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NEUTRON BEAM FROM THE UCLA SPIRAL-RIDGE CYCLOTRON<sup>(\*)</sup>

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### Introduction

The work reported in this paper has been directed toward the production of an intense, nearly monoenergetic beam of neutrons from the UCLA Spiral-Ridge Cyclotron. By bombarding the deuterium contained in heavy water,  $D_2O$ , with the internal proton beam of the cyclotron, a neutron beam with a relatively low energy spread has been obtained. By changing the radial position of this target, the energy of the emitted neutrons can be varied. The fundamental reaction utilized to produce the neutrons is

#### $p + d \rightarrow n + p + p_{\bullet}$

The kinematics of this process at intermediate energies have been studied in the past<sup>1)</sup> and are known to give a sharply peaked neutron spectrum in the forward direction. The large circulating proton currents in the UCLA machine are the source of the high intensity of neutrons produced. By inserting the heavy-water probe target directly into the proton beam, the low energy protons produced in the reaction are swept out of the neutron beam by the magnetic field of the cyclotron. Thus the only contamination of this neutron beam is gamma radiation produced in and around the probe target.

The design considerations, equipment, and measured properties of this neutron beam are presented below. In addition a preliminary measurement of a total absorption cross-section in carbon is presented.

## Experimental Method

The primary mechanical consideration for any target which is to be bombarded by a proton beam current of as much as  $100 \ \mu$ A is to supply adequate cooling to dissipate the heat produced by the beam. Although several different ideas were considered, intensity estimates indicated that it would be most efficient to use a thick layer of heavy water to provide a source of deuterium and simultaneously to cool the walls of the target. Fig. 1 shows a detailed drawing of the target probe tip and the circulating heavy-water system. The heavy water is cooled by a simple heat exchanger connected to the water supply of the building. It should be noted that the high degree of radioactivity produced in the oxygen of the water by the proton bombardment necessitates the use of a closed cooling system. The thin walled probe tip, shown in the detail of Fig. 1, is machined from a single piece of aluminium and is then heli-arc welded to the aluminium tube assembly which transmits the water. The tube is then

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Fig. 1  $D_2O$  probe for the production of neutrons from the UCLA cyclotron.



Fig. 2 Experimental setup for the production and measurement of a neutron beam taken from the UCLA cyclotron. A. D<sub>2</sub>O-filled probe, B. Shielding wall, C. Neutron converter, D. Scintillation counters, E. CH<sub>2</sub> absorber. Session IV

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inserted into the vacuum tank of the cyclotron through a standard Wilson seal.

Fig. 2 illustrates the experimental geometry used to produce the neutron beam. The heavy-water probe is shown inserted into the vacuum chamber of the cyclotron. The neutrons emerge from the vacuum tank through a thin aluminium window 0.010 in. thick. A 5 in. pipe through the shielding wall of the cyclotron vault permits the neutrons to enter the experimental area. Various annular collimators are mounted inside and around the outer wall of the pipe to prevent background neutron and gamma radiation from entering the experimental area. For the present work the pipe has not been evacuated. Estimates of the neutron beam intensity to be expected using this geometry are in fair agreement with the results presented in the following.

The energy spread of the beam was anticipated to arise from the following sources :

1) A spread of neutron recoil energies from the primary proton-deuteron interaction would be expected on the basis of phase space alone. However, the work at Harwell<sup>1</sup>) indicates that this spread is small and less than  $\pm 1$  MeV at proton energies of 50 MeV. This small spread is consistent with the data presented below.

2) Radial oscillations of the beam provide a spread of proton energies at a given radial position of the probe target. Several different measurements<sup>2</sup> are consistent with the fact that the amplitude of the radial oscillations in this cyclotron is such that an energy spread of about 0.5 MeV or less exists at the radius used in the experiment. It might be noted that the small amplitude of radial oscillation forces one to use a thin aluminium wall at the end of the target probe in order that the protons penetrate the heavy water.

3) The ionization loss of energy by a proton traversing the probe tip is 4 MeV. Hence, the protons in the elementary p,d reaction vary in energy by this amount. Assuming that the Harwell results<sup>1)</sup> are true, the neutrons produced will have an energy distribution which is very nearly uniform with an energy spread of 4 MeV. 4) Finally, the measured energy spectrum of the neutrons will depend on the energy resolution of the detector. In this work a scintillation counter telescope was used to measure the range of recoil protons produced by a polyethylene converter placed in the neutron beam just outside the shielding wall of the cyclotron vault as indicated in Fig. 2. The energy resolution of this converter-telescope system was estimated to be 3 MeV.

