Fermilab

Geometry Survey of the Time-of-Flight Neutron-Elastic Scattering (Antonella) Experiment

Babatunde O'Sheg Oshinowo[a] *and Federico Izraelevitch*[a, b]

[a] *Fermi National Accelerator Laboratory (Fermilab), Batavia, IL 60510, USA*
[b] *Departamento de Física, FCEN - Universidad de Buenos Aires, Argentina*

Abstract

The Antonella experiment is a measurement of the ionization efficiency of nuclear recoils in silicon at low energies [1]. It is a neutron elastic scattering experiment motivated by the search for dark matter particles. In this experiment, a proton beam hits a lithium target and neutrons are produced. The neutron shower passes through a collimator that produces a neutron beam. The beam illuminates a silicon detector. With a certain probability, a neutron interacts with a silicon nucleus of the detector producing elastic scattering. After the interaction, a fraction of the neutron energy is transferred to the silicon nucleus which acquires kinetic energy and recoils. This kinetic energy is then dissipated in the detector producing ionization and thermal energy. The ionization produced is measured with the silicon detector electronics. On the other hand, the neutron is scattered out of the beam. A neutron-detector array (made of scintillator bars) registers the neutron arrival time and the scattering angle to reconstruct the kinematics of the neutron-nucleus interaction with the time-of-flight technique [2]. In the reconstruction equations, the energy of the nuclear recoil is a function of the scattering angle with respect to the beam direction, the time-of-flight of the neutron and the geometric distances between components of the setup (neutron-production target, silicon detector, scintillator bars). This paper summarizes the survey of the different components of the experiment that made possible the off-line analysis of the collected data. Measurements were made with the API Radian Laser Tracker and I-360 Probe Wireless. The survey was completed at the University of Notre Dame, Indiana, USA in February 2015.

INTRODUCTION

When a neutron or the hypothesized dark matter particles interacts with the nucleus of an atom, the nucleus can recoil [1]. A fraction of the energy transferred to the recoiling nucleus disturbs electrons in adjacent atoms, producing free electric charge. This fraction is called ionization efficiency. The bigger this number, the larger the signal in the detector and the easier it is to detect nuclear recoils. Ionization efficiency measurements at low energies are important to calibrate the energy measurement of silicon detectors used in dark matter direct-detection search experiments.

The Antonella experiment is a measurement of the ionization efficiency of nuclear recoils in silicon at low energies [1]. It is a neutron elastic scattering experiment motivated by the search of dark matter particles. In this experiment, a proton beam hits a lithium target and neutrons are produced. The neutron shower passes through a collimator that produces a neutron beam. The beam illuminates a silicon detector. With a certain probability, a neutron interacts with a silicon nucleus of [1] the detector producing elastic scattering. After the interaction, a fraction of the neutron energy is transferred to the silicon nucleus which acquires kinetic energy and recoils. This kinetic energy is then dissipated in the detector producing ionization and thermal energy. The ionization produced is measured with the silicon detector electronics. On the other hand, the neutron is scattered out of the beam. A neutron-detector array (made of scintillator bars) then registers the neutron arrival time and scattering angle to reconstruct the kinematics of the neutron-nucleus interaction with the time-of-flight technique [2]. In the reconstruction equations, the energy of the nuclear recoil is a function of the scattering angle with respect to the beam direction, the time-of-flight of the neutron and the geometric distances between components of the setup (neutron-production target, silicon detector, scintillator bars). This paper summarizes the survey of the different components of the experiment, which made possible the off-line analysis of the collected data.

---

* Fermilab-CONF-16-455-PPD

THE ANTONELLA EXPERIMENT

Time of Flight Experiment

The ionization efficiency, ε, of nuclear recoils in silicon at low energies is defined as the ratio of the energy that produces ionization, E_i, with respect to kinetic energy of the nuclear recoil, E_{NR} [2]

$$\varepsilon = \frac{E_i}{E_{NR}}$$

E_i is measured in a silicon detector (SiDet) calibrated with electron recoils and E_{NR} is the kinetic energy of the nuclear recoil calculated from non-relativistic kinematics as

$$E_{NR} = E_n \frac{2}{(A+1)^2}\left[A + \sin^2\theta - \cos\theta\sqrt{A^2 - \sin^2\theta}\right]$$

where θ is the scattering angle with respect to the beam direction, A is the atomic number of the silicon nucleus, and E_n is the energy of incoming neutron. The energy of the neutron is measured by the time-of-flight technique as

$$E_n = \frac{m_n}{2(\Delta t)^2}\left[l + r\,\frac{(A+1)}{\cos\theta + \sqrt{A^2 - \sin^2\theta}}\right]^2$$

where Δt is the total time-of-flight of the neutron from the neutron production target to the neutron detector, m_n is the mass of the neutron, l is the geometrical distance from the neutron production target to the SiDet, and r is the distance from the SiDet to the neutron detector.

