MEASUREMENTS OF NEUTRON FLUX FROM AN
INERTIAL-ELECTROSTATIC CONFINEMENT
DEVICE

Technical Report

Glen A. Westenskow

Brigham Young University
Provo, Utah.

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Glen A. Westenskow

Department of Physics and Astronomy

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ABSTRACT

A neutron-detection system has been built for the purpose of measuring the neutron flux from an Inertial-Electrostatic Confinement Device located at Brigham Young University. A BF_3 proportional counter was used for absolute flux measurements and a pair of scintillation detectors was used to compare neutron output under different operating conditions. The detectors were designed to be compatible with the operating conditions of the device and to be able to measure small changes in neutron output. The detectors were calibrated using a Pu-Be source with corrections made for laboratory conditions. Performance of the counting system was checked and data were collected on the neutron flux from the device.

COMMITTEE APPROVAL:

Andrew L. Gardner, Committee Chairman

Larry V. Knight, Committee Member

B. Kent Harrison, Department Chairman

This thesis, by Glen A. Westenskow is accepted in its present form by the Department of Physics and Astronomy of Brigham Young University as satisfying the thesis requirement for the degree of Master of Science.

Andrew L. Gardner
Andrew L. Gardner, Committee Chairman

Larry V. Knight
Larry V. Knight, Committee Member

July 31, 1975
Date

B. Kent Harrison
B. Kent Harrison, Department Chairman

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Chapter 1

INTRODUCTION

The use of radiation detectors has played an essential role in the development of reactor physics. In analyzing the operation of an Inertial-Electrostatic Confinement Device a measurement of the neutron flux from fusing deuterium ions is a valuable diagnostic tool. This thesis describes studies of this nature that were performed on such a device at Brigham Young University. In order to evaluate small changes in operating conditions of the device, a detector with high sensitivity was needed. Two scintillation detectors were constructed for this purpose. They were designed to be able to make measurements simultaneously with electron density measurements and to be able to make comparison of different operating conditions. The detectors were calibrated in order to make both absolute and relative measurements of flux from the device.

The Confinement Device

The concept of Inertial-Electrostatic Confinement was conceived nearly twenty years ago. Since that time several confinement devices of this type have been built and tested to determine their ability to confine and concentrate ions.

The confinement device (Fig. 1 and 2) studied at Brigham Young University basically consists of two concentric spherical shells and six ion guns. The outer sphere serves as an anode at ground potential

The Confinement Device (below the insulator) showing also the Voltage-viewing Resistor, the Voltage Vacuum Switch, and the Microwave Output.

Another View of the Confinement Device with its High Voltage Power Supply. Four of the six ion guns are clearly visible.

Figure 1. The Confinement Device

Figure 2. Diagram of the Confinement Device

on which the ion guns are mounted. The inner sphere is a high potential cathode. Robert L. Hirsch¹ has discussed the theory and operation of a confinement device similar to the one tested at BYU.

Two scintillation detectors were used so that all guns would be equally favored by the detecting system. They were placed so that as large a solid angle as was practical was covered. The results of the relative measurements were used by Austen Chan² for an evaluation of the device. This thesis does not include an evaluation of the confinement device itself.

Chapter 2

DETECTION AND SPECTROSCOPY OF FAST NEUTRONS BY SCINTILLATION DETECTORS

The use of scintillator counters has become popular for the detection of fast neutrons. The density of the material allows for higher detection efficiencies than that which characterizes gases. The fast response of the material to neutrons permits high counting rates and the light output is related to the energy of the incoming neutrons. The shape of the material can be chosen to allow counting over large solid angles and the material has good light-transmission properties.

Since neutrons lack charge, they are not detected directly through electromagnetic interactions but from scattering events with protons. The scintillator material contains a large number of hydrogen nuclei to which the high energy neutrons give up energy in scattering events. The energetic hydrogen nuclei then react electromagnetically, giving off a pulse of light from each interacting neutron.

