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PRELIMINARY DOSE MEASUREMENTS ON THE NEUTRON GENERATOR

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USAF School of Aerospace Medicine
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FOREWORD

This report was prepared by the following personnel of the Bionucleonics Department:

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ABSTRACT

Neutron fluxes are produced by the neutron generator at the USAF School of Aerospace Medicine, using the $d(d,n)He^3$ and $T(d,n)He^4$ reactions. An experimental procedure for determining the flux produced by the $d(d,n)He^3$ reaction is presented.

This technical documentary report has been reviewed and is approved.

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PRELIMINARY DOSE MEASUREMENTS ON THE NEUTRON GENERATOR

1. INTRODUCTION

A 150,000 v. Cockcroft-Walton accelerator (neutron generator) is being used in radiation research at the USAF School of Aerospace Medicine. Before such a device could be used for this research, however, the radiation field produced had to be experimentally determined. This paper reports the method used to measure the neutron flux produced by the accelerator and the results of this measurement.

There are only two nuclear reactions which can be used in the production of large neutron fluxes using a 150,000 v. accelerator. They are the $d(d,n)He^3$ and $T(d,n)He^4$ reactions. In less abbreviated form they are written:

$$d + d \rightarrow n + He^3 + 3.26 \text{ Mev} \quad \text{(I)}$$

$$d + T \rightarrow n + He^4 + 17.6 \text{ Mev} \quad \text{(II)}$$

Deuterons are the accelerated particles in both of these reactions. In reaction I, deuterons bombard deuterium target atoms, and in reaction II tritium is bombarded. Reaction I produces neutrons in the energy range 2 Mev to 3 Mev for an incident deuteron energy of 150 kev while in reaction II the neutron energy ranges from 13.5 Mev to 15 Mev.

2. TARGETS FOR NEUTRON PRODUCTION

The isotopes deuterium and tritium are normally gaseous and it is difficult to use targets of these isotopes in the gaseous state. A gas must be contained by thin foils to prevent it from leaking into the vacuum system of the accelerator. These foils, however, are still too thick to allow the penetration of a 150 kev incident deuteron without a large fraction of its energy being lost. Further, thin foils cannot withstand large amounts of beam current (which is desirable for high neutron fluxes) without rupturing. To eliminate this difficulty, the gas is normally absorbed into the front surface of a metal foil. Here the trapped atoms form a target for the incident deuterons. These targets may be water-cooled to prevent heating under bombardment. In this laboratory the targets containing tritium are purchased. Tritium is a beta emitter with a half life of 12.3 years. The tritium content of these targets is 1 curie/sq. in. or approximately 0.4 cc. at STP. Deuterium targets are produced in this laboratory by the beam-loading method (1). In this type of target some of the accelerated deuterons are absorbed in a pure metal, forming a deuterium target as a result of the deuteron bombardment. Nickel foils 0.020 in. thick are used. The concentration of deuterium can be inferred from the neutron yield of the reaction. The yield of a deuterium target formed in a nickel foil is approximately equal to that of commercially available titanium-deuterium or zirconium-deuterium targets.

Because of the importance of the $d(d,n)He^3$ and $T(d,n)He^4$ reactions in the production of monoenergetic, high-intensity neutron fluxes, the energetics, angular distributions, and total cross sections of these reactions have been determined experimentally (2, 3, 4). In the original experiments on reaction I, it was discovered that there was a companion reaction which occurred with a slightly greater frequency than I. The reaction is:

$$d + d \rightarrow T + p + 4.02 \text{ Mev} \quad \text{(III)}$$

or in abbreviated notation $d(d,p)T$. The characteristics of this reaction have also been experimentally determined (2-5).