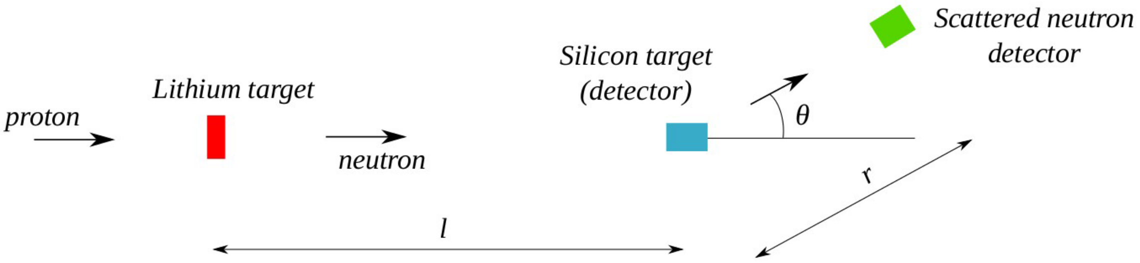


Figure 1. Schematic Layout of the Antonella experiment.

TIME-OF-FLIGHT NEUTRON-ELASTIC SCATTERING (ANTONELLA) EXPERIMENT

The Antonella experiment was carried out at the FN Tandem Van de Graaff accelerator of the Institute for Structure and Nuclear Astrophysics (ISNAP), University of Notre Dame, Indiana, USA [3] (Figure 2). Figure 3 shows the experiment setup.

Figure 2. FN Tandem Van de Graaff accelerator University of Notre Dame, Indiana, USA.

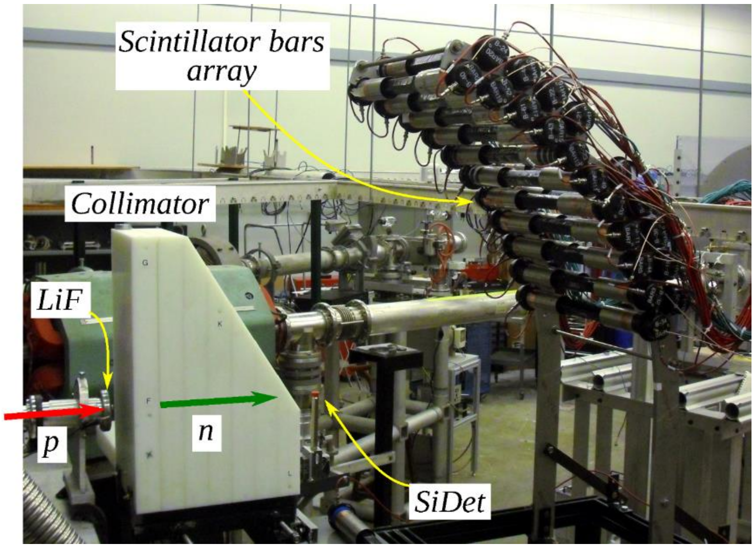
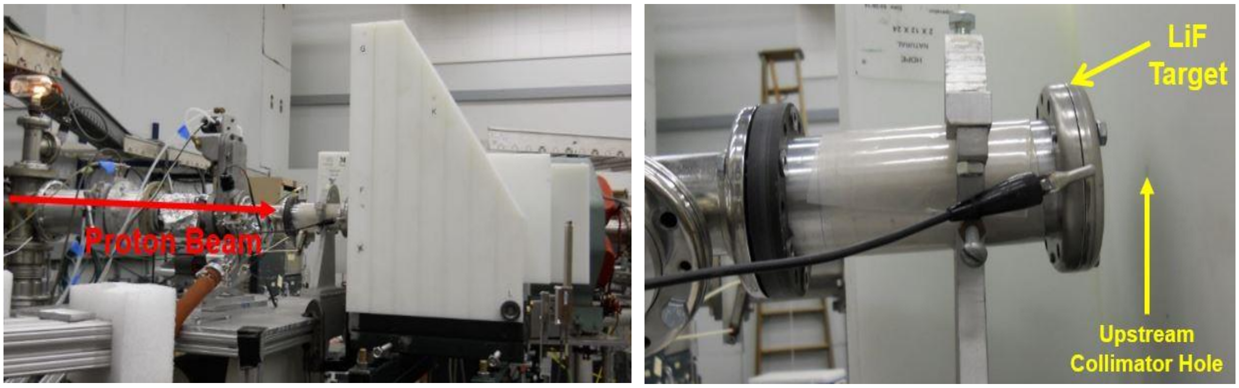


Figure 3. Antonella experiment setup at University of Notre Dame.

Proton - Lithium Target (LiF) - Neutron

A 2.326 MeV proton beam was used on a lithium target to produce a neutron beam. The LiF target was located on the inner face of the downstream flange at the end of proton beampipe as shown in Figures 3 and 4b. The actual target material was a 4.74 mg/cm^2 film of LiF, deposited on 197 mg/cm^2 of Au, onto an Al backing foil. This yielded in a broad-energy neutron production, from 600 keV maximum, tuned with the proton energy, down to reaction threshold [1].