For energies below 10 MeV the n-p scattering process is isotropic in the center-of-mass system.³ In such a case it can be shown that for a monoenergetic neutron beam the pulse-height spectrum (Fig. 3) ideally would consist of a flat distribution of pulses from zero energy up to the energy of the incoming beam. However, there are several factors which alter the spectrum to look more like Fig. 4. One of

Figure 3. Pulse-Height Spectrum for a Monoenergetic Beam in the Ideal Case

Figure 4. Pulse-Height Spectrum for A Monoenergetic Beam in the Real Case

the important factors is the nonlinear response of the scintillator to protons. Also many of the neutrons are moderated due to collisions with material before they reach the detector. Another consideration is the presence of carbon nuclei which also scatter the beam but with a different response. The limited size of the scintillator and the resolution of the counting system also alter the resulting spectrum. These factors limit the application of this type of detector for work in spectroscopy, however it does have a high detection efficiency for fast neutrons.

Gamma-Ray Discrimination

Unfortunately for neutron detection the scintillator material is sensitive to gamma rays as well as to neutrons. Lead shielding around the detector will have a much larger effect on stopping gamma rays from reaching the sensitive scintillator than it does on the neutrons. This is especially effective against low-energy gamma rays entering the detector. A quantitative example will be given later under a discussion of the detector.

Often, however, a means of discrimination is needed to avoid unwanted counts of gamma rays. In plastic scintillators the pulse resulting from a neutron event has a shape different from that of a gamma-ray event, the pulse being flatter for the neutron.⁴ This effect can be used to discriminate between the two events by electronic means. As will be discussed later, tests were performed which indicated that this more sophisticated method was not necessary for the present experiment.

Background-Rate Considerations

Even without a deliberate source there will be light pulses in the scintillator material due to cosmic rays and radioactive material in the environment. This background pulse rate is affected by the laboratory conditions so it needs to be measured under conditions that are similar to those of the experiment. A high background rate in comparison to the sample rate will limit the sensitivity of the measurement. Shielding the detector and limiting its size will reduce the number of counts from the sample. The size and shape of the detector should be chosen to optimize the signal-to-noise ratio.

Chapter 3

THE SCINTILLATION DETECTORS

Two identical scintillation detectors (Figs. 5 and 6) were built for simultaneous use in the experiment. To make the desired measurements the detector system needed to have good sensitivity to neutrons with a few MeV of energy, and to be able to measure the flux of neutrons over the greatest solid angle that was practical.

The plastic scintillator material used was a product of Nuclear Enterprises (NE 110). The block of material used for each detector was cylindrical in shape with a diameter of five inches and a length of five inches. The end that was coupled to the photomultiplier tube was polished and all other surfaces were given a reflective coating of Titanium Dioxide. Silicone grease, which is often utilized to improve the light transmission between the scintillator and photomultiplier tube, was avoided in order to make the contact more reproducible. The scintillation material produces pulses with a width of 3.3 nsec, a decay time of 3.3 nsec, a maximum emission wavelength of 434 nm, and a light attenuation length of 400 cm.⁵

The photomultiplier tubes used were experimental models built by RCA that were obtained through a government surplus outlet. They have a 14-stage venetian-blind construction with a five-inch face. Test data on each tube, taken at the time of fabrication, were obtained through a RCA representative in Lancaster, Pennsylvania. The appendix

Figure 5. Diagram of the Scintillation Detector

An Overall View Showing Counting Equipment
(on the desk at the rear, and Teletype in
right foreground).

A View of One of the Scintillation Detectors

Figure 6. Neutron Counter

contains information of the two tubes used (X-36150, X-36246) and also on two additional tubes that were obtained at the same time.

The tubes were powered through a voltage-divider network (Fig. 7) that was built for the experiment. The signal output was A.C.-coupled to the preamplifiers for pulse-analysis work. Fig. 8 shows the arrangement used for pulse-height analysis and Fig. 9 that used for measuring activity rates.

