# A NEUTRON BEAM FACILITY AT NAC

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## ABSTRACT

A collimated neutron beam facility has recently been constructed and commissioned. It consists of a target chamber, a specially–constructed dump magnet and beam dump, as well as a set of collimators built into a secondary shielding wall at 4° intervals from 0° to 16° to the primary beam direction. The neutron source itself is a lithium target, which provides an almost monoenergetic neutron beam. The first experimental results show that a time resolution of 0.3 nS/m can easily be achieved, while the background of neutrons from beamline sources upstream of the target is not significant, even when using the 0° neutron beam.

## 1. INTRODUCTION

The k=220 MeV separated–sector cyclotron[1] at NAC has been in use for more than a year for the production of radioactive isotopes, for radiotherapy and for radiobiological and nuclear physics experiments. A nuclear physics group based at the University of Cape Town expressed an interest in doing an experiment to measure neutron–proton radiative capture at NAC, and this prompted us to construct a facility for producing an intense collimated beam of (nearly) monoenergetic fast neutrons.

The initial experiment involves the measurement of the angular distribution of photons from the $^{1}H(n,\gamma)^{2}H$ reaction between 20 and 200 MeV. Deuterons from the n–p capture in a liquid scintillator cell are detected in coincidence with the capture gamma rays, and the differential cross–sections derived from the experiment are compared with theoretical predictions, and with data from the inverse $^{2}H(\gamma,n)^{1}H$ photo–disintegration reaction.

Polarized neutrons, produced at a non–zero angle to the incident beam may later be used to measure the analysing power in the n–p radiative capture reaction.

## 2. REQUIREMENTS

A number of investigations are reported in the literature[2-6], including a variety of experimental arrangements for producing a beam of neutrons[7-12].

Firstly, a target is needed which can produce a suitable beam of neutrons. The most suitable is a $^{7}Li$ target[2-6], and a thickness of the order of 1 mm is needed to produce a sufficient neutron yield for the initial experiment.

Secondly, a dump magnet is needed to sweep the primary proton beam away from the detector area, and to deposit it in a well–shielded beam dump equipped with a suitable Faraday cup. For the latter we used a shortened version of the standard NAC beam–dump Faraday cup, which is divided into 4 sectors (for beam centering) and with two outer sections of tube to warn of beam wander or defocusing. The design of the dump magnet must take into account the high levels of radiation to which it will be subjected.

Thirdly, a collimation system is needed to shield off all but those neutron travelling directly from the target to the secondary target and detector system. Because of the relatively high energy of the particles involved and the limited space available, this collimator requires heavy shielding material, and forms an integral part of the beam dump shield as well.

## 3. NEUTRON YIELD

Cross–sections reported in the literature are summarised below for $^{7}Li(p,n)$ at 0°. Only the cross–section to the ground state in $^{7}Be$ is included.

Table 1: Measured $^{7}Li(p,n)^{7}Be_{g.s.}$ cross–sections.

| Energy (MeV) | Cross–section (mb/sr) | Reference |
|---|---|---|
| 94 | appr. 34.0 | Whitehead[2] |
| 50 | 35.2 ± 3.5 | Batty[4] |
| 50 | 31.6 ± 3.0 | Jungerman[5] |
| 60 | 36.4 ± 4.0 | Wachter[6] |
| 50 | 28.9 ± 2.9 | Bosman[7] |

Batty et al.[3] reported a yield of $3.0 \times 10^{-4}$ neutrons per steradian per incident proton (50 MeV) on a 1 MeV thick target, which is a neutron yield of $1.88 \times 10^{9}$ $sr^{-1}.\mu A^{-1}.s^{-1}$.

Although we do not presently envisage that more than 1 $\mu$A will be required for the initial experiments, it must be borne in mind that higher yields may be required for the more difficult polarization measurements at large angles, especially at higher energies where the yield drops dramatically with laboratory angle. For example, a 20 $\mu$A beam of 78 MeV protons has been used elsewhere[7]) to bombard a 10 mm thick natural Li target, giving a yield of of $1.5 \times 10^7$ neutrons per second at 2 m from the target into a 2 cm diameter collimator.

## 4. TARGET

A $^7$Li target was produced by pressing the lithium into a 25 mm diameter hole in a 1 mm thick stainless steel holder, and then covering both exposed sides with a thin film of Havar foil. This was then mounted on a target ladder inside an evacuated target chamber.

