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ADVANCES IN IMAGING WITH THERMAL NEUTRONS

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ABSTRACT

Experiments have been conducted using a modern high-resolution ^{3}He two-dimensional position-sensitive detection chamber combined with coded apertures to produce images by means of thermal neutrons. These images are comparable to those produced by gamma ray imaging, but with some important differences. The detector is much less sensitive to the fast neutrons than to the thermalized component. Therefore, assuming that the neutron source has a fission spectrum, the brightest regions in an image represent moderating material in close proximity to the source, rather than the source itself. Earlier experiments[1] have shown that useful contrast can be produced with thermal neutrons using thin masks made of metallic Cd sheet, but the resolution in those experiments was detector-limited at a few centimeters per pixel. The newer detector can resolve a line image with a fwhm resolution of about 1 mm. The technique could in principle be used in re-entry vehicle on-site inspections to count multiple nuclear warheads. Thermal neutrons carry no detailed spectral information, so their detection should not be as intrusive as gamma ray imaging.

INTRODUCTION

MOTIVATION The ability to form images with thermal neutrons opens doors to many useful applications in the field of arms control and nuclear nonproliferation. First among these would be the verification of the number and positions of warheads deployed in multiple re-entry vehicles. In such cooperative monitoring scenarios, the fact that the number of pixels in the coded aperture mask limits the spatial resolution for a given camera length helps to reduce concerns about intrusiveness. Neutron imaging may also turn out to be useful in the dismantlement process and for verification of the contents of sealed containers. Other possible applications include the determination of the location, size and shape of solid deposits held up in gaseous diffusion plants due to inadequate heating or reactions with in-leaking air. In an active interrogation mode, the detector could also be combined with a portable neutron source to produce images of moderating materials, such as plastic explosives and land mines.

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METHOD

IMAGING THERMAL NEUTRONS A source of spontaneous fission such as ^{242}Pu or ^{252}Cf emits neutrons with a broad spectrum of energies peaking in the 1-6 MeV range. Multiple scattering in low-Z materials such as plastic explosive near to the fission source can reduce the energies of a significant fraction of these neutrons to thermal energies less than 1 eV. In the case of hold-up of UF_6, some neutrons are produced by $F(\alpha,n)$ reactions. These are less energetic than those produced by fission, and a measurable percentage of them should reach thermal energies after passing through large masses of solid deposits. If these thermal neutrons are then emitted into the air, they can travel in straight lines several tens of meters without much attenuation or scattering. Hypothetically, a pinhole mask could be used to cast on a detector array an inverted image of the objects from which the neutrons last scattered. There are difficulties in forming such an image with the energetic neutrons, because the mask would have to be tens of centimeters thick in order to stop half of the energetic neutrons which missed the pinhole. However, the thermalized neutrons can be stopped by resonant capture in materials such as Cd with less than 1 mm thickness. Since ^{3}He - based neutron detectors are most sensitive to thermal neutrons, they can be combined with Cd masks to form images with the thermal neutrons even though a much larger flux of energetic neutrons is transmitted through the mask and the detector array. A major limitation to this capability is due to the intermediate energy, or epithermal component of the neutron flux which is not absorbed by the Cd but has a measurable probability of detection in the ^{3}He detector. In practice, the Cd mask is not in the form of a single pinhole, but consists of multiple rectangular apertures arranged in a mathematically prescribed way to form a uniformly redundant array, or URA (Reference 2). Such an array has 50% open area, which maximizes the rate of acquiring an image with the thermal neutrons. The pattern of a 31 X 29 URA which was used in these experiments is shown in Figure 1.

DETECTOR CHAMBER High-resolution position-sensitive neutron detectors have been developed in the Instrumentation Division at BNL for low-energy neutron-scattering studies of molecular structures (see Reference 3).

