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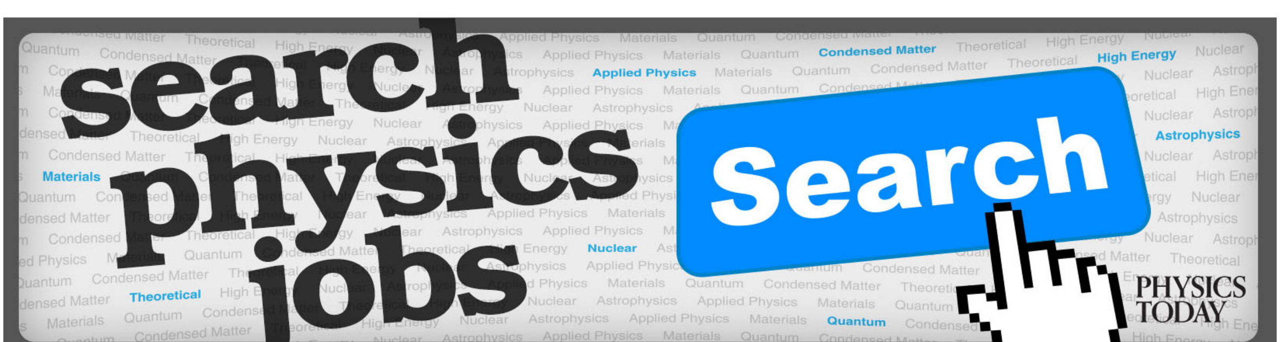

REVIEW OF SCIENTIFIC INSTRUMENTS **87**, 11D801 (2016)

# Application of the coincidence counting technique to DD neutron spectrometry data at the NIF, OMEGA, and Z

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A compact neutron spectrometer, based on a CH foil for the production of recoil protons and CR-39 detection, is being developed for the measurements of the DD-neutron spectrum at the NIF, OMEGA, and Z facilities. As a CR-39 detector will be used in the spectrometer, the principal sources of background are neutron-induced tracks and intrinsic tracks (defects in the CR-39). To reject the background to the required level for measurements of the down-scattered and primary DD-neutron components in the spectrum, the Coincidence Counting Technique (CCT) must be applied to the data. Using a piece of CR-39 exposed to 2.5-MeV protons at the MIT HEDP accelerator facility and DD-neutrons at Z, a significant improvement of a DD-neutron signal-to-background level has been demonstrated for the first time using the CCT. These results are in excellent agreement with previous work applied to DT neutrons. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4958910]

## I. INTRODUCTION

For the successful implementation of neutron spectrometry on inertial confinement fusion (ICF) and high energy density physics (HEDP) facilities, the signal-to-background (S/B) must be fundamentally understood and optimized. The technique must also be robust to intense electromagnetic pulses (EMPs) common in these environments. Over the last couple of decades, CR-39-based neutron spectrometry has proven to meet these requirements.[1–4] The reason for this is that the CR-39 material is a clear plastic that is completely insensitive to EMP and only moderately sensitive (on the order of $10^{-5}$–$10^{-4}$)[5] to neutrons.[5,6]

Neutrons and intrinsic defects in the CR-39 constitute the main sources of background in CR-39 data. In some CR-39 applications, the signal of interest can be much lower than these sources of background, necessitating techniques for significant background reduction. One such method is the coincidence counting technique (CCT)[7] developed for the magnetic recoil spectrometers (MRSs) on the NIF and OMEGA.[2] This technique is routinely applied to the MRS data to obtain down-scattered DT neutron spectra emitted by ICF implosions through which areal densities (ρR) are inferred.[3]

The CCT distinguishes signal tracks from background tracks by taking advantage of the fact that signal charged particles traverse the CR-39 in straight lines, which results in signal tracks that can be correlated by location on two separate surfaces of the CR-39. Antithetically, neutron tracks are the results of charged particles created volumetrically within the CR-39 over a large range of angles. As a result, their locations will vary between two separate surfaces allowing for effective discrimination using CCT. Intrinsic defects are also easily identified since they are unique to individual surfaces.