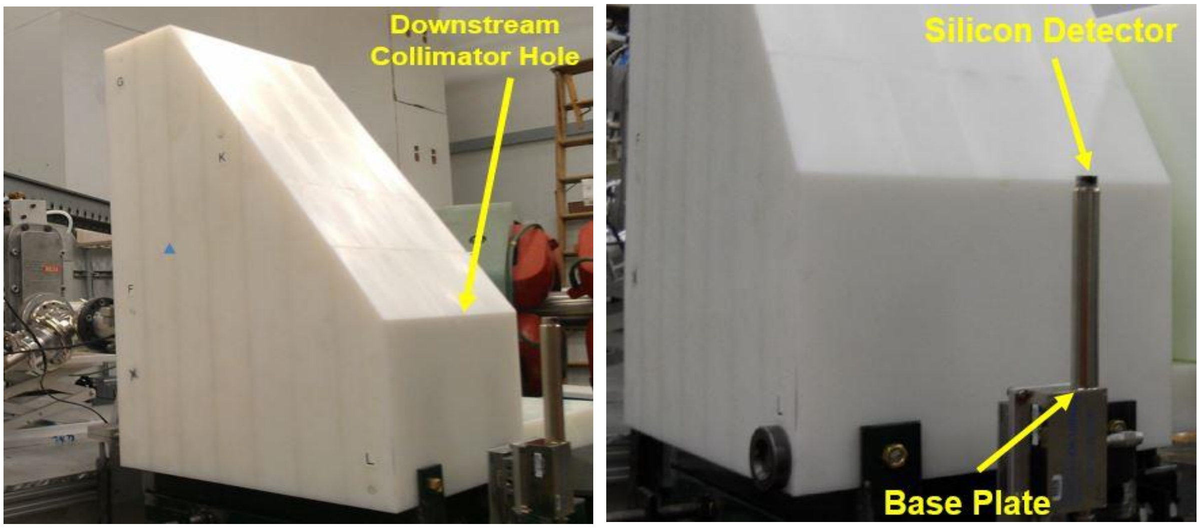


(a) (b)

Figure 4. Proton beam and LiF Target.

Collimator

The neutron beam traveled through the collimator to illuminate a silicon detector. The collimator was a high-density polyethylene collimator with a 6.3 mm diameter hole going through it (Figures 4b and 5a). The length between the holes was 377.7 mm. The collimator was located upstream of the LiF target with the holes in line with the center of the flange. Seven 6.35 mm holes were drilled into the sides of the collimator and were used as survey fiducials for referencing the collimator.



(a) (b)

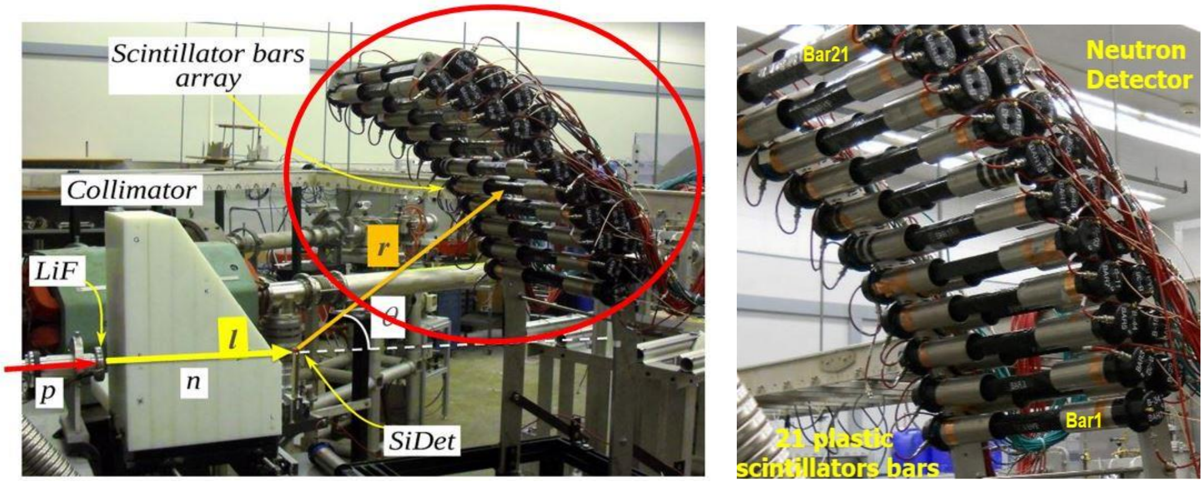
Figure 5. Collimator and Silicon Detector (SiDet).

Silicon Detector (SiDet)

With a certain probability, a neutron interacted with a silicon nucleus of the detector producing elastic scattering [1]. The SiDet was a commercial X-ray detector which consisted of a peltier-cooled silicon-drift diode with a reset-type preamplifier in the same housing (Figure 5). It was located 92.5 mm from the downstream hole of the collimator and 514.9 mm from the LiF neutron-production target (Figures 4b and 5). The center of the SiDet at the top was about 134.7 mm high from the baseplate. The diameter of the SiDet at the baseplate was about 17.5 mm and 14.0 mm at the top (Figure 5). The SiDet was about 0.5 mm above the neutron beamline.