The stainless steel target ladder has been constructed to permit one or more targets to be mounted (in conventional stainless steel holders), and a BeO plate is mounted on the end of the ladder at 45° to the incoming beam direction. The ladder itself is mounted on a pneumatically–activated arm which is used to select the desired target (or viewer) by remote control. At present the targets are uncooled, relying on conduction down the stainless steel shaft, as well as radiative cooling, and the maximum beam current is thus limited to a few microamps. If higher beam currents are requested, a water–cooled target ladder will be provided. The incident proton beam is focused onto the BeO plate and a closed–circuit TV camera is then used to view the target spot on this BeO plate, using a system of mirrors and a zoom lens to avoid subjecting the camera to undue levels of radiation.

## 5. DUMP MAGNET DESIGN

With a view to future experimental requirements, we have designed the dump magnet to be able to bend 200 MeV protons into the beam stop and Faraday cup at 15° to the incident beam direction. This is sufficient to allow the wide mouth of the Faraday cup to stand clear of the neutron collimator on the 0° line. Figure 1 shows the plan of the beamline and target, with the beam dump behind the dump magnet.

The dump magnet is a 15° dipole C–magnet, which bends the primary proton beam to the right, while the neutrons produced in the $^7$Li target are able to pass through the open side of the magnet and the steel vacuum chamber walls.

In order to avoid saturation in the iron of the magnet, we have limited the maximum field $B_0$ in the gap to 1.3 tesla. The magnetic rigidity of 200 MeV protons is 2.15 T.m, and the magnet thus bends those particles through an angle of 15° with a radius of curvature of 1.66 m, and the effective length of the magnet is thus 0.435 m. We ignore the effects of the fringe field, (which for a square–ended magnet can extend well beyond the poles,) as we have used an approximation to a Rogowski profile which reduces this effect. The effective length is also sensitive to coil position, making accurate prediction difficult. [In practice the measured effective edges for this dipole lie 11 mm outside the vertical pole edges.]

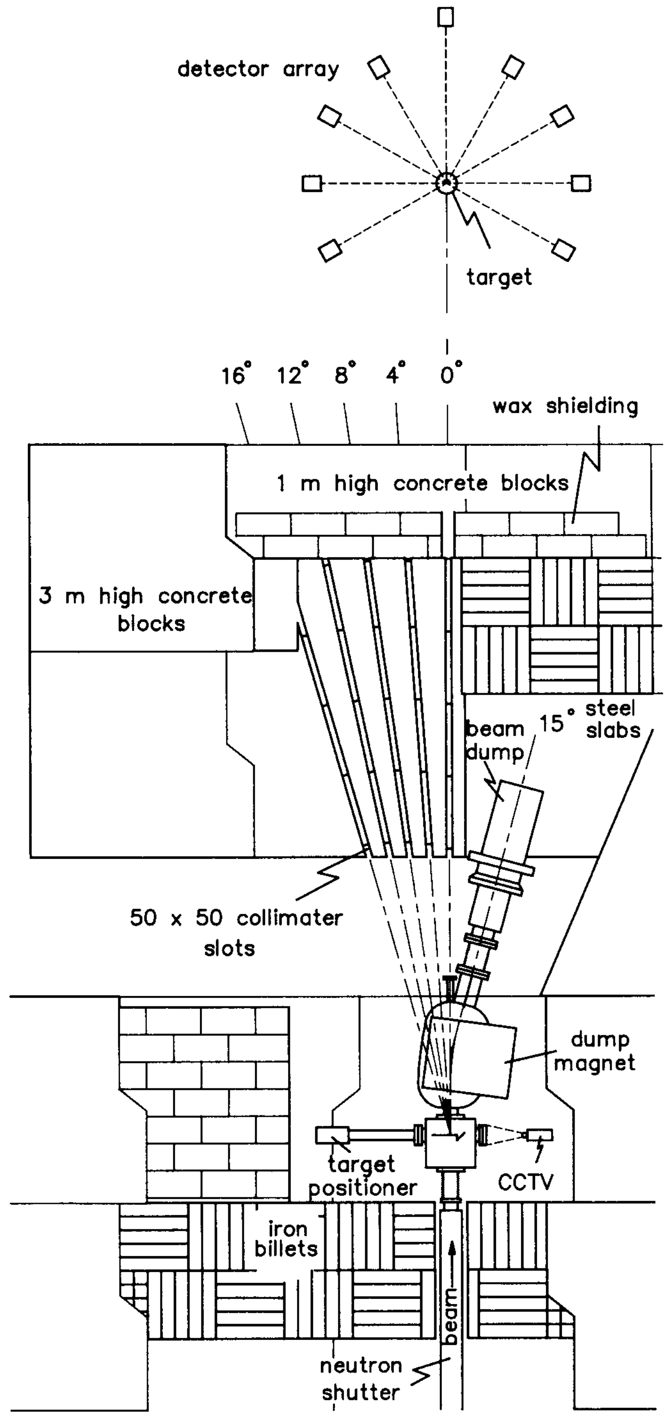


Fig. 1. Plan of the neutron beam facility, showing an experiment set up on the 0° neutron beam. Collimators at other angles are blocked with square iron rods.

