PRNC 24

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Simple Experiments that can be done with a NEUTRON SOURCE

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Students Method for Determining the Binding Energy of the Deuteron

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(Received January 4, 1961)

A recording spectrometer model 1820 manufactured by Nuclear Chicago with a sodium iodide crystal scintillator, a neutron source, water, and paraffin are used to determine the binding energy of H^2 by measuring the energy of the photons emitted when thermal neutrons are captured by H^1.

INTRODUCTION

NEUTRON capture gamma rays were first observed by Lea[1] who appears to have detected the gamma ray produced by the capture of neutrons in hydrogen using a Ra-Be neutron source and a Geiger counter as radiation detector. The experiment suffered from the disadvantage of using a very weak neutron source and a fairly insensitive radiation detecting device. However, more recently, Pringle[2] studied capture gamma rays with a weak Ra-Be neutron source and used a crystal scintillator spectrometer, a more sensitive detector.

The first accurate measurement of the energy of the hydrogen capture gamma ray was made by Bell and Elliot[3] using thermal neutrons from a reactor. The reported value was 2.23 Mev for the binding energy of the deutron.

A number of illustrative students laboratory experiments in neutron physics using a Pu-Be neutron source and commercially available instruments have been developed as part of a sequence of experiments constituting a nuclear and reactor physics laboratory. Measuring the binding energy of the deuteron is one of the simple experiments. The procedure and nature of the resulting data will be discussed.

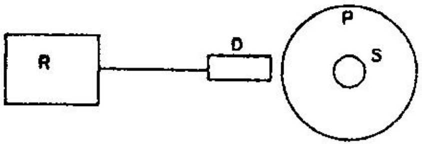

FIG. 1. Experimental setup. *P*—9-in.-diam paraffin cylinder *S*—PuBe neutron source, *D*—NaI scintillator detector, *R*—recording spectrometer.

THEORY

The binding energy of a system of particles is the difference between the mass of the free constituents and the mass of the bound system. Thus the binding energy of the deuteron is

$$B(H^2)=M_a(n)+M_a(H^1)-M_a(H^2), \qquad (1)$$

where M_a refers to the atomic rest masses of the neutral atoms.

The binding energy of the deuteron can be determined experimentally by the measurement of the energy of the gamma rays which are emitted when thermal neutrons are captured by hydrogen. This is possible since the gamma-ray energy approximately equals the binding energy. The validity of this statement can be shown as follows:

The Q value of the nuclear reaction is given by

$$Q=M_a(n)+M_a(H^1)-M_a(H^2) \qquad (2)$$

or

$$Q=T(\gamma)+T(H^2)-T(n)-T(H^1), \qquad (3)$$

where T refers to the energy of the particles. Notice that the right-hand side of Eqs. (1) and (2) are the same. This means that the binding energy of the deuteron is equal to the Q value of the reaction. That is,

$$B(H^2)=Q. \qquad (4)$$

In as much as the energy of recoil of H^2, the energy of the slow neutrons and the energy of H^1 can be neglected with respect to the energy of the emitted gamma-ray photon, it follows from Eq. (3) that the Q value of the reaction is approximately equal to the energy of the photon emitted. That is,

$$Q\doteq T(\gamma) \qquad (5)$$

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* Established by the U. S. Atomic Energy Commission as part of the Atoms for Peace Program and operated by the University of Puerto Rico.

[1] D. E. Lea, Nature **133**, 24 (1934).

R. Pringle, Phys. Rev. **87**, 1016 (1952).

[3] R. E. Bell and L. G. Elliott, Phys. Rev. **79**, 282 (1950).

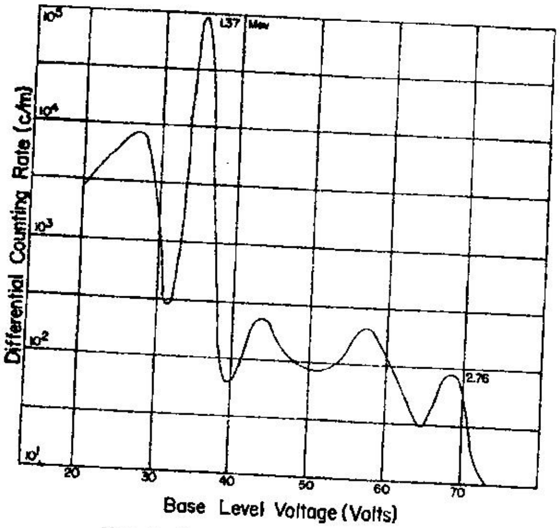

FIG. 2. Gamma spectrum of Na^{24}.

and from Eqs. (4) and (5) it follows that

$$B(H^2) \doteq T(\gamma). \tag{6}$$

Equation (6) shows that the gamma-ray energy is approximately equal to the binding energy of the deuteron.