Neutron Detector

A scattered neutron detector is a single scintillator bar. The Antonella neutron detector was an array of 21 plastic scintillators bars. Each bar was 30 mm x 30 mm of cross section and 250 mm in length coupled to two photomultiplier tubes (PMTs) [1] (Figures 3 and 6). The neutron detector array covered from $\theta = 12.6°$ to $\theta = 74.0°$ with respect to the beam axis. The bars were positioned in two layers, to pack them as close as possible given the mechanical restrictions imposed by the existing PMT bases. The distance, *r*, from the SiDet to the scintillator bars ranged between 800 to 889 mm depending on the bar location. The collimator, SiDet and neutron detector were mounted on a cart with the adjustments needed to position and align the system [1].



(a) (b)

Figure 6: Neutron Detector - Array of Plastic Scintillators Bars.

SURVEY OF THE GEOMETRY OF ANTONELLA EXPERIMENT

The geometry parameters of the Antonella Experiment *l*, *r and* θ (Figure 7) were surveyed by the Alignment and Metrology Department of Fermilab at the FN Tandem Van de Graaff accelerator of the Institute for Structure and Nuclear Astrophysics (ISNAP), University of Notre Dame, Indiana, USA.

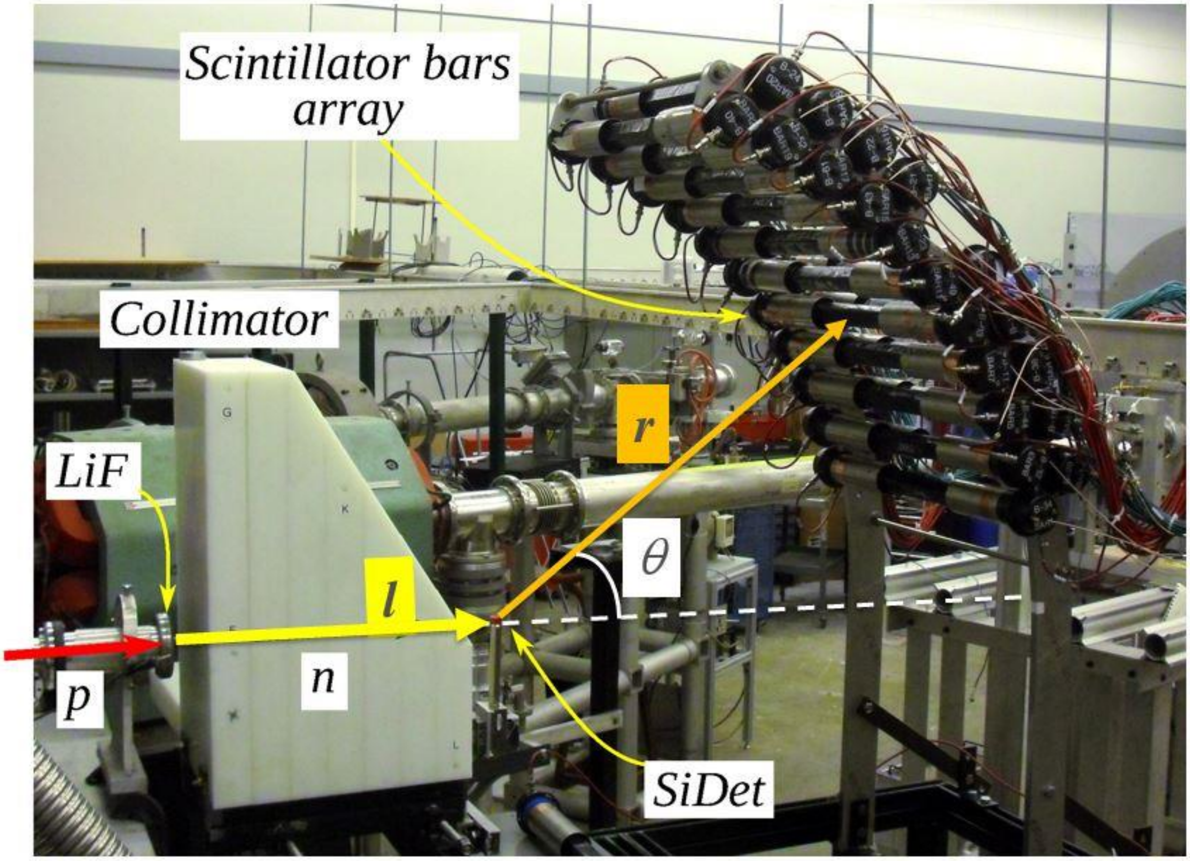


Figure 7. The geometry parameters of the Antonella Experiment - *l*, *r* and *θ*.