Lead Shielding for the Detector

To reduce the number of gamma rays being counted, an inch of lead shielding was placed in the front of the detector. Neutrons of one to four MeV are reduced by only about 9% by the lead while most of the low energy gamma rays are absorbed. Fig. 10 shows the transmittance of gamma rays through one inch of lead as a function of energy.⁶

As a verification that the counts recorded were a result of fusion reactions, rather than coming from other sources, hydrogen was substituted for the deuterium which was normally used to supply the ion guns. At voltages below 40 kV, the counting rate remained at background level for hydrogen, while for the same settings the counting rate for deuterium was appreciable. The counting rate increased for voltages above this level (Fig. 11), but all measurements taken simultaneously with electron density measurements were performed below 40 keV because of the voltage stand-off limitation of the high-voltage switch. Thus, for runs below 40 KeV, the counts recorded with deuterium operation were considered to result from fusion reactions. To extend the useful range of the detectors, an additional 3/16 inch of

Figure 8. Arrangement for Pulse-Height Analysis

Figure 9. Arrangement for Measuring Counting Rates

Figure 10. Transmittance of Gamma Rays through One Inch of Lead

Figure 11. Gamma-Ray Radiation in the Region of 50 keV of Higher

lead shielding was placed around the detectors. With this additional shielding counting rates remained near background for voltages below 50 keV. The maximum voltage obtainable with the removal of the high voltage switch was 65 keV. At this level the counting rate for deuterium remained substantially above that for hydrogen. This indicated that additional means of discrimination between neutron and gamma rays was not necessary under the operating conditions that were used.

Chapter 4

CALIBRATION OF THE DETECTORS

To determine the absolute flux from the confinement device, a BF_3 proportional counter was used which was calibrated with a Pu-Be source. The BF_3 counter was then used to calibrate the scintillation counters. The scintillation detectors were also used to indicate the approximate energy spectrum of the neutrons from the device.

The Plutonium-Beryllium Source

To determine the sensitivity of the detectors, a Pu-Be source was used whose activity and composition were measured in 1962 by the manufacturer.⁷ The composition at that time was 91.57% Pu^{239} , 7.73% Pu^{240} , and .70% Pu^{241} . Pu^{241} has a mean life of 18.6 years and decays to Am^{241} . Pu^{239} , Pu^{240} , and Am^{241} have long half lives and decay with the emission of alpha particles. The alpha particles then interact with the Beryllium to give off neutrons ($\text{Be} + \text{He}^4 \rightarrow \text{C} + \text{n} + \text{energy}$). Since Pu^{241} was present in the source, its strength (i.e., the neutron emission rate) has changed over the last thirteen years. The following equation⁸ was used to estimate the present activity.

$$Q_t/Q_0 = 1 + k [1 - \exp(-t/18.6y)]$$

where in our case

$$k = \frac{1.27 a(\text{Pu}^{241})/T(\text{Am}^{241})}{\frac{a(\text{Pu}^{239})}{T(\text{Pu}^{239})} + \frac{a(\text{Pu}^{240})}{T(\text{Pu}^{240})}}$$

and

Q_t = the neutron emission rate at time t

Q_0 = the neutron emission rate in the absence of
any Am^{241}

t = the time from the start of the Am^{241} accumulation

a = the relative abundance of the isotope

T = the half-life of the isotope

The experimentally-obtained value of 1.27 is due to the difference in cross-sections for the higher-energy alpha particles given off by Am^{241} . From the data supplied with the neutron source, the value of k was calculated to be 0.393. Therefore

$$\begin{aligned} Q_t &= 1.02 \times 10^7 \text{ n/sec} [1 + .393 [1 - \exp(-13y/18.6y)]] \\ &= 1.22 \times 10^7 \text{ n/sec.} \end{aligned}$$

This is an increase of 19.7% in neutron output over the 1962 value.

Boron Trifluoride Proportional Counters

Calibration of absolute strengths of neutron sources becomes a difficult problem with scintillator counters because their detection efficiency is dependent on the energy of the incoming neutrons. Thus to measure the absolute flux of neutrons from the device with a scintillator counter, a calibrated source with a similar spectrum would be needed.