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3. DETECTION PRINCIPLES

The neutron is an uncharged particle and hence its interaction with matter (i.e., its ability to ionize) is weak. Since only charges can be detected and counted, the detection of a neutron by virtue of its ionization is impracticable. Neutrons, however, produce secondary nuclear reactions which can be detected, since charged particles are normally produced in these reactions. If the cross section (probability of reaction) of a particular neutron-induced reaction is known and if the total number of reactions is counted, then the total number of neutrons and the neutron flux can be determined. This, however, is not the most accurate method of neutron flux measurement since the cross sections are not as accurately known for neutron-induced reactions as they are for charged particle reactions (e.g., reactions I, II, and III). Also, the cross sections are strongly energy dependent, and because of the experimental geometry, the neutron flux is not entirely monoenergetic. If, on the other hand, one can detect the associated charged particle produced in reactions I, II, and III then the neutron flux can be more accurately measured since the detection of a charged particle indicates production of a related number of neutrons. Corrections must be made to the count of charged particles since reactions I and III are not isotropic and detection of a charged particle at one angle may mean that two neutrons have been produced at another angle. This requires knowledge of the angular distributions of the reactions as a function of energy. In the procedure described in this paper, the charged particles detected and counted are the He^4 in reaction II and the proton reaction III.

4. TARGET AND DETECTOR HOLDER

None of the charged particles produced in reactions I, II, and III have enough energy to penetrate the walls of the accelerator tube. Hence, in order to detect these charged particles, a detector must be placed in the vacuum system. With this prerequisite, a new target section (fig. 1) was designed to replace the target section originally on the accelerator. It consisted of a flange, two Pyrex cylinders which acted as insulators, an electron-suppressing electrode which was placed between the cylinders, and a target and detector holder. These components were bonded together with Scotchcast 8 epoxy resin. The target and detector holder consisted of three copper cylinders each 6 in. long, silver-soldered together as shown in figure 1. The target was fastened to the rear of the 2 in. diameter central section by means of a hollowed backing plate through which cooling water could be circulated directly against the back of the target foil. Two symmetrically placed 1 in. diameter cylinders were hard-soldered to the central cylinder at an angle of 150 degrees. One cylinder provided an unobstructed path to a charged particle detector while the other was sealed with a Plexiglas flange so that the target could be observed during bombardment. Between the detector and target section was placed a 1½ in. nylon insulating cylinder also containing an electron suppressing ring. The detector (ORTEC surface barrier) was soldered to a metal-to-glass vacuum seal which in turn was soldered into a brass flange. All flanges were sealed by "O" rings except for the metal-to-glass seals which were accomplished with epoxy resin.

5. DETECTION SYSTEM AND MONITOR

The detector used had an active area of 7 $mm.^2$ This was subsequently reduced to approximately 3 $mm.^2$ by placing a small brass cover with a 0.080 in. diameter aperture over the surface of the detector. Because these devices are extremely photosensitive, a $^1/_{50}$ mil aluminum foil covered the 0.080 in. aperture and prevented light produced by the beam bombarding the target from hitting the detector. The detector was approximately 176 mm. from the target and subtended a solid angle of 1.01×10^{-4} steradians.

The detector was back-biased by a 90 v. dry cell and the charged particle pulses were fed from the detector into an ORTEC Model 101 charge-sensitive preamplifier, where the proton pulses were amplified to a pulse height of approximately 1.5 v. He^3 and T pulses were