Survey Methodology

The survey instrumentation that is being used for the detector survey is as follows:

i) Automated Precision Inc. (API) Radian^{TM} Laser Tracker and Spatial Analyzer^{TM} software were used to establish temporary control points around the experiment. It was also used to measure the proton beamline, collimator and SiDet. The Laser Tracker (Figure 8) is a portable 3D measurement system that uses laser feed-back and motorized steering mirrors to track the location of a spherical mounted retroreflector (SMR). The instrument accuracy is 10 µm [4].

ii) API Intelliprobe 360^{TM} Wireless (I-360 Probe) was used to measure the scintillator bars in the neutron detector. The I-Probe 360 (Figure 8) is more accurate at measuring hidden points that cannot be obtained with SMR. It is used as an accessory to the Radian Laser Tracker. The instrument accuracies for 3D points for up to 7 m distance from the Laser Tracker are 100 µm for horizontal probe position and 125 µm for vertical probe position [5].

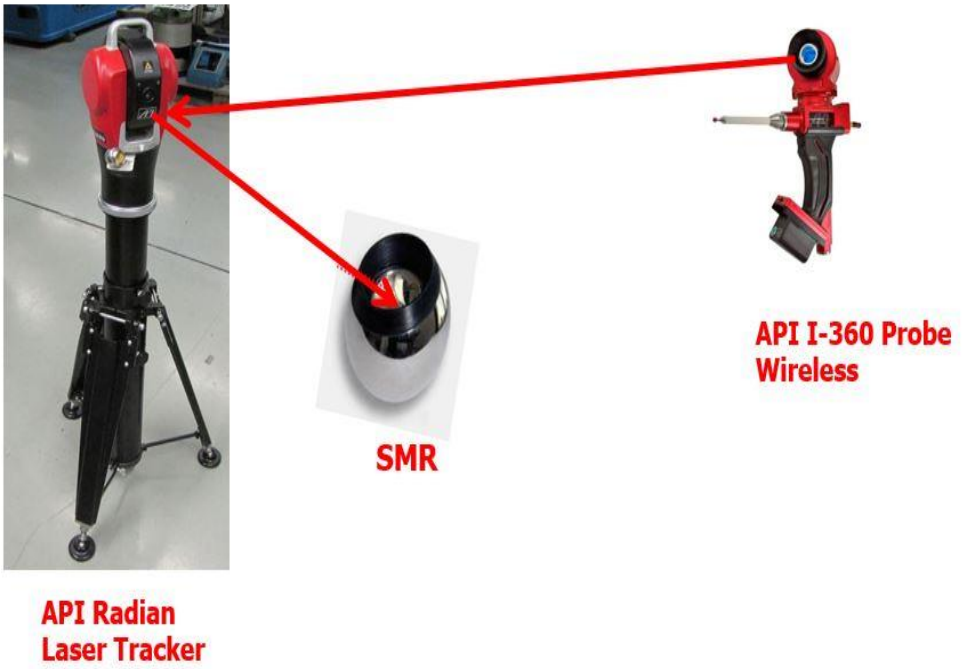


Figure 8: API Radian Laser Tracker and API I-360 Probe Wireless.

Laser Tracker Measurements

A local control network was established around the volume of the experiment by gluing fiducials (magnet rings) on the floor and some vertical structures in the experiment hall. Measurements to these fiducials allowed the Laser Tracker setups be connected to one another in the same local coordinate system. There were three Laser Tracker setups for the entire job (Figure 9). The first setup (Instrument 0) was used to measure the proton beampipe, LiF target flange, the upstream collimator hole, the collimator fiducials, SiDet detector center, and the upstream parts of the scintillator bars (Figure 10). All the sides of the scintillator bars were not visible from this setup. The second setup (Instrument 1) was used to measure the collimator fiducials, SiDet and the downstream parts and other parts of the scintillator bars (Figure 11). The third setup (Instrument 2) was used to measure the downstream collimator hole, the collimator fiducials and the SiDet detector center (Figure 12).

