INTRODUCTION

Neutrons interact with matter in a way that is quite complementary to X-rays, and so neutron imaging and neutron radiography are important techniques for non-destructive testing, most suited for visualization of light elements in the interior of (heavy) metallic objects. Neutron imaging is being used as non-destructive testing (NDT) since the five decades. Unlike X-rays, neutrons interact with various materials with very specific cross-section largely independent of atomic number (Z) of the material. Examples of high absorption cross-section materials include hydrogen and boron while iron has lower neutron cross-section. Hence with neutron imaging it is possible to image such materials even if present in minute quantities in the specimen. However for objects with poor neutron absorption cross-section conventional neutron radiography fails. In recent years, a new method known as neutron phase contrast imaging has been developed to overcome limitations of conventional imaging techniques. These methods are based on the coherence properties of the X-ray and neutron sources. Most coherence based imaging techniques at present are being implemented using X-rays due to the availability of high flux coherent radiations sources such as synchrotrons. These techniques have several advantages over the conventional incoherent imaging techniques. Some of the advantages are high sensitivity; retrieval of the phase information etc. As neutrons can provide complementary information about the object to that of X-rays, there is great potential to these techniques, if these can be implemented using neutrons. The relative transparency of many high Z elements to the neutrons essentially allow us to obtain an inside look into objects and to make 3D reconstructions of their internal structure. Similarly materials like Pb, Be, C, Al, Si are more easily probed using neutrons than X-rays. Moreover, the phase sensitive measurements in combination with neutron imaging can also provide 3D spatially resolved information on the scattering length density distribution. This work describes propagation based phase measurement and imaging technique which is an extension to conventional thermal neutron radiography using phase as the contrast mechanism.

The propagation based phase contrast imaging technique requires spatial coherence of the neutron beam [1]. This is generally obtained by using a pinhole neutron source with low beam divergence [2-3]. These requirements favor high intensity sources to perform such imaging. Most of the facilities where phase contrast imaging is being performed are located at high intensity neutron sources with source fluxes reaching \(>10^{14}\) n/cm²/s. However, the 40-MWth CIRUS reactor represents a medium flux (\(10^9\) n/cm²/s) facility with a neutron flux one order of magnitude lower than existing sources. Moreover, the all the beam ports are radial in nature resulting into high gamma noise, the high energy neutron spectrum. This work shows a successful demonstration of neutron phase imaging technique at such a reactor.
The derivation of the refractive index for neutrons is quantum mechanical in nature. Neutrons which move inside a medium experience a spatially dependent potential \( V(r) \). The energy eigenstate \( \psi(r) \) and the wave function

\[
\psi(r,t) = \psi_0 e^{i\mathbf{k} \cdot \mathbf{r}}
\]

satisfies the time-independent Schrödinger equation

\[
\nabla^2 \psi(r) + \frac{2m}{\hbar^2} V(r) \psi(r) = 0
\]

outside the medium, and

\[
\nabla^2 \psi(r) + \frac{2m}{\hbar^2} \left( E - V(r) \right) \psi(r) = 0
\]

within the medium. Both equations are Helmholtz scalar wave equations and can therefore be written as

\[
\nabla^2 \psi(r) + \frac{2m}{\hbar^2} E \psi(r) = 0
\]

With the wave vector \( k \) outside the medium

\[
k^2 = \frac{2mE}{\hbar^2}
\]

and wave vector \( K \) inside the medium (region of the potential)

\[
K^2 = \frac{2m}{\hbar^2} \left( E - V(r) \right)
\]

It is natural to define the spatially dependent refractive index as the ratio of this spatial dependent wave vector \( K(r) \) to the free space wave vector \( k \), such that

\[
n(r) = \frac{K(r)}{k} = \sqrt{1 - \frac{V(r)}{E}}
\]

Since the range of the neutron-nucleus interaction is much smaller than the wavelength of a thermal neutrons the scattering is isotropic. This allows to use the Fermi pseudo potential \( V(r) \) to describe the interaction of a neutron with a sample containing many nuclei

\[
V(r) = \frac{2\pi k^2}{\hbar^2} \sum_j \delta(r - R_j)
\]

where \( R_j \) is the position of the \( j \)th nucleus and \( b \) is the neutron scattering length. The mean interaction potential, or optical potential, for a material is defined as

\[
\langle V(r) \rangle = \langle \mathbf{P} \rangle = \frac{2\pi k^2}{m} \sum_j \delta(r - R_j)
\]

where \( N \) is the mean number of scattering nuclei per unit volume and \( b = \langle b \rangle \) is the mean coherent scattering length. Any absorption and nuclear reaction effects are described by the imaginary term of the scattering potential in Eq. (9), that is, the scattering length \( b \) becomes complex: \( b \rightarrow b' - ib'' \). This yields a complex index of refraction as follows:

\[
n = \sqrt{\frac{\mathbf{P}}{E}} = \left[ 1 + \frac{\lambda^2 N}{2\pi} \sqrt{\frac{2\pi e}{\hbar c}} \left( \frac{\sigma_r}{2\lambda} \right)^2 \right]^{-1/2}
\]

where

\[
\sigma_r = \frac{\sigma_{a} + \sigma_{s,\text{coh}}}{4\pi}
\]

The complex refraction index counts for absorption (\( \sigma_a \)) and incoherent scattering (\( \sigma_{s,\text{coh}} \)) processes. \( \sigma_r = (\sigma_a + (\sigma_{s,\text{coh}})) \) is the total reaction cross section per atom. The imaginary part is typically small, and therefore the index of refraction can be approximated as

\[
n \approx 1 - \frac{\lambda^2 b}{2\pi}
\]

In summary, the complex refractive index for neutrons with a wavelength \( \lambda \) propagating through a medium can also be described as [4]

\[
n(\mathbf{r},\lambda) = n(\mathbf{r}) - \beta(\mathbf{r},\lambda)
\]

Where the real part \( \delta \) corresponds to the phase of the propagating wave and \( \beta \) represents the absorption in the medium. Thus one can say that phase contrast imaging exploits the real part of the refractive index (1 - \( \delta \)) while neutron radiography exploits the imaginary part (\( \beta \)).

