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# Cross Section Measurements Using the Zero Degree Detector

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**Abstract:** The Zero Degree Detector (ZDD) is an instrument that has been used in accelerator exposures to measure the angular dependence of particles produced in heavy ion fragmentation experiments. The ZDD uses two identical layers of pixelated silicon detectors that make coincident measurements over the active area of the instrument. The angular distribution of secondary particle produced in nuclear interactions for several heavy ions and target materials will be presented along with performance characteristic of the instrument.

## Introduction

The Zero Degree Detector (ZDD) was developed to study the secondary particles produced at large laboratory angles by nucleus-nucleus interactions for several projectile-target combinations at energies between 0.3 GeV/u to a 10 GeV/u. The ZDD was designed to operate along with the Lawrence Berkeley Laboratory (LBL) spectrometer that has been used for extensive fragmentation measurements [1]. These studies support NASA's manned missions as related to radiation health for astronauts [2]. The accelerator beam particles and energies are representative of the interplanetary flux due to the galactic cosmic rays and solar energetic particles. The target materials are selected as representative materials for spacecraft or habitat shielding. The measured cross sections are used in nuclear transport codes that are used to determine the radiation exposure for various spacecraft and habit designs. We report here on measurements made by one of three detector systems used in these measurements, the ZDD, which provides wide angular coverage of off-axis secondary particles produced with fine segmentation and measures the ionization energy loss of these charged particles. The accelerator measurements reported here were made in conjunction with the LBL on-axis spectrometer, but in this paper only ZDD data is presented.

## Exposures

Exposures have been made at NASA's Space Radiation Laboratory and the Alternating Gradient Synchrotron at Brookhaven National laboratory. Exposures have also been completed at the Heavy Ion Medical Accelerator in Chiba, Japan. The primary beams used in the exposures include Fe(0.5, 1, 3, 5, 10GeV/u), Si(0.8, 0.6, 3, 5, 10 GeVu), C (0.3, 1, 3, 5, 10GeV/u) , protons (1 GeV), He (0.3 GeV/u), Ar(0.7 GeV/u). The target materials have included elemental targets of Fe, Al, C, Cu, and Pb as well as compound targets such as polyethylene and specialized composite materials. The elemental target thicknesses include both thin (~2g/cm$^2$) and thick (15-30 g/cm$^2$) targets used for cross section data and shielding effectiveness measurements respectively. These combinations have been selected to supplement existing cross section data, and to improve the cross section data specific to radiation shielding for typical spacecraft materials. Results reported here are from the high energy exposures.

## Experimental Setup

The current measurement program builds on past measurements performed by the LBL group. The set of instruments used in these exposures consists of an on-axis detector system, including multiple plastic scintillators and monolithic silicon detectors, to measure particles near the beamline axis; the ZDD that measures secondary charged particles that are produced at large angles to the beam line; and an alternate off-axis detector system composed of silicon strip detectors developed at University of Houston [3]. The experimental layout is depicted in figure 1 which shows the relative position of all 3 detector systems.

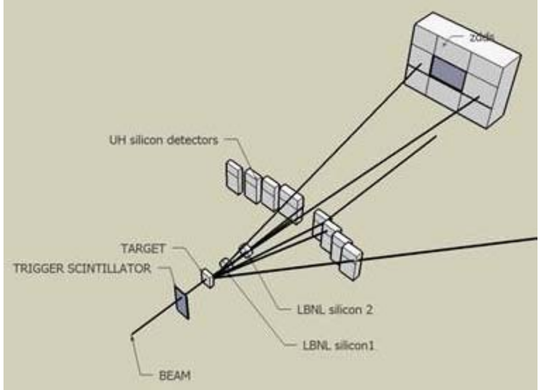

**Figure 1: Experimental setup. Three separate detector systems were integrated to provide additional coverage and information about the interactions.**

### Detector

A brief description of the ZDD detector is provided here and a more detailed description has already been published [4]. The ZDD consists of two planes of 512 contiguous pixels each with dimensions 1.2×1.2cm$^2$ made from silicon wafers 0.3 mm thick (figure 2). Each plane has an overall dimension of 30×30cm$^2$, but there is a central 10×10cm$^2$ cut-out to allow particles near the beam line to pass through. The two planes are mounted close together with the pixels on each plane aligned to form 512 detectors pairs. These detector pairs are used in coincidence to reduce the effects of background, electronic noise and spurious signals.