EXPERIMENT AND RESULTS

Figure 1 illustrates the experimental arrangement. A one curie Pu-Be neutron source is immersed in a container 15 in. in diameter and 12 in. high or inserted into the cavity of a cylindrical block of paraffin 9 in. in diameter and 10 in. high. Measurements of the neutron energy spectrum from this source has shown that most of the neutrons are fast. Upon elastic collision with hydrogen atoms in water or in paraffin the neutrons are moderated to thermal energies. When the neutrons are thus thermalized they can be captured by H^1 with the emission of a gamma-ray photon. The gamma ray interacts with the NaI scintillator[4] and its energy recorded by the spectrometer.

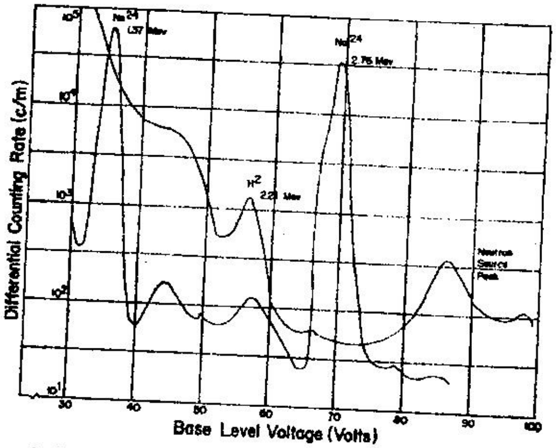

FIG. 3. Gamma spectra of Na^{24} and neutron source in water.

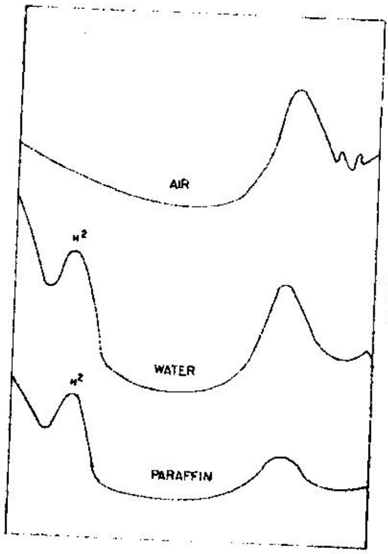

FIG. 4. Gamma spectra of neutron source in air, water, and paraffin.

Figure 2 shows the two gamma rays of 1.37 Mev and 2.76 Mev from Na^{24}. In as much as the binding energy of H^2 lies between the two Na^{24} gamma peaks it was decided to use this radioisotope to calibrate the spectrometer. The Na^{24} was prepared at the P.R.N.C. Swimming Pool Research Reactor.

Figure 3 shows a superposition of gamma-ray spectra from Na^{24} and the neutron source in water. The gain of the spectrometer was varied at about 2.5 Mev during the measurement of the Na^{24} spectrum. The energy of the deuteron peak was found by interpolation between the Na^{24} gamma peaks. The experimental value of the binding energy of H^2 so determined was 2.21 Mev.

The current best value for the binding energy of the deuteron which has evolved from a compilation of mass measurements and reaction data is 2.22 Mev.[5]

Figure 4 illustrates the gamma spectra of the neutron source in air, water and paraffin. The

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[4] K. Siegbahn, *Beta and Gamma Ray Spectroscopy* (North Holland Publishing Company, Amsterdam, 1955), Chap. 5.

[5] F. Everling *et al.*, Nuclear Phys. **15**, 342 (1960).

position of the H^2 peak which is seen in water and paraffin is characteristic of hydrogen containing matter.

CONCLUSIONS

This experiment has been a valuable teaching tool in our nuclear and reactor physics laboratory because:

(1) The student can calculate from the definition, the theoretical value of the binding energy of H^2 and then verify their calculation experimentally.

(2) In addition this experiment serves to acquaint the student with the theory and operation of a gamma-ray spectrometer.

(3) It demonstrates that an intense beam of thermal neutrons is not necessary to make a fairly accurate determination of the binding energy of H^2.

ACKNOWLEDGMENTS

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An Inelastic Neutron Scattering Experiment*

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(Received May 14, 1962)

A recording spectrometer model 1820 manufactured by Nuclear Chicago with a NaI crystal scintillator, a neutron source, and an iron scatterer were used to measure the gamma ray at 0.84 MeV from Fe^{56} by inelastic scattering of fast neutrons.

INTRODUCTION

IN 1933, Auger[1] observed a large increase in the short proton recoil tracks when blocks of copper, aluminum, or lead were placed near a Ra-Be neutron source and a cloud chamber containing hydrogen. He suggested that this might be due to neutrons slowed down by inelastic scattering with nuclei, the latter being left in an excited state which could return to ground state by gamma emission.

The gamma radiation produced by the fast neutron bombardment of a number of materials was studied by Lea[2] demonstrating that in many cases the gamma rays did not appear as a result of neutron capture. They were due to the excitation of nuclei involved in elastic scattering collisions. This observation by Lea is considered as the first establishment of the $X(n,n)X^*$ nuclear reaction.