Another method used to measure strengths is to slow all the neutrons down to the same energy before they are counted. This technique has been shown to be accurate for comparing sources with different spectra.⁹ Usually some hydrogenous material is used to moderate the neutrons and then a thermal neutron detector is used to measure the thermal neutron flux. The uniformity in counting is a result of the moderator used. This does not necessitate that the detector's efficiency be independent of energy.

To obtain an absolute measurement of the neutron flux from the device, a neutron detector built by Eberline (Model # PNC-1, Serial # 241) was used. It uses a BF_3 proportional counter surrounded by paraffin that is enclosed in a cadmium shield. The cylindrical counter tube is filled with BF_3 gas.

The cross section of Boron is proportional to $1/v$ in the thermal range ($\text{B}^{10} + n \rightarrow \text{He}^4 + \text{Li}^7 + 2.8 \text{ MeV}$). The energetic products of the reaction ionize other particles in the gas. The electric field present then accelerates the charged particles, resulting in a small avalanche, and the current in the detector indicates that a neutron has been captured.

Calibration of the BF_3 Detector

The confinement device was located in a room about 12 feet by 20 feet with a 7-foot ceiling. All the walls, floor, and ceiling were made of concrete. The reflection of fast neutrons by the concrete walls around the device added to the total number of neutrons being counted. The fast neutron albedo (fraction of reflected neutrons to incident neutrons) for concrete¹⁰ is of the order of 0.1. Calibration

measurements on the detector were made in three different locations (Fig. 12) to evaluate the scattering effect on the counting rate. The value of C in the figure is given by:

$$C = \frac{NPS}{D^2 \times CPM_{BF-3}}$$

where

NPS = Strength of source in neutrons per second

D = Distance in cm between the center of the source to the center of the detector

CPM_{BF-3} = Counts per minute in the BF_3 detector

If a purely inverse square relationship held, then C would be a constant. However, there are several reasons for the variation of C with distance. The effect of the scattering of neutrons by the walls is most noticeable at large distances from the source because of an increase in the ratio of reflected to direct neutrons being counted. At small distances the effects of the shape and size of the detector result in a deviation from a $1/D^2$ relationship.

The data for the bottom curve of Fig. 12 was obtained in a room (8 x 10 x 8 feet) smaller than that in which the confinement device was located. Five of the sides were of concrete and the remaining wall was constructed of cinder blocks (8 x 10 feet with a 3 x 7 foot door). The data for the middle curve was taken in a room larger than the experimental area, and the top curve near the edge of a balcony in a very large open room. The bottom and middle curves should bracket the conditions of the room in which the experiment was performed as far as the evaluation of C is concerned. In the

Figure 12. The Value of C as a Function of Distance

experiment the center of the detector was located 32 cm from the center of the confinement device. The value of C to be used in the experiment should thus be between 1.25 and 1.40. A value for C of 1.3 is chosen as the best estimate for the sensitivity of the detector under the laboratory conditions present. This value is considered to be accurate to within about 10%. Thus

$$NPS = (1330 \pm 133) \times CPM_{BF-3}$$

Calibration of Scintillation Detectors

To calibrate the scintillation detectors runs were examined in which the counting rates for both the BF_3 and scintillation detectors had been recorded (Fig. 13). The correlation coefficient between the counting rates for the two types of detectors was 0.94 with most of the error due to inaccuracy in reading the BF_3 detector and statistical fluctuations in the counting rates. The result was

$$CPS_{Scin} = 5.8 \times CPM_{BF-3}$$

or

$$NPS = 230 \times CPS_{Scin}$$

where

$$CPS_{Scin} = \text{counts per second in the scintillation detectors}$$

Data shown in Fig. 14 represent some of the information on counting rates obtained from the confinement device. At 50 keV and a pressure of 1.25×10^{-3} Torr, the counting rate was 120 cps per milliampere. Assuming a linear dependence on current, this corresponds to about 2.7×10^5 neutrons per second at 10 milliamps. Hirsch¹ for 50 keV, 10 milliamps, and 1.1×10^{-3} Torr reported a rate of 1.5×10^6

Figure 13. Comparison of Counting Rates for the BF₃ and the Scintillation Detector

Figure 14. Measurements of Neutron Flux from the Confinement Device

neutrons per second. Minor changes in the device and such factors as the alignment and focusing at the ion beams could easily account for the difference.