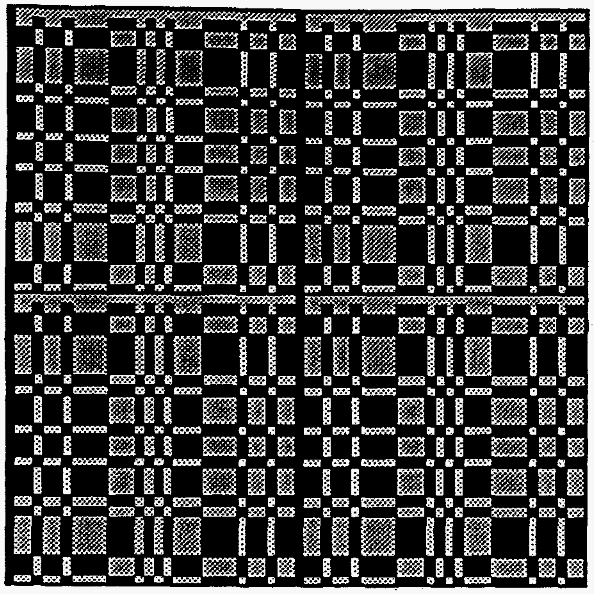


FIGURE 1. UNIFORMLY REDUNDANT ARRAY OF APERTURES ARRANGED IN 4-FOLD MOSAIC OF 31 X 29 PATTERN

Devices of this type have achieved a spatial resolution of 300 μm. They exhibit a high degree of spatial linearity, stability and uniformity of response. These detectors consist of 3 layers of wire arrays (2 cathode planes on either side of an anode plane) suspended in high pressure ^3He. The readout electronics include multiple hybrid preamplifiers and a specialized circuit which locates the centroid of the charge collected from each event. The x and y coordinates of the event are transferred to the digital circuits as start and stop timing pulses, the intervals between which are digitized by a multichannel time-to-digital converter card in a CAMAC crate. The crate is controlled by a Macintosh computer which is used to display the raw data and the reconstructed images. For most of the experimental results presented in this paper, count rates were limited to about 10 counts/s by the data transfers between the crate and the computer, but considerable increases in count rates up to 600 counts/s are possible with the recent addition of an auxiliary list sequencing crate controller.

OVERSAMPLING AND BINNING The timing pulses were digitized with a precision of 1 part in 2000, but before the data were stored the counts were binned into larger intervals which were adjusted so that the image of one tile of the mask mosaic would match an area of 248 x 232 intervals in the stored bins. This meant that for each pixel of the 31 x 29 mask, if it were placed on the face of the detector and illuminated by a distant neutron source, there would be an 8 x 8 array of stored intensities. The advantage of such over-sampling is that, after the data is recorded, adjustments in the alignment of the source, mask and detector can be accomplished in software in order to produce the optimum image. Without this freedom of adjustment, it is possible that a small source might be located such that it could produce a high intensity only near an edge or a corner of a pixel in the final image. This intensity would then be shared by two or four pixels, and might be indistinguishable from background fluctuations. With 1/8 pixel adjustments in both dimensions, it is possible to optimize the number of counts in a single pixel by interactive choices of the x- and y- offsets.

Once the images are reconstructed, it is possible to apply various image processing techniques to enhance the visibility of objects of interest. One such technique is nearest-neighbor averaging, which tends to smooth out random fluctuations, and can emphasize objects whose images are larger than one pixel but also can reduce the contrast of a real object whose image is limited to a single pixel. These viewing functions were performed on a Power Macintosh 8100 computer using the public domain NIH Image program (Reference 4).

RESULTS

POINT SPREAD FUNCTION To demonstrate the spatial resolution of the detector, as well as the image contrast achievable with the Cd mask, a 31 x 29 coded aperture with 5 mm pixels was placed as close to the detector as possible, i.e., in contact with the front flange bolt heads. A source was placed in a paraffin thermalizer at a distance of 300 cm in order to cast a sharp shadow of the mask on the detector. The raw data which was acquired is displayed in Figure 2, where the dark areas represent higher counts of neutrons transmitted through the apertures. The finest features of the mask are clearly visible, although subject to counting statistics, indicating that the resolution of the detector is entirely adequate for this mask geometry.

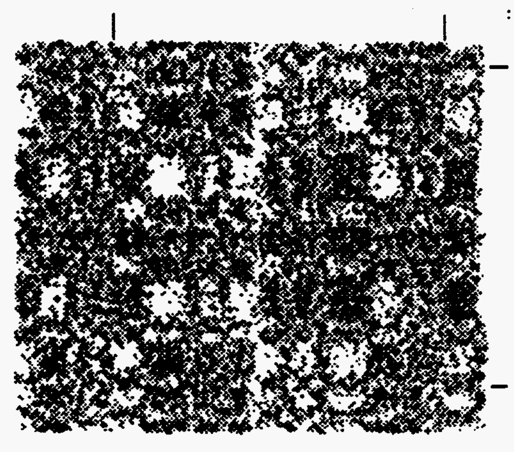


FIGURE 2. RAW DATA COLLECTED WITH MASK CLOSE TO FACE OF DETECTOR, WITH SCALE MARKS INDICATING A UNIT CELL OF THE MASK MOSAIC