A number of illustrative student laboratory experiments such as the measurement of the binding energy of the deuterons[3] using a Pu-Be neutron source and commercially available instruments have been developed as part of a sequence of experiments constituting a nuclear and reactor physics laboratory. Measurement of the inelastic scattering from iron using a neutron source is one of the simple experiments. This experiment is very important in reactor design and shielding because the chief process by which fast neutrons are degraded in energy in all but the lightest elements is by inelastic scattering. The gamma rays produced simultaneously have to be considered also in shielding problems. The procedure and nature of the resulting data are discussed.

THEORY

In their passage through matter, neutrons collide with nuclei and scattering occurs in which there is a transfer of energy between the fast neutrons and slow moving nuclei. In the inelastic process momentum is conserved but the kinetic energy is not. Part of the kinetic energy of the neutron is used to excite the struck nucleus. De-excitation takes place by gamma emission to the ground state. The process may be denoted as follows:

$$\begin{array}{l} {}_0^1n + {}_Z^Ax \rightarrow \left({}_Z^Ax\right)^* + {}_0^1n \\ \qquad\qquad\qquad\quad \searrow \\ \qquad\qquad\qquad\qquad {}_Z^Ax + \gamma \end{array} \qquad (1)$$

and is graphically illustrated by Fig. 1. In the illustration (a) shows the neutron incident into the target nucleus ${}_Zx^A$, (b) shows the interaction of the neutron with the nucleus in which the neutron loses part of its energy and a nuclear particle is lifted to a higher state, and (c) shows the de-excitation of the nucleus by gamma emission some time after the exciting neutron recoils.

The ingoing neutron must, of course, supply the energy required for the formation of the excited state plus the energy transferred to the center of mass by the collision. If E_γ represents the energy of the excited state of the nucleus, the minimum kinetic energy $T_{\min}$ of the neutrons to produce inelastic scattering to this state is given in the laboratory system by

$$T_{\min} = [(M+m)/M]E_\gamma, \qquad (2)$$

where M and m are the masses of the target nucleus and neutron, respectively. Since, in

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* Based on a paper read at the Annual Meeting of the AAPT, New York, January 27, 1962.

† Established by the U. S. Atomic Energy Commission as part of the Atoms for Peace Program and operated by the University of Puerto Rico.

[1] P. Auger, Compt. rend. **196**, 170 (1933).

[2] D. E. Lea, Proc. Roy. Soc. (London) **A150**, 637 (1935).

[3] E. Ortiz, Am. J. Phys. **29**, 684 (1961).

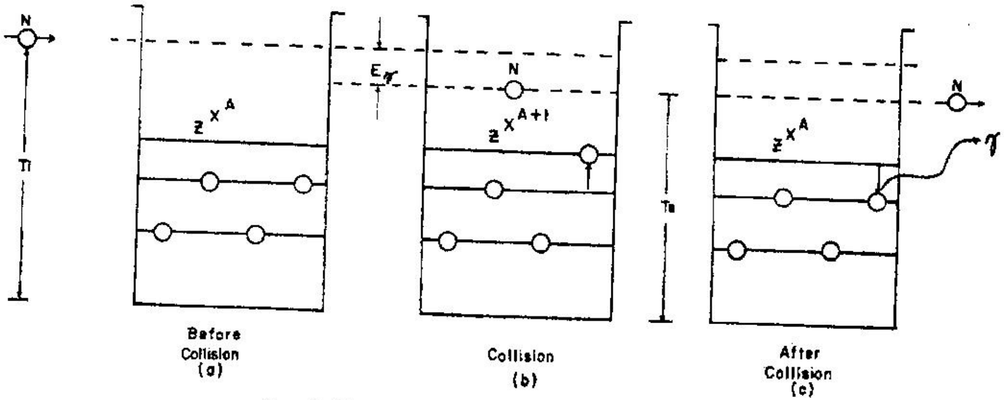

FIG. 1. Neutron inelastic scattering interaction.

general, the initial kinetic energy T_i of the ingoing neutron is larger than $T_{\min}$, the kinetic energy of the scattered neutron T_s is given by

$$T_s = T_i - E_\gamma, \tag{3}$$

if the nuclear mass is very large.

It has been found that for neutron energies, in excess of 1 MeV, the inelastic scattering cross section approaches the geometrical cross section, that is $\sigma_{\mathrm{in}} \rightarrow \pi R^2$, where R is the radius of the nucleus. Since the radii of atomic nuclei, except for very low mass number can be represented by $R = 1.4 \times 10^{-13} A^{\frac{1}{3}}$ cm, where A is the mass number of the nucleus, the inelastic scattering cross section may be represented approximately by

$$\sigma_{\mathrm{in}} = 0.062\, A^{\frac{2}{3}} \text{ barns}. \tag{4}$$

It follows from the above equation that in order to have a large inelastic scattering cross section, nuclei should have a moderate or high mass number.