We chose 50 mm for the pole–gap separation, to be consistent with a 50 × 50 mm square collimator between the Li target and the secondary target. Wider gaps would naturally increase the size of the magnet, the mass of steel and copper, and the power required in a nearly linear manner. A pole width of 150 mm was chosen to give 1% homogeneity over a 1/2–width of 50 mm, and 0.1% over a 1/2–width of 25 mm. The area of the yoke was then made equal to that of the pole, to keep B low in the iron.

The magneto–motive force required to induce 1.3 T in the pole gap is given by

$$Ni = \int \vec{H}.d\vec{\ell} = \int_{gap} \vec{H}.d\vec{\ell} + \int_{yoke} \vec{H}.d\vec{\ell}$$

$$= \frac{B_0}{\mu_0 \ \mu_{air}}.2g + \frac{B_{iron} \times \ell_{iron}}{\mu_0 \ \mu_{iron}}$$

where $\ell_{iron}$ = the path length in iron,
$\mu_{air}$ = 1,
and $\mu_{iron}$ $\geq$ 1000 for $B_{iron} \leq$ 1.5 tesla.

If we neglect the second term in this expression, assuming that the value of $B_{iron}$ is low enough not to cause $\mu_{iron}$ to drop significantly, then

$$Ni = \frac{1.3T \times 0.05m}{4\pi \times 10^{-7} \times 1.0}$$

$$= 5.17 \times 10^4 \text{ A–turns.}$$

Existing power supplies on site are capable of delivering 100 A at 4 kW. (The 100 A current was chosen to minimize resistive losses in the long cables from the power supply room to the beamlines.) We wanted to use a standard supply, using 100 A maximum, and thus we needed 517 turns. The chosen coil configuration was 10 pancakes per pole of 2 layers each, with 14 turns per layer, i.e. 28 turns per pancake, giving 560 turns total. We used 8 × 8 mm square copper conductor, with a 5 mm diameter cooling channel. Four cooling circuits were used with 5 pancakes per circuit, needing 4.3 atmospheres of water pressure for a 20° temperature–rise The magnet is shown in diagrammatic form in fig. 2.

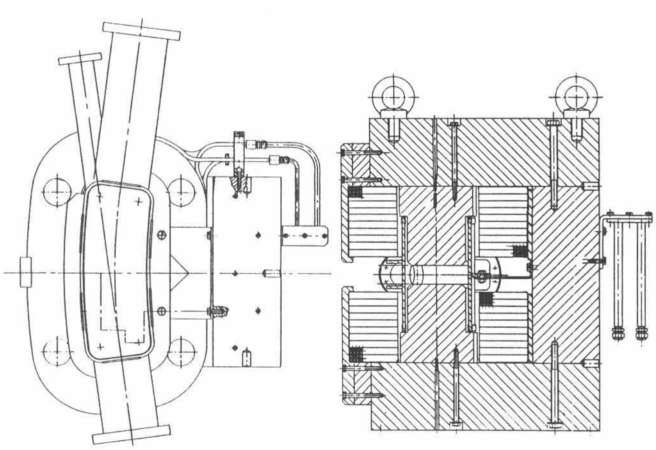

Fig. 2. Horizontal and vertical sectional views of the dump magnet.

As epoxy resin is degraded (becoming brittle and permitting the ingress of water vapour) at dose–rates of $>10^6$ Gray, epoxy–potted coils located at 0° and only 20 cm from such a neutron source would only last for a few thousand hours of irradiation. An alternative method of insulating the coil had to be found, and we have accordingly used only 1/2–lapped glass–fibre tape without epoxy resin, relying on the heat generated by the coil to drive off any moisture. As the inter–layer voltage in the coils is not high, shorting between layers is not a problem.

## 6. BEAM DUMP SHIELDING

A beam of 200 MeV protons striking a copper or aluminium beam stop will produce a copious quantity of neutrons, with a pronounced forward peak. Ordinary concrete is a fairly cheap shielding material containing heavy aggregate as well as water. The hydrogen in the water is effective in reducing the energy of the neutrons prior to thermal neutron capture. However, the density of concrete being only 2.3 means that a huge volume is needed: about 6 metres of concrete would be needed in the forward direction to attenuate the neutron fluence from a 1 μA 200 MeV proton beam striking the beam stop to a dose–equivalent rate of 25 $\mu Sv.h^{-1}$ (2.5 $mrem.h^{-1}$). [This level was chosen rather arbitrarily, on the grounds that detectors and their local electronics are about as sensitive to neutrons as people are!]