Efficiency of the Scintillation Detector

The efficiency of the scintillation detectors is determined from the fraction of the number of neutrons recorded to the number of neutrons passing through the detectors. The distance from the center of the scintillation material to the center of the confinement device was ten inches. Comparing the cross-sectional area of the detectors ($\pi \times 2.5^2 \text{ in}^2$) to the area of a sphere with a radius of ten inches, gives a ratio of 1 to 32. This means that for every 32 neutrons leaving the device, one, on the average, will pass through the detector. However, one count has been determined (see above) to correspond to an emission of 230 neutrons from the confinement device, but part of the counts are a result of reflected neutrons. This implies that the efficiency of the detector is below 14%. Most of the reflected neutrons have lost energy in scattering collisions and probably add little to the counting rate because of rejection of low amplitude pulses by the discriminator. Small changes in the discriminator or amplifier settings influenced the counting rate. Higher efficiencies could have been obtained by accepting pulses with a lower amplitude, but this would have resulted in an increase in unwanted background counts.

Energy Calibration

By examining the height of the light pulses in the detector, one can determine the energy spectrum of the protons in the n-p scatterings. This is related to the energy of the neutrons. A Pu-Be source was used to calibrate the detectors. The energy spectra for Pu-Be sources have been determined by many different methods and the general shape is known. Fig. 15 shows the neutron energy spectrum¹¹ for several known sources. Fig. 16 shows the energy spectrum of the protons scattered by the neutrons from the Pu-Be source. The derivative of Fig. 16 is given in Fig. 17. Ideally this would correspond to the neutron energy spectrum from the Pu-Be source. Matching the maxima and minima points indicated by letters in Fig. 17 with points indicated by corresponding letters in Fig. 15, the energy values shown in Fig. 17 were assigned. The correlation coefficient between the energy values of the points in Fig. 15 and the channel number of the corresponding points of Fig. 17 was nearly one. Thus knowing the response of the detector, the energy values of the spectrum (Fig. 18) from the confinement device were determined. Fig. 18 shows that most neutrons from the device had an energy of about 2.5 MeV. The principle reactions taking place in the device are: $D + D \rightarrow He^3 + n + 3.2 \text{ MeV}$, and $D + D \rightarrow T + p + 4.0 \text{ MeV}$. Particles other than neutrons are stopped from reaching the detector by the walls of the confinement device. Applying the principle of conservation of momentum to a calculation of neutron energy shows that most of the neutrons will carry away about 2.4 MeV of energy, which is approximately the value measured.

Figure 15. Known Energy Spectra of Pu-Be Sources

Figure 16. Energy Spectrum of the Protons Scattered by the Neutrons from the Pu-Be source used

Figure 17. Derivative of the Energy Spectrum Shown in Fig. 16

Figure 18. Energy Spectrum of the Protons Scattered by the Neutrons from Confinement Device

Chapter 5

SWITCHED OPERATION

Many of the counting rate measurements were taken simultaneously with measurements of electron density. The latter measurement required that the high voltage be continuously switched in order to provide a comparison between "on" and "off" conditions and to avoid thermal expansion of the cathode, which was used as a resonant cavity. Triggering and gate pulses had been prepared¹² for electron density measurements. Fig. 19 shows the pulses used for neutron counting and the cathode voltage during one switching cycle. Fig. 20 shows the counting rates over the same time period for hydrogen and for deuterium. Counting rates were measured for times around 100 msec on the figure and the background rates were measured for times around 200 msec. The ripple in the counting rate is a result of the 120 cycle ripple in the high-voltage supply. A surge in the counting rate, for times between 20 to 60 msec was observed for both the hydrogen and deuterium. This suggests many of the counts recorded during the surge for deuterium were not a result of fusion reactions but were from other sources.