### Trigger

The raw trigger is formed by two plastic scintillators that are in the beam line: one upstream of the target and immediately behind the target material. An event trigger was produced when this raw trigger was present and the data acquisition system (DAQ) was not busy. This event trigger is formed internal to the on-axis detector system and was distributed to the ZDD and UH detectors. A separate set of scintillators immediately behind the ZDD triggers on off-axis particles that strike the ZDD. Both triggers are used to initiate the readout of the ZDD. The triggers reliably detect minimum ionizing particles (MIP).

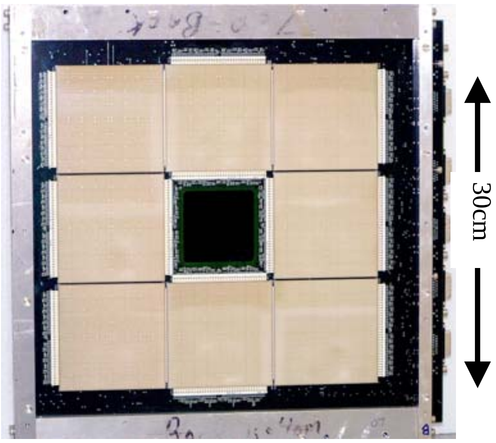

Figure 2: Picture of one plane of the ZDD. Each plane is made of 8 modules each with 64 pixels. The detector is placed on the beam line such that the high rate primary beam goes through the hole in the center and lower rate off-axis secondary particles are recoded.

To link the detector systems, a unique number was generated for each ZDD event and recorded by the DAQ systems. The on-axis trigger was approximately 70% effective at selecting useful events. The efficiency for identifying events in both the LBL and ZDD DAQs was nearly 100% for most of the data presented here.

### Data Analysis

An example of an event recorded by the ZDD is shown in figure 3. The pulse height analysis of each pixel on both planes is needed to determine the relevant quantities. Each electronic channel has individual gain and noise characteristics.

These responses are normalized to a standard signal response by injecting precise fixed amounts of charge into each channel. The charges range from 0.8fC to 8pC, which corresponds to sub-MIP to 2000 MIP signals. The response function of each channel is measured and recorded. All signals from each plane then are normalized. Data collected during this process is also used to characterize the cross talk between neighboring channels and pixels, which becomes significant for the upper range of signals that are produced in these exposures.

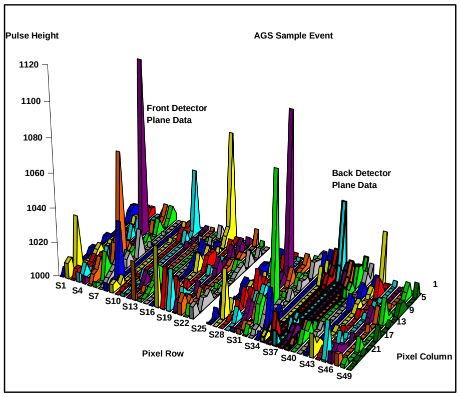

Figure 3: Sample raw data from a single event recorded by the ZDD. The vertical axis indicates the relative pulse height of the signal in each pixel (offset by 1000). The other two axes identify row and column on each detector plane. Several correlated pairs of hits can be seen between the two planes.

To make an absolute calibration of the recorded signals, special exposures are made with the primary beam of known energy and charge (Z). Several of these runs have been completed covering a wide range of charge and energy. Calibration data collected with a silicon beam at 0.8 GeV/u is shown in figure 4. The residual mass on the beam line produce some secondary fragments in the beam which are resolved by the ZDD.

The majority of secondary particles are singly charged with a velocity component comparable to the primary particle and the ZDD can reliably detect them. The data from the individual detectors can be combined to provide high statistic sample of the secondary particles. An unbiased sample of data is shown in figure 5 which shows a clear minimum signal peak. The peak corresponds to 15(12) ADC channels for the front (back) plane.

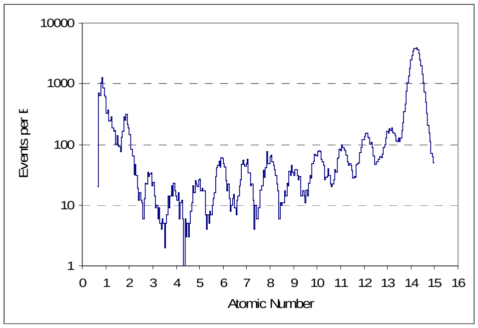

Figure 4: Charge Calibration measurement using a silicon beam. Some fragmentation occurred because of the residual mass on the beam line. Surviving fragments are clearly resolved.