EXPERIMENT AND RESULTS

The experimental arrangement for the gamma-ray measurements is one which employs a ring geometry as illustrated in Fig. 2. The iron scatterer which is of the form of an annulus surrounding a sodium iodide crystal, received the neutrons emitted at a small angle from the neutron source. A cone made of paraffin with a base having a "boral" disk is used to shield the crystal from direct impact by thermal neutrons. The crystal and the photomultiplier are mounted in a thin wooden container to shield them from light. The neutron source is placed at about 8 in. from the iron ring. The ring dimensions are approximately 2 in. i.d. and 4 in. o.d. A sliding window spectrometer is used to record the gamma-ray photon energy emitted from the excited state of Fe^{56} which is produced during the bombardment of iron with fast neutrons.

Figure 3 shows the energy distribution spectrum from a Pu-Be neutron source.[4] The fact that the source is very rich in fast neutrons made its use possible in the inelastic scattering experiment.

Figure 4 shows the response of the crystal spectrometer with the iron ring present and with

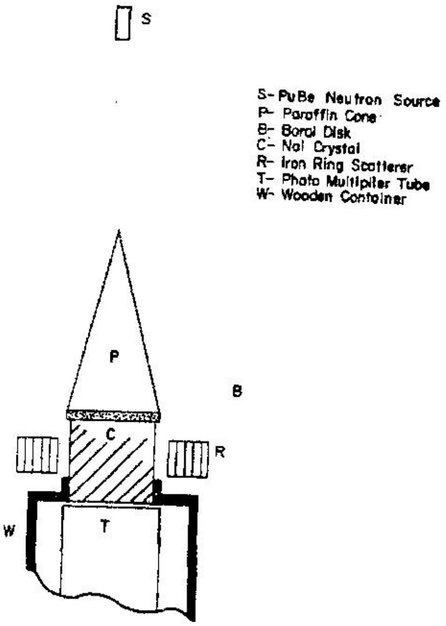

FIG. 2. Experimental setup.

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[4] L. Stewart, Phys. Rev. 98, 740 (1955).

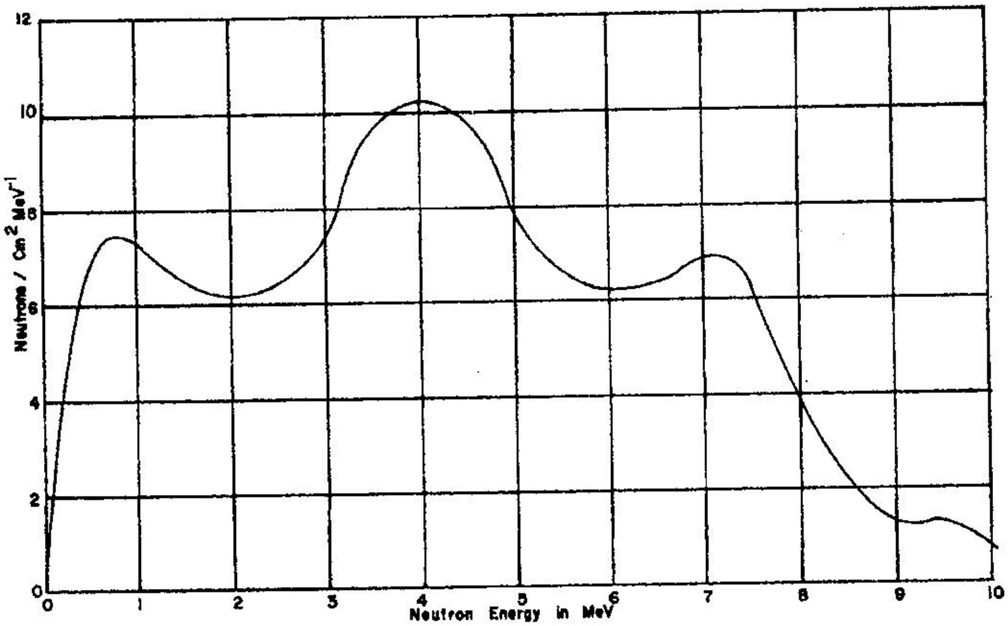

FIG. 3. Energy distribution of a Pu-Be neutron source.

the iron ring removed. Iron was used as the scatterer because Fe^{56} produces a very intense gamma line at about 0.84 MeV. This was very easy to detect with the simple experimental setup used. Both spectra show a visible peak at about 0.5 MeV due to inelastic scattering in the NaI crystal. The calibration of the spectrometer was performed according to the instruction manual using a Cs^{137} source.

