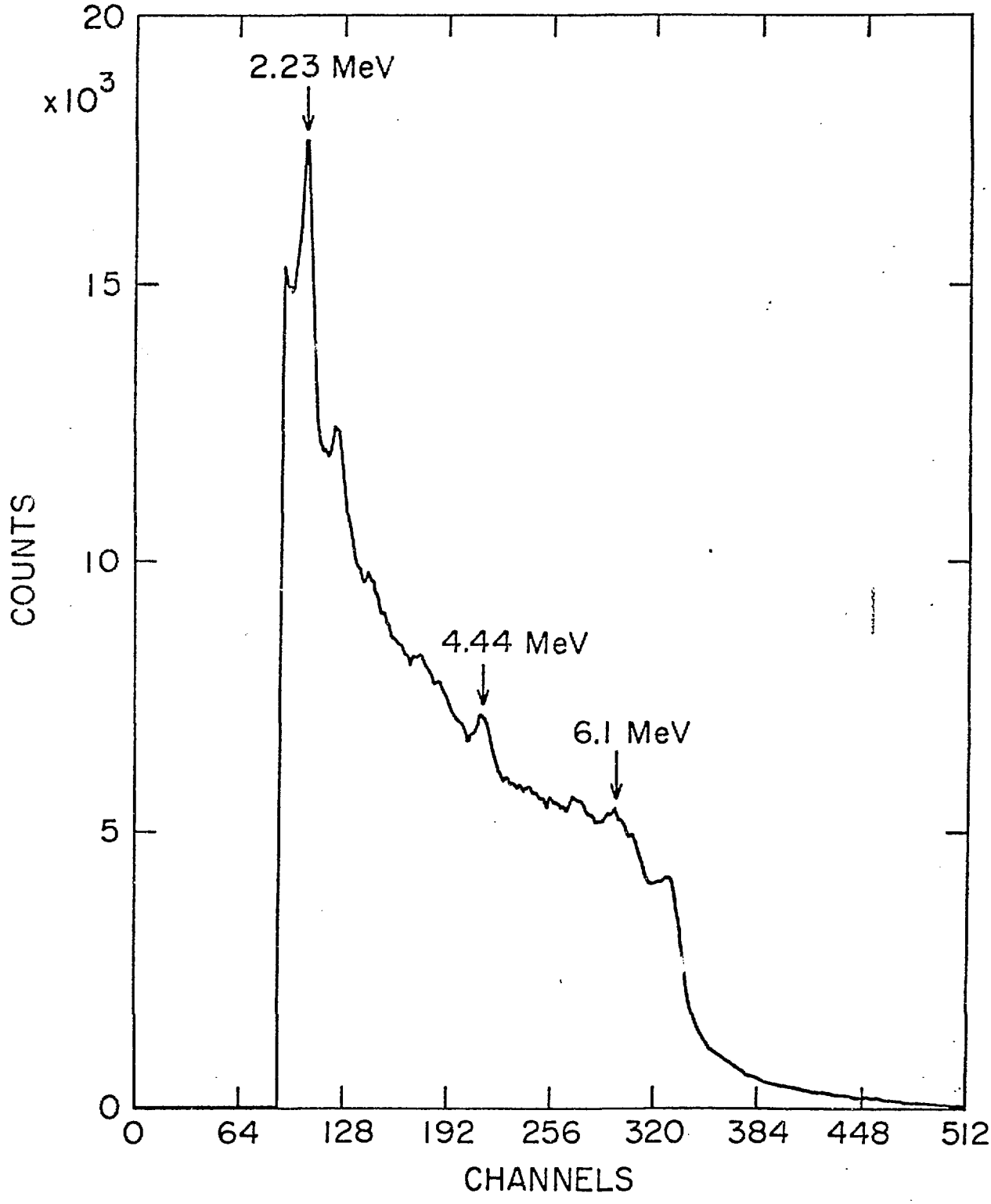
20
x10^3
15
10
5
0
COUNTS
2.23 MeV
4.44 MeV
6.1 MeV
0
64
128
192
256
320
384
448
512
CHANNELS

FIG. 5