In this paper, the extension of the CCT to lower-energy signals relevant to DD-neutron spectrometry is discussed. This extension is vital to the design of a compact DD-neutron spectrometer based on a CH foil for the production of recoil protons and CR-39 detection.[8] In order for this diagnostic to measure both the primary and down-scattered spectra at the NIF, OMEGA, and Z, the CCT must reduce the background to acceptable levels. To test this, CR-39 was exposed to 2.5-MeV protons obtained at the MIT HEDP accelerator facility[9] and DD-neutrons obtained at Z. These experiments have demonstrated, for the first time, significant improvement in DD-neutron S/B levels from applying the CCT.

The structure of this paper is as follows. Section II discusses experiments that illustrate the coincidence counting of 2.5-MeV protons. Section III discusses the demonstration of DD-neutron background rejection using the CCT. Section IV concludes and discusses the path forward.

## II. COINCIDENCE COUNTING OF SIGNAL

The ability to correlate coincidence tracks created by 2.5-MeV signal protons was demonstrated in experiments using the MIT HEDP accelerator facility. In these experiments, a piece CR-39 with two different types of filtering was exposed to a total of ~$10^4$ DD protons (3.0 MeV). One half of the piece was filtered with 20 $\mu$m of Al to range the protons down to the desired 2.5 MeV whilst the other half was over-filtered to completely range out the protons creating a background region.

After exposure, the CR-39 was track etched for 3.0 h and analyzed using a standard counting technique (SCT). Then,

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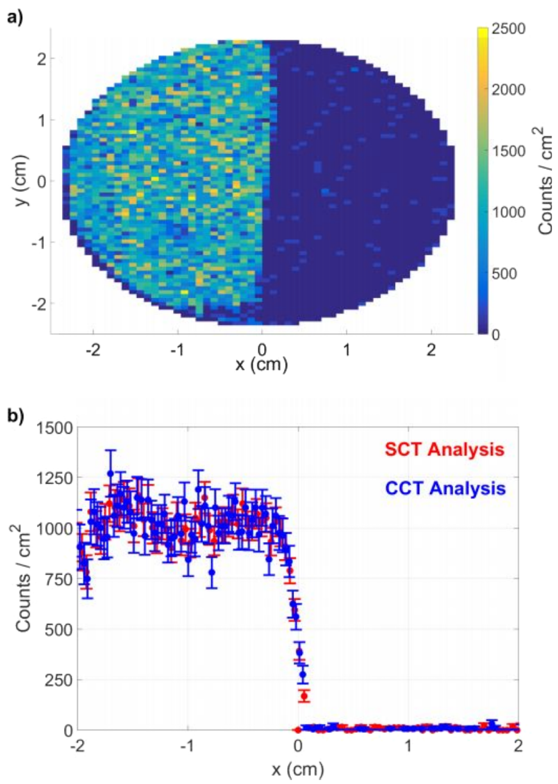


FIG. 1. Test of the CCT applicability to 2.5-MeV proton data. (a) Spatial distribution of tracks obtained from 2.5 MeV protons generated by the MIT HEDP accelerator facility shot A2015091702. The left hand side of the piece was filtered by 20 $\mu$m of Al to range DD protons down to 2.5-MeV while the right hand side was over-filtered to range out all protons. (b) Horizontal lineout of the average track density as determined by the SCT (red) and the CCT (blue). Data are in excellent agreement between the two methods indicating that the CCT successfully counted all of the coincidences and subtracted any random coincidences.

~50 $\mu$m of material was removed via bulk etching and then the piece was track etched for additional 3 h to redevelop the tracks for the CCT analysis. After ranging through this thickness of CR-39, the protons would have a remaining energy of ~1.5 MeV, which is detectable.