If we assume that the attenuation curves for iron are similar to those for concrete[13)], but with thickness inversely proportional to density, we find that only 1.7 m of iron is needed for the same dose–equivalent rate. Thicknesses needed for various angular ranges are summarized in Table 2.

Table 2. Shielding material thickness (see text)

| Angular Range (degrees) | Concrete (m) | Steel (m) |
|---|---|---|
| 0° – 30° | 5.7 | 1.70 |
| 30° – 60° | 4.8 | 1.45 |
| 60° – 90° | 3.6 | 1.10 |
| 90° – 180° | 2.5 | 0.75 |

Now, it is important to keep the distance between the neutron source and the secondary target fairly small, so as keep the neutron flux density as high as possible. Hence, by embedding the beam dump in sufficient steel, this can be achieved. (Refer to fig. 1.) Flat iron slabs, 1.7 m × 2.4 m × 100 mm thick were stacked up on concrete blocks. These are standard 1 m high wall blocks, which are 1.5 m square, with a 200 mm vertical "joggle" midway along two opposite sides. Where steel shielding was not required, full 3–metre high wall blocks could be used.

Where necessary, extra shielding was added in the form of stacked concrete bricks, with some wax blocks added on the detector side of this wall, especially where the steel billets are exposed, in order to absorb thermal neutrons This wall almost closes off the lithium target chamber and dump magnet, leaving a narrow labyrinth for access, while at the same time forming the beam dump shielding and housing the neutron collimator.

## 7. COLLIMATION

Collimation of the neutrons into a proper beam for experimental purposes is achieved by a 50 × 50 mm square steel collimator 1.7 m long, with its exit face a distance of 4 m from the $^{7}$Li target. At 7 m from the target point, this collimator then limits the beam to 87.5 mm × 87.5 mm, which defines the largest useful target–cell area for such a collimator.

The collimator has several ports at angles of 0°, 4°, 8°, 12° and 16° to the incident beam direction, as shown in Fig. 1. These were constructed by sandwiching machined wedges between two flat steel plates built into the beam dump shielding wall, between the 100 mm thick iron plates mentioned above. During a given experiment, only one collimator port is open, the others being blocked off by insertion of a number of stainless–steel rods of 50 × 50 mm square section.

## 8. EXPERIMENTAL RESULTS

The incident proton beam from the 200 MeV separated–sector cyclotron can be used with a pulse–selector which suppresses 6 out of every 7 pulses. The structure of the beam can be monitored to ensure that there is no break–through of the unwanted intermediate pulses.

A thin lead shield was placed over the entrance to the collimator to remove low–energy scattered particles and to reduce the gamma ray background reaching the target cell. In the first experiments a 50 mm diameter × 50 mm high NE213 liquid scintillator cell acted both as target and particle detector[14]. Pulse–shape discrimination was then used to distinguish the various particle types. Fig. 3 shows a pulse–height spectrum with neutron time–of–flight on the other axis, recorded for those particles identified as protons in this way.

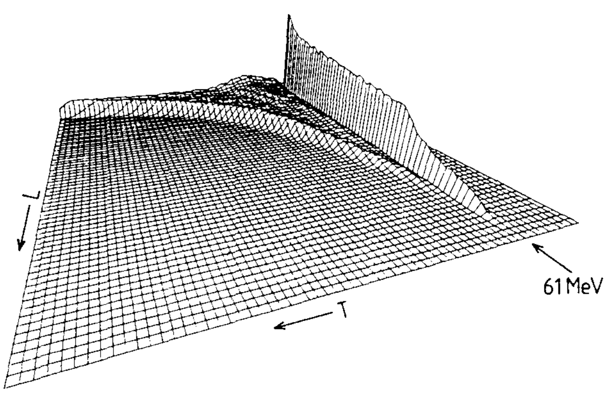


Fig. 3 Plot of counts versus time–of–flight T and pulse height L for those events in the NE213 scintillator identified as protons by pulse–shape discrimination. The sharp ridge (right) corresponds to the intense beam of 61 MeV neutrons from the $^{7}$Li(p,n)$^{7}$Be reaction at an incident energy of 65 MeV.

The neutron time–of–flight resolution of 0.3 ns.m$^{-1}$ was measured with the 7 m flight path from target to scintillator cell on the 0° line. The pulse–selector was used to remove all but one pulse out of 5, to reduce the repetition rate of the beam pulses to only 3.2 MHz, thereby permitting measurement of neutron energies as low as 20 MeV without pulse overlap problems.

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