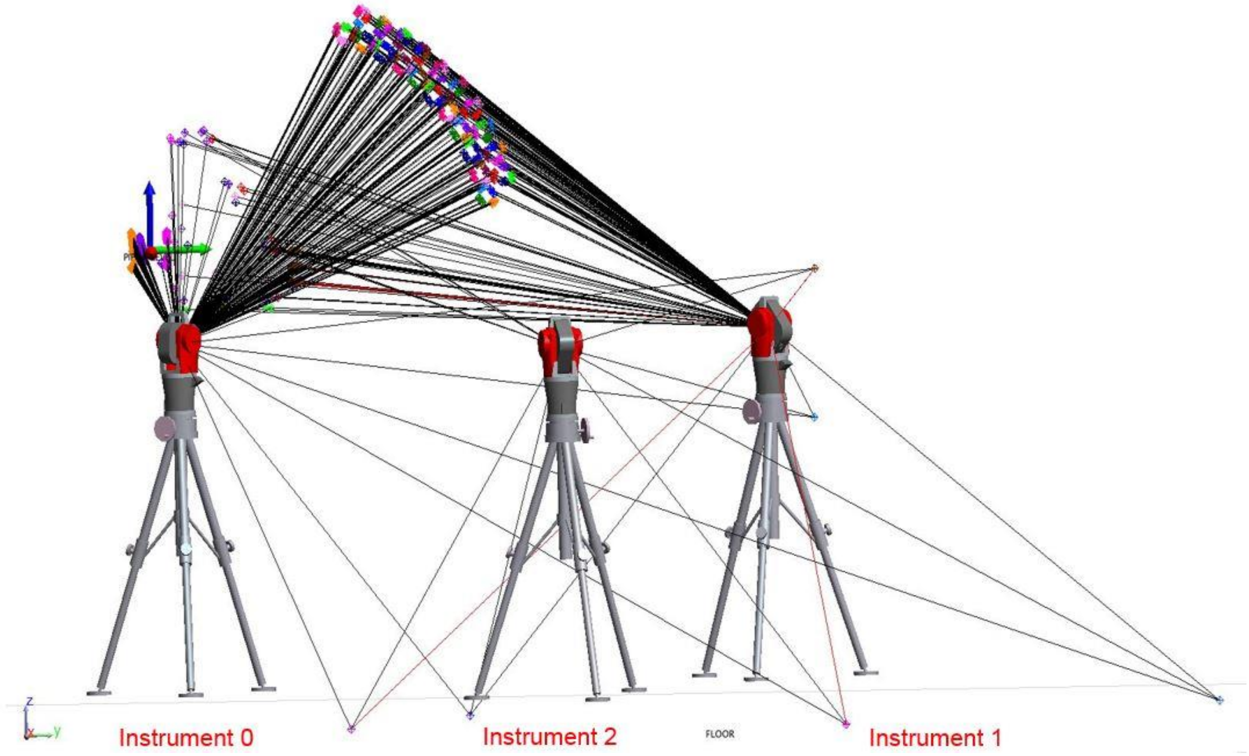


Figure 9: Laser Tracker Setup – All Instruments.

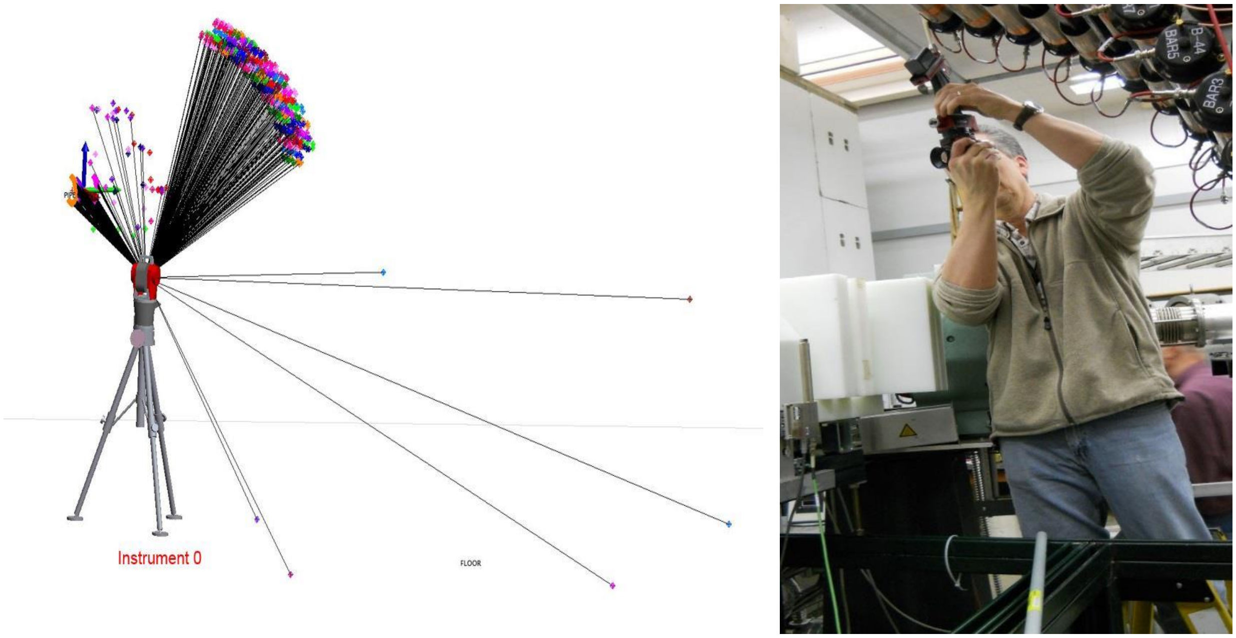


Figure 10: Laser Tracker Setup – Instrument 0.