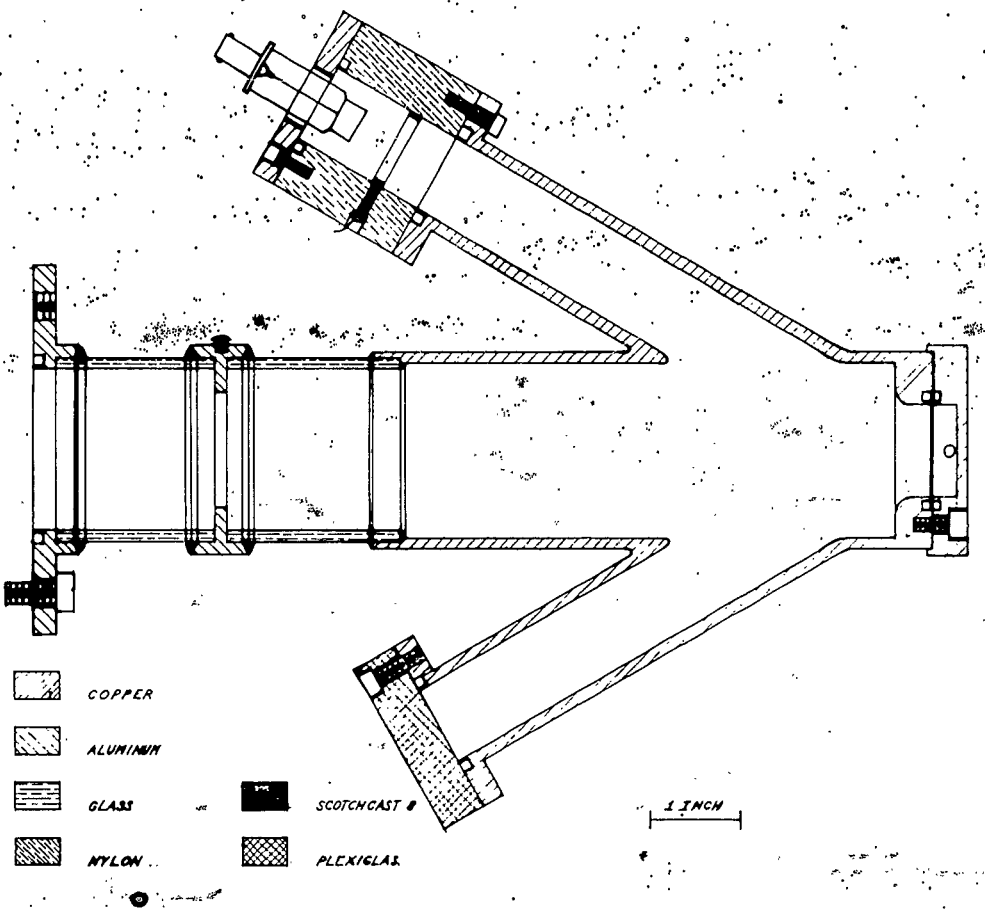

FIGURE 1

Target section.

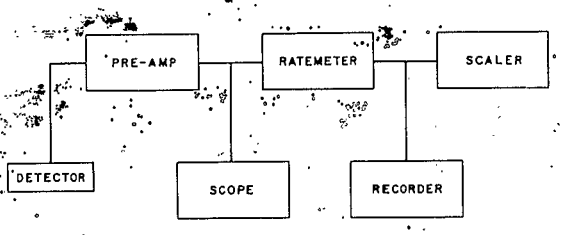

FIGURE 2

Block diagram of counting equipment.

roughly one-fourth this value. The amplifier pulses were simultaneously fed to a Tektronix Model 541 oscilloscope for visual monitoring, and to an RCL Model 20405 log-linear, count-rate meter. The Hc^3 and T pulses were adequately rejected in the count-rate meter by a low-level discriminator which was set at a level of 1.25 v. Thus, only those pulses which were greater than 1.25 v. were counted. The count-rate meter output was simultaneously fed to an RCL Model 20303 scaler where the total proton count was obtained, and to a dual-channel Brown recorder potentiometer where a record of proton count rate was made. The second channel was used to record beam current. Since the count rate is proportional to beam current, measurement of this quantity served as a useful monitor of count rate and precluded the necessity of using a second detector as a monitor. Figure 3 is a typical recorder trace showing beam current and count rate. Visual monitoring of the amplifier output