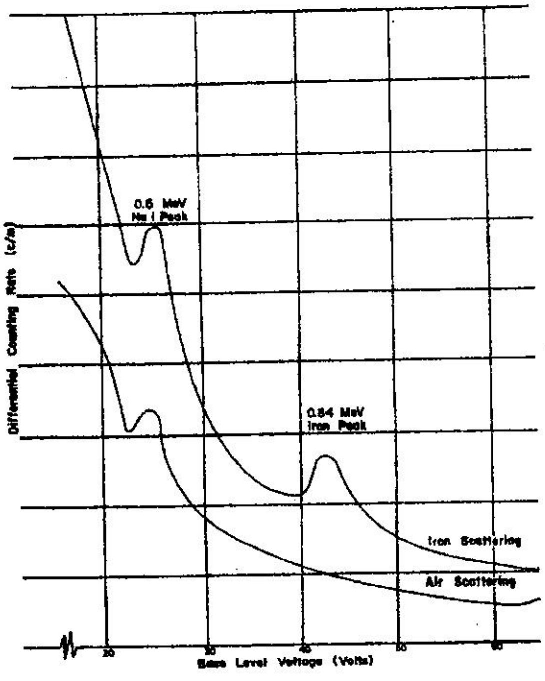

FIG. 4. Gamma spectra of iron and neutron source in air.

CONCLUSIONS

This simple experiment has been a valuable teaching tool in our classes for the following reasons:

(1) After a brief introduction to the elementary theory of inelastic scattering, the student is able to perform an experiment and to determine the energy of the intense gamma peak from Fe^{56} at 0.84 MeV.

(2) The student becomes acquainted with the theory and operation of a gamma-ray spectrometer.

(3) It demonstrates that at least one of the lines from the inelastic scattering spectrum of iron can be determined fairly accurately with a Pu-Be neutron source.

ACKNOWLEDGMENT

The writer wishes to express his sincere appreciation to the physics major student Mr. Angel Hermida for his cooperation in the preparation of the experimental setup and for running the spectra.

A Versatile Experiment Using a Neutron Source and a Tank of Water

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Purposes:
- a- To determine the optimum water depth for neutron moderation.
- b- To show the effect of neutron reflection in water.
- c- To obtain the distribution of thermal neutrons in water.

INTRODUCTION

The experiment described below was worked out in the course of research undertaken by two graduate students at this College for their master's thesis. S. Pinto Vega, from Colombia, was working on the determination of the optimum thickness of paraffin for the neutron balance between moderation and capture in order to incorporate the data in the design of a high-energy neutron conversion device. H. Plaza, from Puerto Rico, was trying to measure the neutron albedo in water. Since the results were highly interesting in both cases, it was decided to modify the experimental set-up and prepare it for two further experiments in the Nuclear and Reactor Physics Laboratory. The new experiments were designed to establish the precise water depth required for neutron moderation and also the body of water which would be equivalent to an infinite reflector. Furthermore, the data obtained in this experiment can also be used to show the distribution of thermal neutrons in water.

EQUIPMENT AND PROCEDURE

The experimental set-up is shown in Fig. 1. A neutron source is centered at the bottom of a 43"x43"x51" stainless steel tank. A 1/2" dia. and 4" active length BF_3 counter is coupled to an aluminum tube by an L-shaped plastic tube and sealed to secure water-tight fitting. The aluminum tube is supported by horizontal bars at the top of the tank and the detector unit can be raised or lowered along a vertical line above the source. With the detector at a fixed distance d from the bottom of the tank, the water level is increased at 1" intervals and the count rate C recorded at each level until the water is about 10" above the detector. The respective levels are measured by a calibrated water manometer. If the count rate is plotted against the water level H, a curve is obtained for the fixed position of the detector. After emptying the tank by means of a pump, the procedure can be repeated by varying d so as to obtain a family of curves with d as a parameter, as shown in Fig. 2.

INTERPRETATION OF RESULTS

The nature of the experimental curves may be explained qualitatively by taking a particular curve, dividing it into three regions, and considering its course. Fig. 3 shows the three regions: (1) Slowing-down, (2) Absorption and (3) Reflection.

Regions (1) and (2) are similar to those obtained in a transmission experiment when the thickness of the material between detector and source is varied. In order to explain re-

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*Established by the U. S. Atomic Energy Commission as part of the University of Puerto Rico.

gion (1) the following factors must be taken into consideration: The Pu-Be neutron source emits fast neutrons; the count rate of the BF_3 detector is energy-dependent because B^{10} is a 1/v absorber; neutron energy is degraded by elastic collision and geometrical effects may be neglected.

As the water level rises, the energy spectrum of the neutrons escaping toward the detector will vary, depending on the number of collisions with H nuclei, and the neutrons within the energy threshold of the detector will be counted. With further rises in the water level, the neutrons escaping toward the detector become practically thermal and consequently the count rate will increase. When a water level is reached at which the neutrons are thermalized, however, the curve starts bending toward a maximum due to absorption. At point B, where there is a state of balance between moderation and capture, the maximum count rate is obtained. Curve AB is called the slowing-down curve.

Since at H_b thermalization is at its optimum, raising the water level beyond this point will increase neutron absorption with a consequent decrease in the number of thermal neutrons escaping toward the detector. Curve BC is a typical attenuation curve due to neutron absorption.

At water level H_c, back-scatter of neutrons to the detector will begin, while some neutrons will escape or be absorbed. Consequent rises in the water level will increase the neutron count due to collision and reflection until a steady rate is obtained. Curve CDE represents the reflection or back-scatter region.