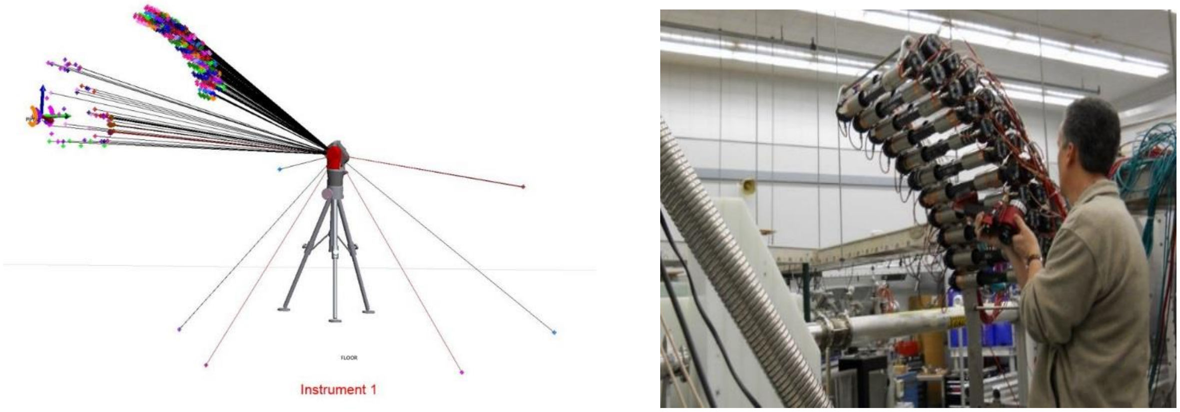


Figure 11: Laser Tracker Setup – Instrument 1.

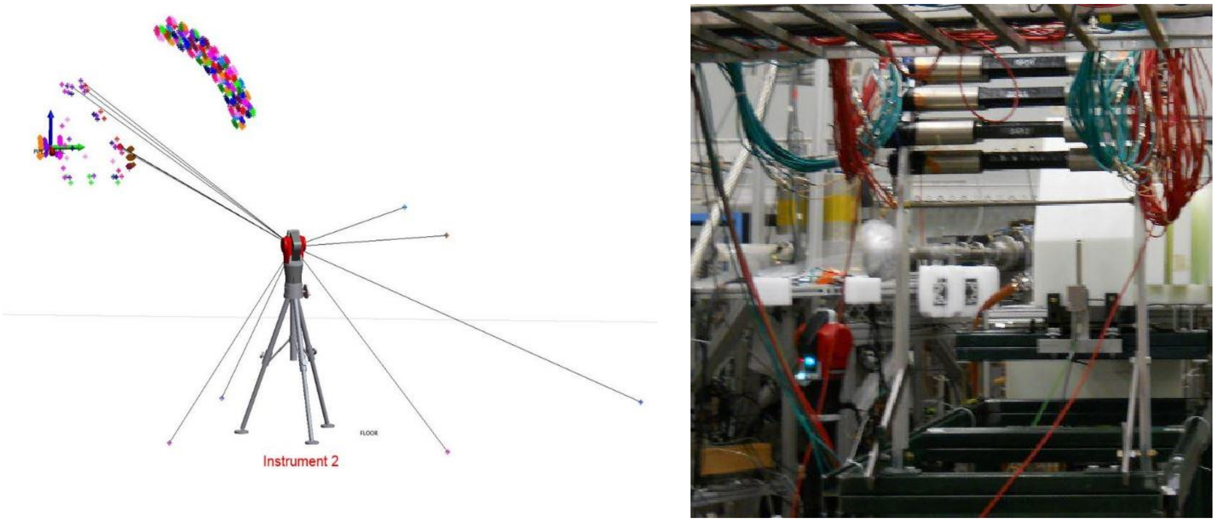
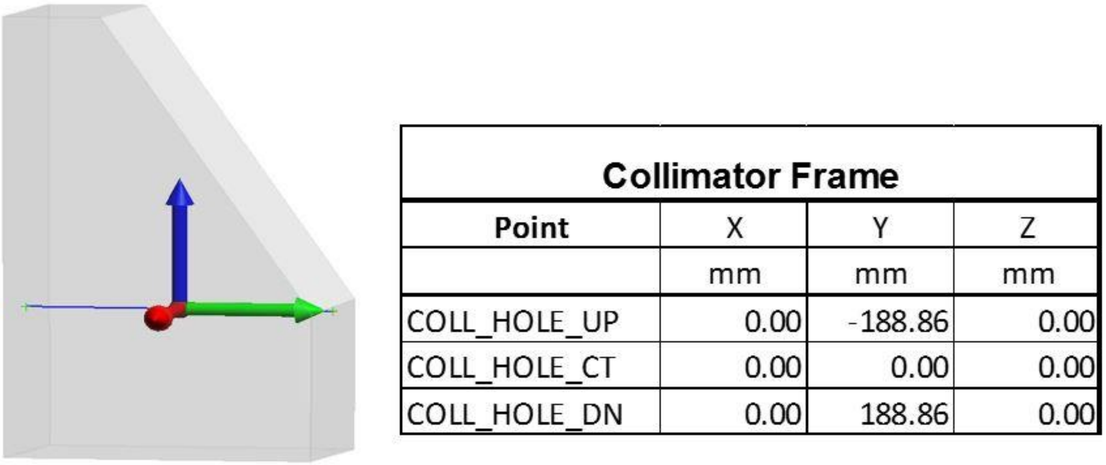


Figure 12: Laser Tracker Setup – Instrument 2.