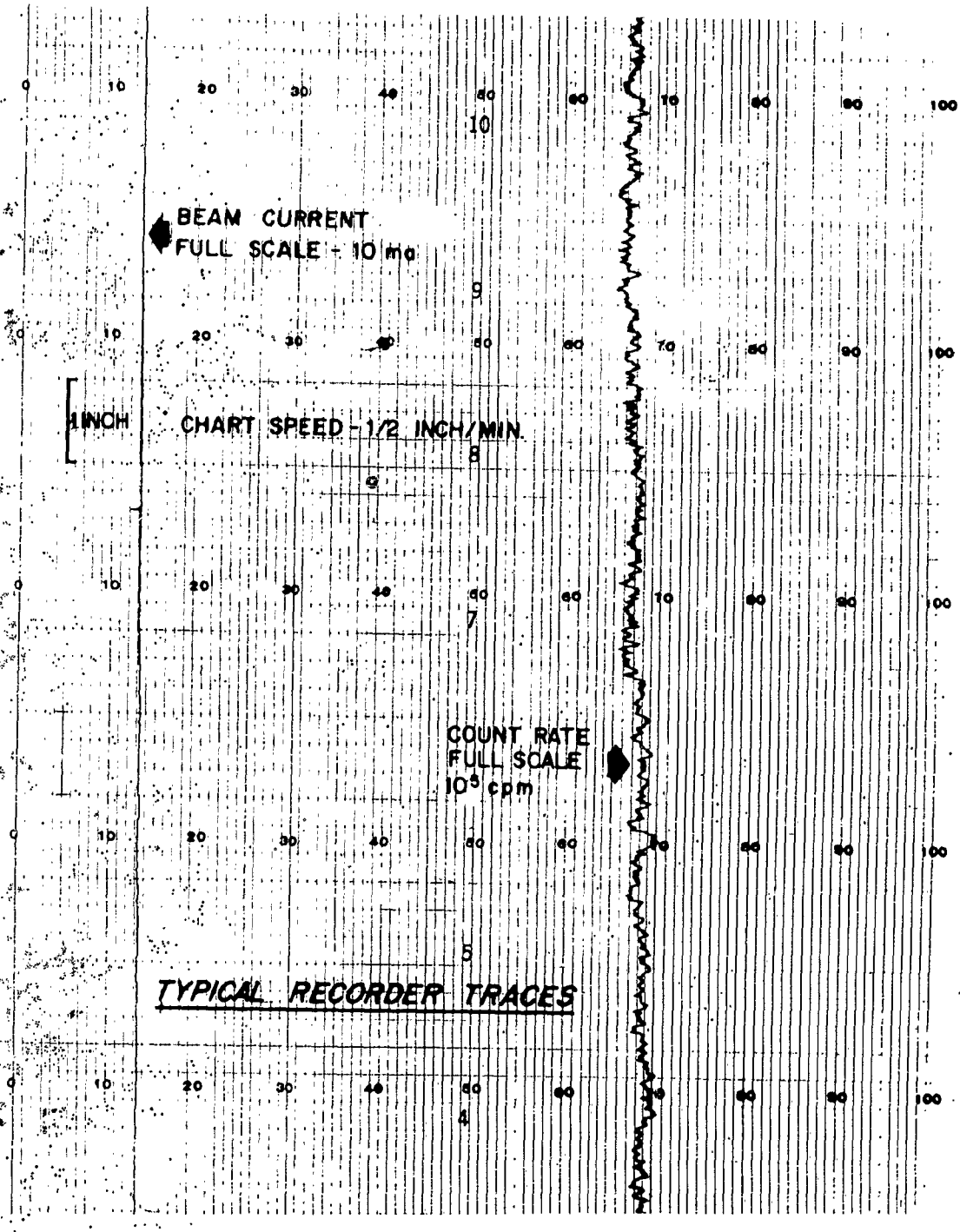

FIGURE 3

Typical recorder traces.

served as a second check of the count-rate measurement.

6. DETERMINATION OF NEUTRON FLUX FROM CHARGED PARTICLE COUNT RATE

The neutron flux from reaction II is determined by the $_2He^4$ count rate (6).

The neutron flux for reaction I is determined by counting the protons produced in its companion reaction III. Protons are detected at 150 degrees with respect to the incident deuteron direction. The effective source of protons for this detection angle $S_p(150)$ is given by

$$S_p(150) = \frac{4\pi N_p}{d\Omega} \text{ p/sec.}$$

where $d\Omega$ is the solid angle subtended by the detector and N_p is the proton count rate. If a second detector is placed at a laboratory angle θ, the effective source of neutrons will be

$$S_n(\theta) = \frac{4\pi N_n}{d\Omega\, \eta} \text{ n/sec.}$$

where $d\Omega$ is the solid angle, N_n is the neutron count rate and η is the detector efficiency.[1] $S_n(\theta)$ is related to $S_p(150)$ by an angular correlation factor which is primarily dependent on the angle of the neutron detector, the stopping power of the metal in which the deuterium is embedded, the incident deuteron energy, and the density distribution of the embedded deuterons in the metal. This factor has been calculated on the basis of known parameters assuming a uniform deuterium distribution by Seagrave et al. (7). The metals considered are titanium and zirconium and a 20% probable error is assigned to these calculations. The flux values, although expressed as two-digit numbers, also contain this error.