Fig. 1(a) shows the number of proton signal and background tracks (or counts) per cm$^2$ deduced from the SCT analysis. The left-hand side of the image shows the signal region (filtered by 20 $\mu$m-Al) while the right-hand side shows the over-filtered background region. Fig. 1(b) shows the horizontal lineout of the counts acquired from the SCT (in red) and the CCT (in blue). Both the SCT and CCT provide the same number of total counts, as well as the same spatial distribution of tracks within error bars. This indicates that all of the 2.5-MeV proton tracks can be correctly correlated between the two surfaces and that any random coincidences have been effectively subtracted using CCT.

## III. BACKGROUND REJECTION USING CCT

The primary purpose of the CCT is to isolate a signal of interest from a large background component. In the aforementioned accelerator experiments, no such background source existed to test the technique. Basic packages of CR-39 were fielded at the Z facility on MagLIF[10] shots Z2849, Z2850, Z2851, and Z2852 as a part of developing the DD-neutron spectrometer. Several of these pieces were exposed to intense neutron fluences (~$2 \times 10^8$ n/cm$^2$), resulting in a large number of neutron-induced tracks.

To test the background rejection capabilities of the CCT, some of these CR-39 pieces were brought back to MIT and exposed to a total of ~$5 \times 10^4$ DD-protons generated by the MIT HEDP accelerator. This number was chosen to ensure that S/B was ~0.7 to effectively test the CCT. During this exposure, one half of the CR-39 was filtered with 20 $\mu$m of Al (to range the protons to 2.5 MeV) and the other half was filtered to completely block the protons. Fig. 2(a) shows the number of proton signal and background tracks (or counts) per cm$^2$ that was used in the CCT analysis. Fig. 2(b) shows the vertical lineout of the background-subtracted data obtained with the SCT (red) and the CCT (blue). Again, it is shown that the CCT is able to correlate and accurately count the proton tracks in the presence of a neutron background.

The background levels obtained with the two methods are of particular interest. Using the SCT, the neutron background measured in the over-filtered region of the CR-39 is due to neutron induced tracks. The proton signal is determined by

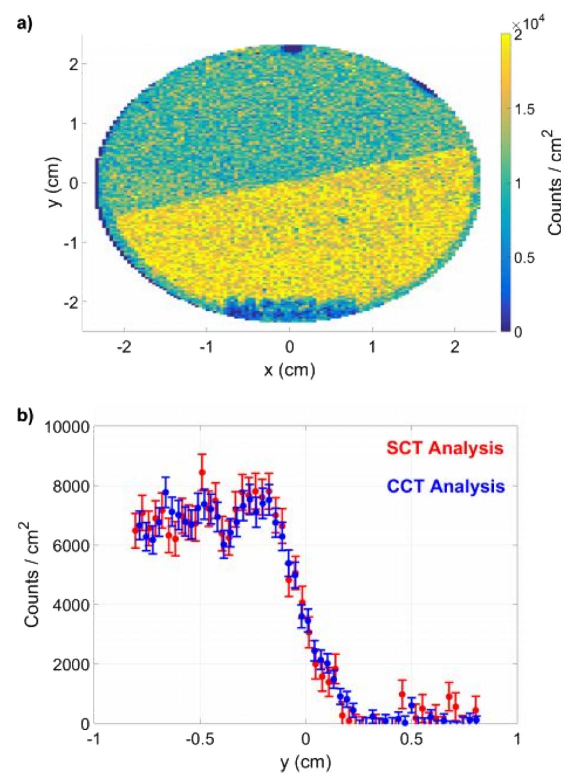


FIG. 2. (a) Spatial distribution of all tracks on the CR-39 used in the SCT and the CCT. Both halves of the piece were exposed to DD-neutrons generated from MagLIF shot Z2850 which accounts for the uniform background. The bottom half of the piece was exposed to DD-protons generated by the MIT HEDP accelerator facility shot A2016021002 ranged down to 2.5 MeV via a 20-$\mu$m Al filter. (b) Vertical lineout of the average track density as determined by the SCT (red) and the CCT (blue). Data are in excellent agreement between the two methods indicating that the CCT successfully discriminated all of the 2.5 protons from the large neutron background. The right-hand side of the graph corresponding to the background region is more uniform when analyzed with the CCT as a result of the lower background levels.