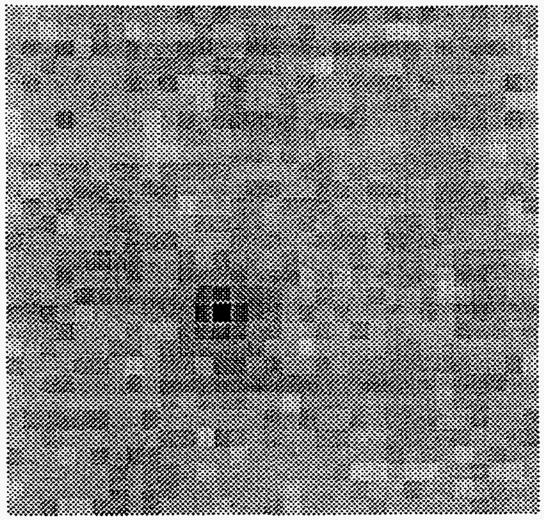


FIGURE 3. RECONSTRUCTED IMAGE OBTAINED FROM DATA IN FIGURE 2

The image shown in Figure 3, obtained by applying the reconstruction algorithm to this data file gives an empirically determined approximation to the point spread function of the system. A single pixel contains most of the signal of interest, amounting to approximately N/10, where N is the total number of counts in the image. The rest of the picture appears to be small random fluctuations with a standard deviation of the order of $\sqrt{N}$, which is expected by Poisson statistics. A 3-D view of this image (Figure 4) shows the size of the signal relative to the surrounding fluctuations.

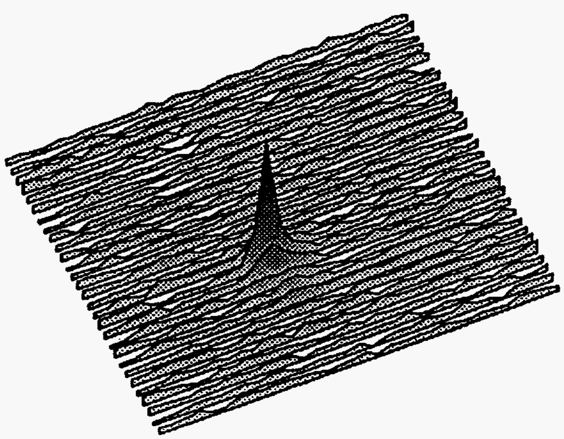


FIGURE 4. 3-D PROJECTION OF DATA FROM FIGURE 3

SINGLE AND MULTIPLE SOURCES The neutron imaging system was shown to be capable of locating a source of thermal neutrons at a distance of 20 m with the mask placed 30 cm from the detector. The resulting image, containing 5300 counts is shown in Figure 5. If the source is divided in two parts, separated by a sufficient distance, the two weaker sources can be resolved as in Figure 6. However, the intensity of each component of the scene is a factor of 2 lower while the random fluctuations in the background remain the same for the same total number of counts. As the number of objects in the scene increases, it becomes more difficult to discern them from the background, and it becomes necessary to count for longer periods to obtain adequate statistics.

Further examples of images obtained with multiple sources are shown in Figures 7 and 8, which are depicted in this paper as grey scale images, but can be displayed on a color monitor or printer in false color, showing, for example, the most intense regions as red and the low intensity regions as blue. It is clear that images of this sort provide more information than can be obtained with traditional neutron counting methods, in which arrays of ^{3}He tubes are embedded in large amounts of moderating material so as to maximize the collection efficiency. Those methods provide little or no directionality or information on inhomogeneity in the source of the neutrons.