During the exposures pedestal triggers are routinely sent to the DAQ to record pedestal information. This data also provides a measure of the chance coincidence between the two planes and between each pair of pixels. The measured chance coincidence rate is 4/13000 for a threshold of 10 ADC channels and 85/13000 for a threshold of 6 ADC channels. There were no chance coincidence hits with a threshold equal to the average MIP signal out of 13000 events. A typical width of the noise distribution is 2-3 ADC channels. Five pixels on the front plane and 3 on the back plane had excessive noise and were eliminated for most of this analysis.

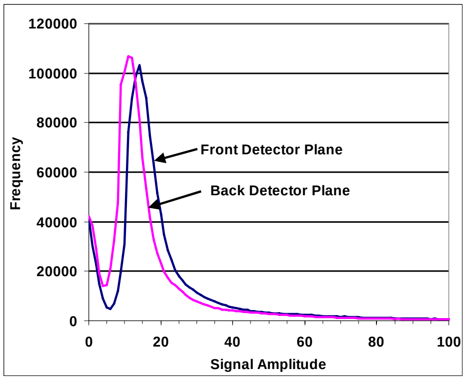

Figure 5: Unbiased pulse height distribution of data recorded by the front and back detector planes. The singly charge particle peak is clearly separated and this separation improves requiring coincidence between the planes.

## Results

We have analyzed the number of secondary particles striking the ZDD for triggers that pass the selection criteria described above. The resulting distributions for several different beam-target-energy combinations have been recorded and the average of the distributions is plotted in figure 6. We use the coincidence requirement between the pixels on the front and back plane to insure the detected signal is a penetrating particle. The recorded signals are further required to be in pixels that are aligned front to back. The separation between the two planes is 4 to 6mm and the relative mis-alignment of the two planes is <0.3mm. The ZDD is 96cm from the target so that the overlapping coverage by two pixels is about 95%. The charge of secondary particles can be identified assuming they are near the beam velocity. The multiplicity data quantifies the relative importance of off-axis data from these interactions as related to radiation shielding considerations

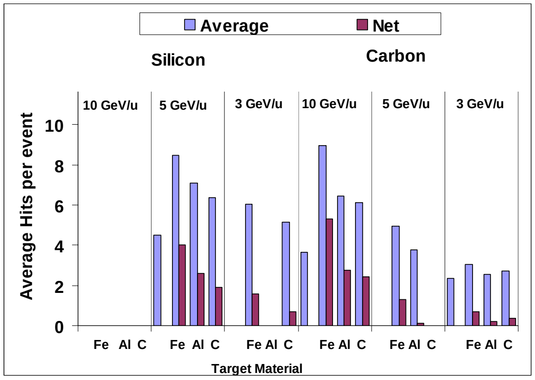

Figure 6: Measured multiplicity for 3 different target materials with silicon and carbon projectiles at 3, 5 and 10 GeV/u. The no target data is used to estimate the contamination in the beam and due to interactions in material upstream.

At 96cm from the interaction the ZDD detector detects secondary particles that are 3-15 degrees off-axis from the interaction point. The inner and outer regions are partially sampled, due to the layout of the detectors. Since the precise position of a hit within a pixel is not known, we assign the center of each hit pixel in defining the angular measurement. Figure 7 shows the radial distribution of hits recorded in the ZDD for events that satisfy the selection criteria above. The angular measurements depend on the relative position of the detector to the primary beam axis and the width of the beam spot. The mis-alignment of the detector during the exposure was as large as 1.8 cm and has been corrected in the results.

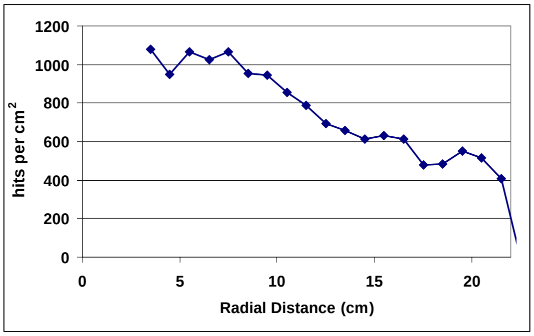

Figure 7: Radial distribution of secondary particles measured by the ZDD for 60,000 silicon primaries incident on an iron target. The distribution is for signals less than <200 ADC channels.

## Conclusion

The data presented here was for primary nuclei with 3, 5 and 10 GeV/u energy. Heavy fragments are near to the beam line and therefore the data recorded by the ZDD in these exposures is predominantly singly charge particles (protons, pions, muons, electrons etc). Analysis of data at lower primary energies will contain more heavy nuclei.

## References

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