TABLE I. Signal and background tracks determined by the SCT and CCT analysis. The resulting S/B for the two techniques is also shown.

| Analysis technique | Signal (tracks $cm^{-2}$) | Background (tracks $cm^{-2}$) | S/B |
|---|---|---|---|
| SCT | $(7.0 \pm 0.6) \times 10^3$ | $(10.0 \pm 0.4) \times 10^3$ | 0.7 |
| CCT | $(6.9 \pm 0.5) \times 10^3$ | $(2.4 \pm 0.2) \times 10^3$ | 2.8 |

subtracting the total signal in the signal region from the neutron background in the background region.

For the CCT, false coincidences can be registered if two non-correlated tracks appear at the same location on the two surfaces by random chance. The probability of these random coincidences scales strongly with the total track density and they serve as the primary background source for this technique. In the analysis, this is assessed by misaligning the two surfaces (typically by ~500 $\mu$m) and analyzing the signal region for any coincidences. Because they are misaligned, any coincidences found this way must be random in nature and set the background levels for the measurement. As a result, the over-filtered background region is unnecessary for the CCT. Table I shows the signal and background-induced number of tracks obtained with the two methods. In this example, the CCT reduced the total background by over a factor of 4 as indicated by the S/B values in Table I.

In Ref. 7, it is show that the CCT background density due to random coincidences ($B_{CCT}/A$) can be expressed analytically as

$$B_{CCT}/A = n_1 n_2 \pi R_c^2, \tag{1}$$

where $n_1$ and $n_2$ are the total track densities on the first and the second surfaces, respectively, and $R_c$ is the correlation radius or the maximum offset two tracks can have to be considered correlated in the analysis. For the analysis shown in Table I, $n_1$ and $n_2$ were $(17.0 \pm 0.6) \times 10^3$ and $(37.3 \pm 0.9) \times 10^3$ tracks $cm^{-2}$, respectively, and a $R_c$ of 11 $\mu$m was used. The increase in the number of tracks between the first and the second surfaces is a result of a larger volume of CR-39 having been etched away. Since this volume acts as the source of the neutron-induced tracks, the total number of tracks will increase with etch time.[5] With those parameters, the background fluence from random coincidences is predicted to be $(2.4 \pm 0.05) \times 10^3$ $cm^{-2}$, which is in excellent agreement with the inferred value in Table I.

## IV. CONCLUSIONS AND PATH FORWARD

It has been shown that the CCT can be readily extended to lower-energy protons relevant to the design of a DD-neutron spectrometer for the NIF, OMEGA, and Z. Reductions in background levels were shown to be in excellent agreement with predictions derived by previous work, suggesting that the CCT will enable measurements of down-scattered DD-neutron spectra with a CR-39 based spectrometer. Because the down-scattered DD-neutron spectra have energies well below 2.5 MeV, future work will be focused on characterizing the lower-energy bound of the CCT. At lower energies, the range of protons in CR-39 decreases rapidly, limiting the thickness of material that can be bulk etched away for the CCT analysis.

Finally, the CCT is subject to additional sources of background coincidences (such as intrinsic) that are relevant at track densities lower than those explored in this work. Because the background due to random coincidences decreases rapidly with decreasing track density, understanding the behavior of these additional sources will be crucial for defining the optimal conditions for a DD-neutron spectrometer. Future work will characterize the level of these background sources at energies relevant to down-scattered DD-neutron spectra.

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