At this stage of the experiment, purposes (a) and (b) have been accomplished, viz.:

a- The optimum water depth for neutron thermalization is about 5", independently of the position of the detector.

b- At a level higher than 4" above the detector, the count rate remains constant; accordingly, this level can be considered equivalent to an infinite amount of water above the detector.

In order to accomplish purpose (c) of the experiment, the data from Fig. 2 can be replotted to show the relationship between C and d, H being kept constant. If this is done for $h \geq d + 4$, the relationship between the count rate and the distance of the detector from the bottom for a filled tank of infinite size is obtained. If r is the distance from the source to the detector, we find that $r = d - 2$ since the source is 2" high. If a semi-log plot of Cr^2 against r is made, results similar to those shown in Fig. 4 are obtained. Here the curve represents the distribution of thermal neutrons in water. Since if r is large the curve is a straight line, this relationship can be expressed by the function

$$C \propto (1/r^2)\ \exp - r/\lambda$$

where λ is the attenuation length. From the e-folding value of the count rate, an attenuation length of 4.4" is obtained.

CONCLUSION

The above experiment is of great practical value for the following reasons:

1- After an introduction to the theory of the neutron slowing-down and reflection properties of moderating media, the student should perform the experiment so as to determine that the optimum depth of water for neutron thermalization is about 5", and that 4" of water are equivalent to an infinite body of water above the detector. Also, the student will be made to realize that the reason why the critical mass of a reactor can be reduced by surrounding the reactor core with a reflector is the consequent decrease in the probability of neutron leakage.

2- From the thermal distribution of neutrons in water, the student will establish that starting at 6" from the source, the attenuation length is 4.4". This aspect of the experiment is very important in connection with thermal neutron shielding design.

3- The simplicity and relatively low cost of the equipment needed makes the experiment feasible in any laboratory possessing a neutron source and neutron counting accessories, that is to say, it can be carried out in practically any modern physics laboratory at College or University level.

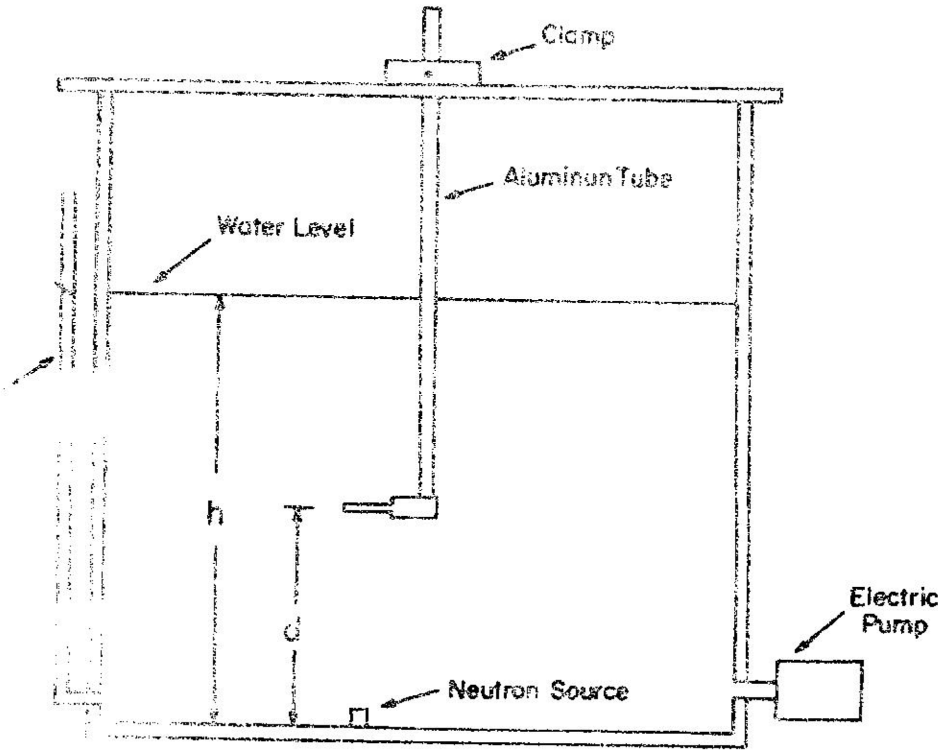
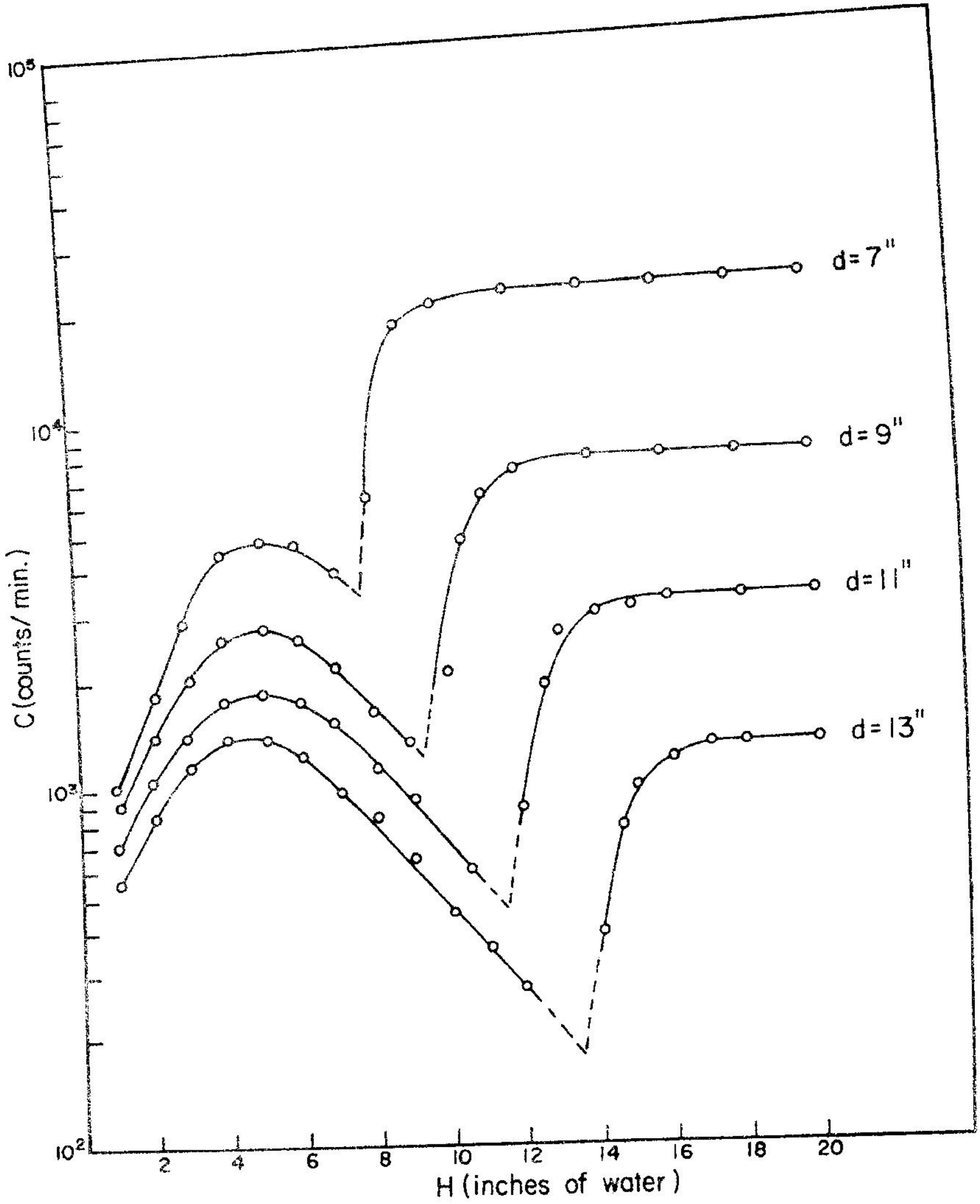