If these various sources of energy resolution are numerically folded together, a peaked proton recoil spectrum of approximately 5 MeV full width at half maximum is obtained, with the peak displaced by 5 MeV below the circulating proton beam energy.

#### Measurement of the Beam Properties

The energy spectrum of the neutrons was determined by measuring the range of recoil protons produced in a 2 mm thick polyethylene converter placed in the beam. The axis of the counter telescope was set at an angle of  $15^{\circ}$  to the neutron beam

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direction, and the measured values of the differential n.p scattering cross-sections from Harwell<sup>3)</sup> were used to estimate the incident intensity from the measured count rate. The differential energy spectrum was obtained from integral range curves taken with 1 mm polyethylene sheets placed between the second and third counters in the telescope. Not shown in Fig. 2 are two beam monitors. The first is a single counter which is used to count proton recoils from a small polyethylene converter just at the exit of the beam pipe from the shielding wall. The second was a scintillation detector mounted inside the cyclotron vault. This provided a measure of the beam level in the machine by integrating the current from a photomultiplier. These two devices together with the two-fold coincidence rate of the first and second counters in the recoil proton telescope were used to insure that comparable numbers of neutrons were counted while taking the range curves. Background counting rates were taken by replacing the polyethylene converter with a disk of carbon of similar dimensions and appropriate thickness to permit a direct subtraction of the contribution of the carbon in the polyethylene from the observed count rates. The measured differential range curve is shown in Fig. 3. The abscissa gives both the range and corresponding energy of the recoil protons. It should be noted that the lowest energy detected by the telescope is 30.5 MeV. The total integrated intensity of the distribution shown in Fig. 3 corresponds to a neutron flux of  $10^5$  neutrons/cm<sup>2</sup>-s.

In order to determine the number of neutrons contributed by p,n reactions in the oxygen of the heavy water, an energy spectrum of neutrons was measured using distilled water,  $H_2O$ , in the probe target. The measured spectrum indicated a maximum contribution of 5% to the points on Fig. 3 between 0 and 2 mm of polyethylene absorber. The other points received an even smaller contribution. Since these corrections are of the same order as the statistical uncertainty of each point, no correction was applied to the data.

## **Discussion**

Although it is clear from the measurements that this neutron beam has the high intensity and small energy spread which was desired, several points should be mentioned.

First, the peak of the measured energy spectrum is shifted downward from the proton bombarding energy by 8 MeV rather than the 5 MeV predicted. Furthermore, the spectral shape is not that which was calculated, so that it is not possible to fit the two. Thse discrepancies could be accounted for<sup>4</sup> by multiple traversals of the heavy water by the protons in the beam with an additional 4.5 MeV energy loss on each traversal. However, in order to fit the data of Fig. 3, this assumption implies that



Fig. 3 Differential energy spectrum of recoil protons.

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essentially no protons are lost from the beam as it passes through the target and that at least two traversals occur. In this case the neutron spectrum would be peaked at 36 MeV and have a full width at half maximum of approximately  $8 \pm 2$  MeV. Further work is in progress with a detector telescope whose low energy cut-off is 26 MeV to investigate the possibility of multiple traversals

The spectrum shown in Fig. 3 was used in an attenuation measurement of the neutrons between 31 and 33 MeV in carbon to determine its total absorption cross-section. The measured value obtained is  $1.29 \pm 0.05$  barn and compared reasonably well with that of  $1.231 \pm 0.014$  barn obtained by the Harwell group<sup>5</sup>.

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- 4) The authors are indebted to B.T. Wright, who first suggested this possibility to them.
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#### DISCUSSION

STAFFORD : A week ago at Harwell we made some time-of-flight measurements on the 50 MeV proton linac, and we got a very sharp neutron peak. The target thickness was about 1 MeV and there might be an additional 1/2 MeV spread. We found very little extra spread at all, both at 30 and 50 MeV.

YORK : When I visited Harwell last fall, Batty gave me the data presented at the meeting of the Physical Society. The best that could be said at that time was that, within the resolution of the time-of-flight equipment which they used,  $\Delta E$  was actually less than 2 1/2 MeV. I think that Castillejo and Singh predict an energy spread of about 1/2 MeV at 50 MeV. This means that you will have to reduce your target thickness even further.

LANGMANN : Do you have any plans for making the energy analysis of the neutrons by time-of-flight techniques?

YORK : Some measurements of this kind were done last fall. They showed that the beam burst has a duration of about 3 ns. This is also shown in Fig. 4 of the paper by Crowe and Haddock (see paper IV/5). We have circuits which generate a very sharp timing pulse. derived from the 20 MHz RF system, with a rise time of 1/4 ns and a width of 1/2 ns. We use this in coincidence with our counters.