Since nickel is the material used in this laboratory, a correction was made which consists of equating the average factors of titanium and zirconium to the nickel factor. Since detectors are normally placed at only two angles in this laboratory—namely, 0 and 90 degrees—the factors were calculated for only these angles. The factors are:

$$F(90) = .78$$
$$F(0) = 1.74$$

Thus, $S_n(\theta) = S_p(150)F(\theta)$, and the neutron source term at these angles is determined. It then becomes a simple matter of calculating the neutron flux ϕ by means of the formula:

$$\phi = \frac{S_n(\theta)}{4\pi r^2} \text{ n/cm.}^2\text{/sec.}$$

where r is the radial distance from the sample to the target. If the detector is placed very close to the target, the $\frac{1}{r^2}$ law is no longer valid because the target can no longer be considered a point neutron source and the following formula is used:

$$\phi = \frac{S_n(\theta)\,\Omega}{4\pi A} \text{ n/cm.}^2\text{/sec.}$$

where Ω is the solid angle subtended by the detector and A is the detector area.

A rough check of this method was made by measuring the neutron flux using gold-activation analysis. A 4.84 gm. gold sample 0.020 in. thick and 1 in. in diameter was placed 1.05 cm. from the target and irradiated for 60 minutes. The 412 kev γ peak was counted for 10^5 counts and a second count of 4×10^4 was made, each using a Baird Atomic Model 810BL NaI well counter calibrated for counting γ ray photopeaks. The measured peak efficiency for a 412 kev γ ray was 0.31 ± 0.01, which is in close agreement with the efficiency of a well counter of similar size (8).

The neutron flux passing through the sample as calculated by the method described in this report was 5.0×10^6 n/cm.^{2}/sec. A flux of 5.4×10^6 n/cm.^{2}/sec. was measured by means of gold-activation analysis, in which corrections were made for a perceptible flux of low-energy, backscattered neutrons. A probable error of 25% is assigned to the latter value primarily because of poor agreement on the value of the gold (n, γ) cross section for a

[1] A detector here is taken to mean any sample which is placed in the neutron field. An example would be some type of neutron dosimeter.

2.85 Mev neutron (9). In any event, the agreement between the values of the neutron fluxes is acceptable.

7. DOSE CALCULATION

The radiation dose administered to a sample is calculated on the basis of the neutron flux using the following expression:

$$D = \phi \, Et \sum_i (q_i f_i \sigma_i) \frac{\text{Mev}}{\text{gm.}}$$

where

- ϕ is the neutron flux.
- E is the neutron energy in Mev.
- t is the time of irradiation in seconds.
- q_i is the average fraction of neutron energy lost per collision with the i^{th} atom.
- f_i is the fraction of i^{th} atoms present.
- σ_i is the neutron cross section for the i^{th} atom in $cm.^2$

8. REMARKS

A higher degree of accuracy is desirable for 2.5 Mev neutron dosimetry based on values of the neutron cross sections that are not very well known. Until better cross-section values are obtained, dosimetry will contain the uncertainty in the cross sections. It might be remarked here that in an organic medium the primary factor in dose contributions for neutrons in the Mev energy range is energy loss due to elastic collisions with hydrogen, whose cross section is very accurately known. Secondary contributions from collisions with heavier elements whose cross sections are not very well known do not add very much to the dose due to recoil protons. It is therefore desirable to know the angular correlation factors to a more accurate value since this is the main source of error in any dose calculation made in this laboratory.

In spite of its concomitant error, this method of neutron dosimetry remains a very convenient one to use for accelerator-produced neutrons because the count rate of associated charged particles produced in a nuclear reaction, which also produces neutrons, determines the neutron flux, and a given dose can be administered simply without the necessity of passive dosimeters for a later measurement of the neutron dose.

With the use of known neutron fluxes, neutron detectors and dosimeters of unknown characteristics may be precisely calibrated for use in other experimental configurations in which the neutron flux is unknown.

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