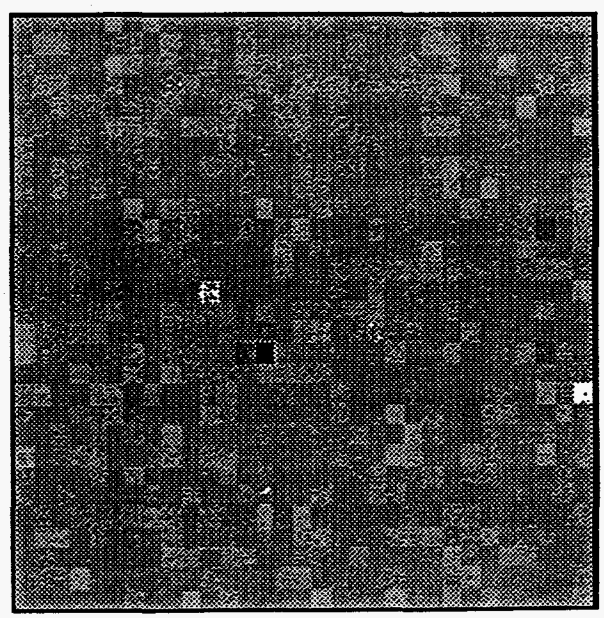


FIGURE 5. RECONSTRUCTED IMAGE OBTAINED WITH SINGLE SOURCE AT 20 M

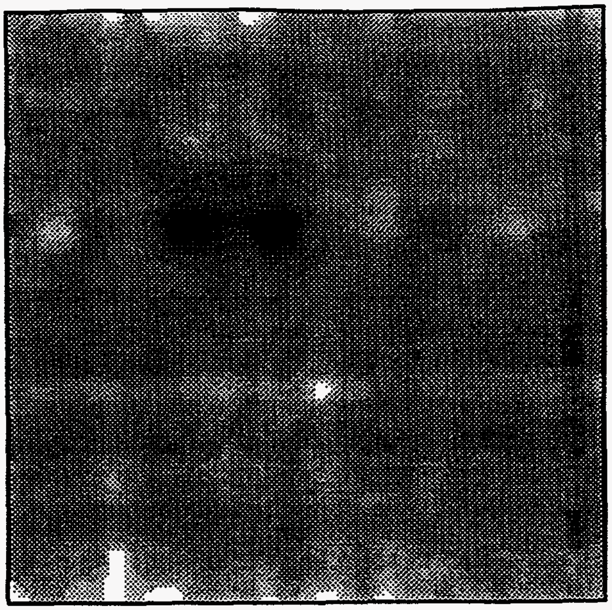


FIGURE 6. IMAGE OBTAINED WITH TWO 15-CM DIAMETER MODERATORS SEPARATED BY 45 CM VIEWED AT A DISTANCE OF 300 CM

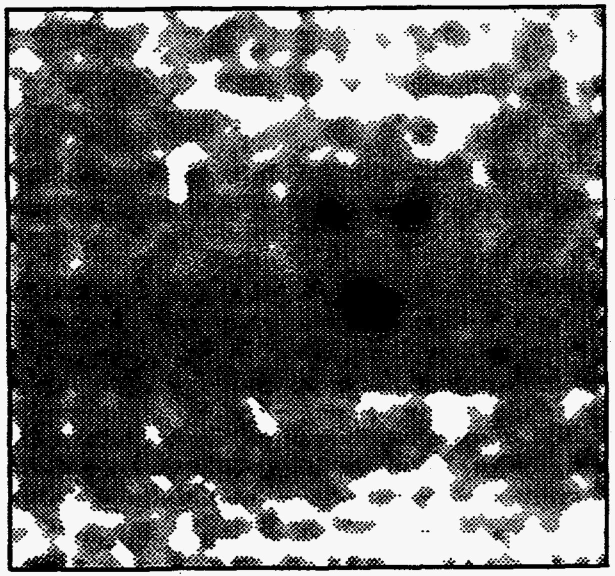


FIGURE 7. IMAGE OF THREE 7-CM DIAMETER SOURCES SEPARATED BY ABOUT 45 CM RESOLVED AT A DISTANCE OF 300 CM

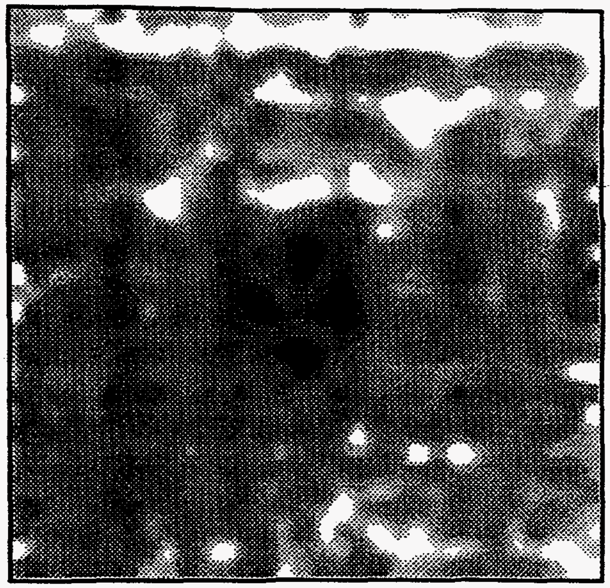


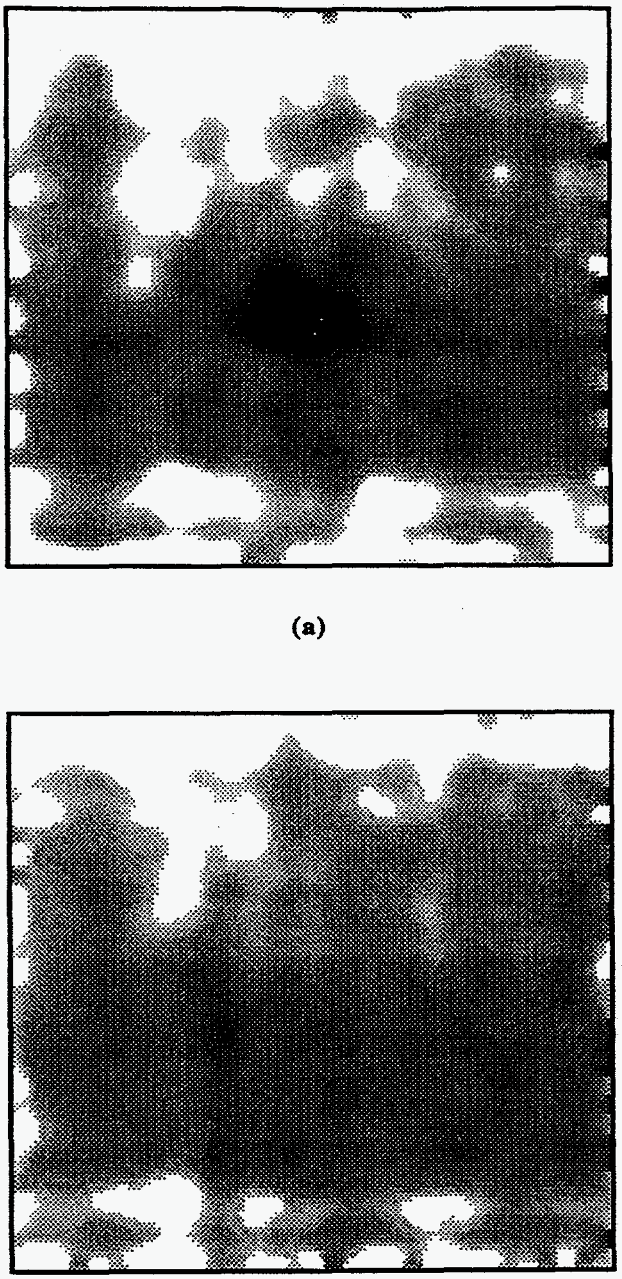
FIGURE 8. IMAGE OF FOUR SOURCES RESOLVED

When combined with other measurements, the information obtained by neutron imaging may be useful in modeling the details of the configuration of a source, and may allow more reliable estimates to be made of inventories of nuclear materials. In some situations, present methods may make the assumption that material is uniformly distributed in some volume, but neutron imaging may indicate a concentration in certain locations. This information could also be useful for considerations of criticality.

ILLUMINATION BY AN EXTERNAL SOURCE The source of the neutrons does not have to be embedded in the moderator, since the thermal neutrons radiate isotropically from the moderating material, regardless of the directions of the original energetic neutrons. Therefore, a portable fission source or accelerator-based neutron generator could be used to flood an area with energetic neutrons and an image could be formed by means of the returning thermal neutrons. For example, one might be able to locate land mines buried in sand using such images. A test of this application was performed by burying a 2.5 cm thick square of polyethylene below 3 cm of sand and placing the ^{252}Cf source on the surface of the sand. After an image was recorded, the plastic was removed and a second image of the sand was acquired for the same counting period. The resulting images are shown in Figure 9a and 9b.

SUMMARY

A new tool is being developed for possible use in the areas of nuclear materials management and arms control. The advantage of imaging over traditional neutron counting is that positional and configurational information is obtainable. One advantage over gamma-ray imaging is that no spectroscopy is involved, so that neutron counting is less intrusive and more likely to be used in a cooperative monitoring agreement. The device may be used in a passive mode to view moderated neutron sources or in an active mode where an external source of neutrons is necessary to illuminate moderating materials.



(a)

(b)

FIGURE 9 IMAGES OF SAND PRODUCED USING EXTERNAL NEUTRON SOURCE:

(a) WITH PLASTIC INSERTED
(b) WITHOUT PLASTIC

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