All the phase contrast imaging techniques systems seek to form images of transparent or near-transparent features in a sample, which have a greater effect on the phase than the intensity of the radiation passing through them. The goal, therefore, is to visualize the transverse phase shifts in the input wave-field, in the intensity of the corresponding output wave-field. The simplest form of phase contrast imaging involves propagation of a coherent wave-field through a transparent object and after propagating through a distance \( z \) of free-space, the intensity is measured by a spatially-resolved detector. In the absence of the object, a constant intensity would be recorded. If the propagation distance is zero, we have a contact image which shows only absorption-contrast. A contact image of a completely transparent object shows nothing but the constant background intensity. The wavefield will have been phase-shifted by the object, but the wave amplitude is unchanged and so the intensity is unchanged. As the detector is moved away from the object, refraction and diffraction cause amplitude variations in the wavefield and so variations in the measured intensity. The measured variation in the intensity in the detector plane is proportional to the phase gradient in the object. As the phase gradients are expected to be quite high across the interfaces or boundaries, this leads to the corresponding enhancement in the measured intensity in the detector plane at these edges. Thus phase contrast techniques provide alternative mechanism for improving the sensitivity of conventional neutron imaging techniques for materials with low neutron absorption cross-section. The free space propagation technique uses a unique contrast mechanism in comparison with other phase sensitive imaging techniques that has advantages concerning the simplicity of the experimental set-up, which requires no optics to form images. This technique is very useful for neutrons where lenses are difficult to fabricate and, as there are no optical elements, produces no aberrations. This technique is applicable across a broad range of areas and has become an area of active development [5-6].

**EXPERIMENTAL SET-UP**

We have designed dual purpose collimator in order to carry out both neutron tomography and phase imaging experiments.
The collimator with L/D=125 has been installed at CIRUS beam hole No.12 for conventional neutron radiography and tomography experiments. It is made up of 1S aluminum and is kept in between inner and outer gates (Fig. 1). The measured neutron flux at the exit of beam port with this collimator was $9.0 \times 10^6$ n/cm$^2$/s and at the sample location was $1.0 \times 10^6$ n/cm$^2$/s and the cadmium ratio was 10. Although these parameters are good enough for conventional imaging, they can not be used for phase contrast mode due high spatial coherence requirement of phase contrast experiments. For phase contrast imaging experiments a removable collimator with variable aperture was designed and installed. This collimator can be inserted in the empty space of preceding collimator and its gives a maximum L/D of 3800. Thus this modular design helped us to carry out both the conventional and phase based neutron imaging within the same experimental area without any modification of existing experimental set-up.

EXPERIMENTAL RESULTS

A number of samples have been studied to demonstrate the propagation based phase contrast technique using neutrons and some of these results are reported in this work. The Fig.2 shows iron spring embedded in aluminum matrix. Aluminum has very low absorption cross-section for thermal neutrons. The absorption image Fig. 2(a) show very poor contrast even for spring made of iron. On the contrary the phase contrast image Fig. 2(b) shows much improved contrast both for the aluminum matrix and iron spring and structure within the

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**Fig. 1:** (a) Schematic layout and (b) photograph of the neutron imaging facility at CIRUS

**Fig. 2:** (a) Absorption (b) Phase radiograph of iron spring embedded within aluminum matrix

**Fig. 3:** Neutron phase radiograph of lead sample within conical hole and its profile showing edge enhancement
matrix is clearly visible due to the edge enhancement effects. A neutron radiograph of lead matrix with conical hole is shown in Fig.3. The edge enhancement profile clearly shows the effect of interference at the edges thereby increasing the contrast in the acquired images. Fig. 4 shows the neutron phase contrast images of different types of materials such as hollow aluminum cylinder, Lead sinker with metallic spring, aluminum matrix containing zirconium disk. All these images were acquired using 25 µm resolution neutron imaging plate and data acquisition time was 35-45 minutes.

**SUMMARY**

In the present work performance of phase contrast neutron imaging was demonstrated at the CIRUS reactor which is a medium intensity neutron source. The design requirements for such an imaging exercise are more difficult to achieve particularly for low/medium intensity neutron sources with high gamma noise like CIRUS. A step-by-step design methodology was followed to design the collimator meeting the required objectives and constraints. Experiments depicting the phase contrast effect were performed using the custom designed collimator. The system was designed in such a fashion so that conventional absorption based and phase based imaging experiments can be performed with minimal modification. This demonstration of neutron phase contrast imaging at CIRUS reactor makes the technique feasible to implement at other such facilities located on medium neutron flux sources. Such implementations will enable usage of this technique for practical neutron imaging applications on a routine basis as and when desired.

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**REFERENCES**