The BF_3 detector averaged the counts over the entire cycle. Fig. 21 shows readings for the same voltage made simultaneously on both the BF_3 and the scintillation detector. Values for the counting rate for the scintillation detector were taken for times around 100 msec. Under these conditions, the counting rate for two detectors is

Figure 19. Cathode Voltage and Gating Pulse During a Switching Cycle

Figure 20. Counting Rates During a Switching Cycle for D_2 and for H_2

Figure 21. Comparison of Counting Rates of 3F_3 and the Scintillation Detectors for the Switched Condition

related by

$$\text{CPS}_{\text{Scin}} = 5.6 \times \text{CPM}_{\text{BF-3}}$$

When hydrogen was used in the device, the counting rate of the BF_3 detector was zero. The small difference in the constant that relates these two detectors for the steady state (5.8) and the switched state (5.6) indicates that with switched operation there is a high rate of neutron emission at the first part of the cycle, which essentially compensates for the time the high voltage is turned off. Higher voltages and currents are to be expected in the surge conditions at the beginning of the "on" time.

One of the objectives of building a more sensitive neutron detection system was to measure small changes in neutron output due to changes in the symmetry of the active ion guns when less than six guns were used. To do this, neutron output per milliamper was compared for sets of guns that were symmetrically opposed to each other (all guns) and for non-opposing sets (guns 1, 2, 3 or 4, 5, 6). Above 40 keV (when the microwave detection could not be used) the neutron detectors indicated a small enhancement, when all the ion guns were operated simultaneously, over that obtained with operation of non-opposing sets of guns.

Chapter 6

SUMMARY

This thesis has discussed a neutron-detection system that was used to measure the neutron flux from an Inertial-Electrostatic Confinement Device. These measurements have been used to analyze the operation of the confinement device located at Brigham Young University. The neutron counting system was made to be able to detect small changes in operating conditions, and to be able to make measurements under conditions where the high voltage of the device was switched "on" and "off".

Two identical scintillation counters were constructed that would be able to make relative flux measurements for comparison of different operating conditions. These detectors were checked for their sensitivity to gamma rays from the confinement device.

A BF_3 proportional counter was calibrated using a Pu-Be source with corrections made for laboratory conditions. This detector was then used to calibrate the scintillation detectors to make quantitative flux measurements.

The detectors were used to make measurements for several hundred different combinations of voltage, current, and pressure with all ion guns operating, and similar measurements for cases where only part of the ion guns were in use. These measurements provided information of interest about the device.

APPENDIX

SPECIFICATIONS OF PHOTOMULTIPLIER TUBES

Tube	X-32794	T-33424	X-36150	X-36246
White Cath. Sens. $\mu\text{a/lumen}$	190	290	140	200
Anode, Sens. at 25000 amp/lumen	6400	2000	12000	15000
Dark Current μa	0.7	11	0.46	0.45
Volts	2040	2400	1930	1815
Dark Current at 25000 μa	6.4	19	20	18
Red Sens. with Corning filter C S2-62 $\mu\text{a/incident lumen}$	82	110	42	82
Blue Sens. with Corning filter C S-558 $\mu\text{a/incident lumen}$	6.2	1.7	8.3	7.0

PIN ARRANGEMENT

1. No connection	11. Dynode 14
2. Dynode 1	12. Dynode 12
3. Dynode 3	13. Dynode 10
4. Dynode 5	14. Dynode 8
5. Dynode 7	15. Dynode 6
6. Dynode 9	16. Dynode 4
7. Dynode 11	17. Dynode 2
8. Dynode 13	18. No connection
9. No connection	19. Focus grid
10. Anode	20. Cathode

Comments

Tubes are red sensitive and peak around 400 nm.

The outside shield should be at cathode potential.

Operate with as low of voltage as possible. About 1800 - 2000 v.

The output impedance is fifty to several thousand ohms.

The tubes have time constants around 10^{-4} sec.

The focusing grid is internally connected to the metal flange.

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