Clamp
Aluminun Tube
Water Level
h
d
Electric Pump
Neutron Source

FIG. 1



10⁵
10⁴
10³
10²
C (counts/ min.)
2
4
6
8
10
12
14
16
18
20
H (inches of water)
d = 7"
d = 9"
d = 11"
d = 13"

FIG. 2

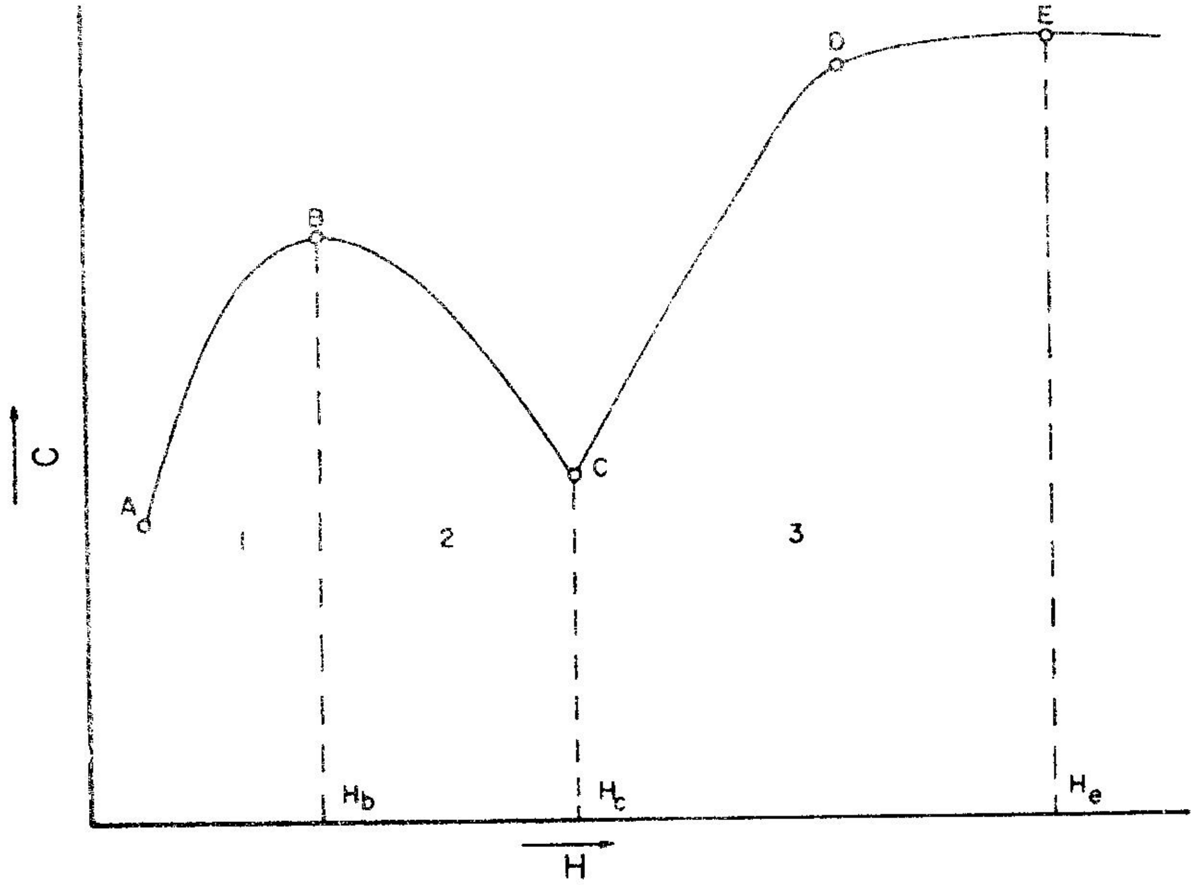


FIG. 3

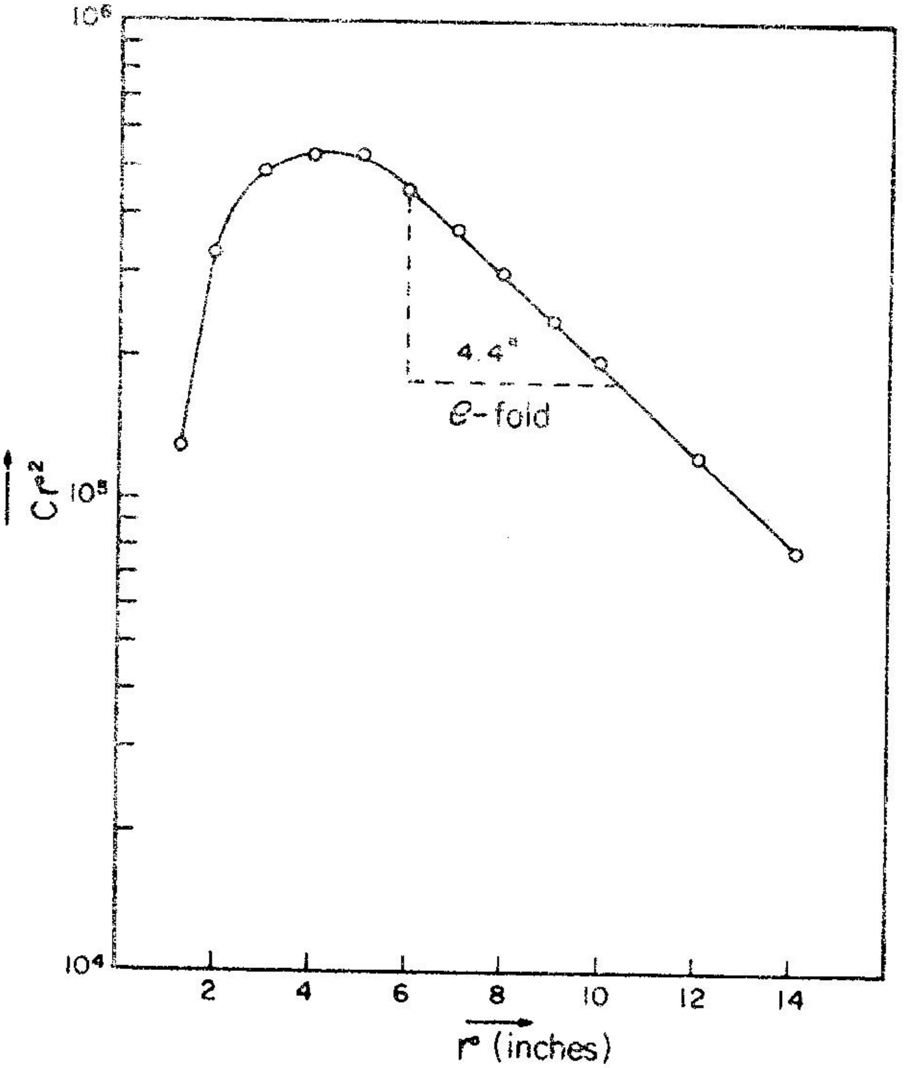


FIG. 4