Neutron Beamline Coordinate System

The neutron beamline is defined by the centers of upstream and downstream holes of the collimator. A collimator frame - Collimator with level Z - is defined such that the origin (0, 0, 0) is at the midpoint between the two holes (COLL_HOLE_CT). The primary +Y-axis (green) is defined by the origin and the center of the downstream hole (COLL_HOLE_DN). The secondary +X-axis (red) points beam right perpendicular to the Y-axis. The +Z-axis (blue) is up (gravity) (Figure 13).



Collimator Frame			
Point	X	Y	Z
	mm	mm	mm
COLL_HOLE_UP	0.00	-188.86	0.00
COLL_HOLE_CT	0.00	0.00	0.00
COLL_HOLE_DN	0.00	188.86	0.00

Figure 13. Neutron Beamline Coordinate System.

Survey Calculations and Results

Figure 14 shows the graphical summary of all the calculations and results from the Spatial Analyzer™ software for the geometry parameters of the Antonella experiment - *l*, *r* and θ.

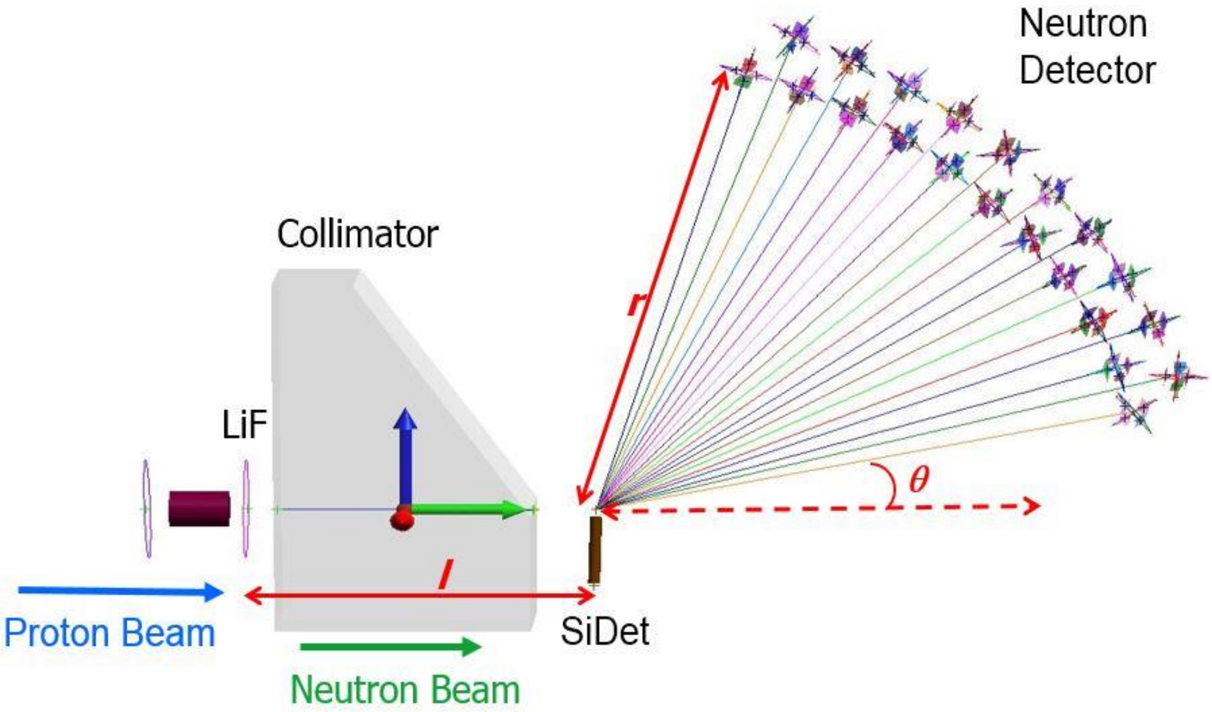
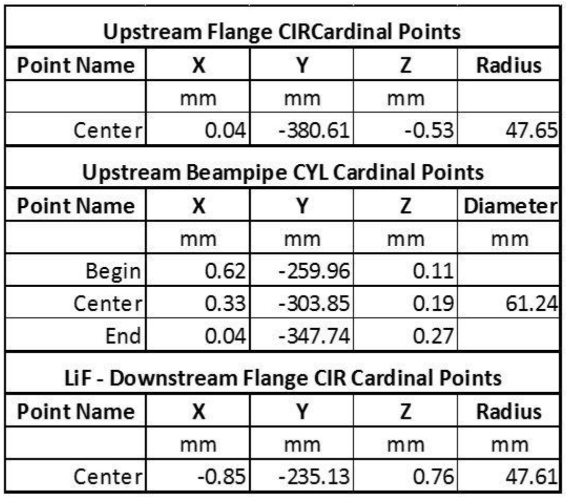


Figure 14. Graphical summary of geometry parameters of the Antonella experiment - *l*, *r* and θ.

LiF Target and Proton Beamline

The proton beampipe was measured as a cylinder and the upstream and downstream flanges in Figure 4b were measured as circles. Table 1 shows the results of the cylinder and circle fits.



Upstream Flange CIRCardinal Points

Point Name	X	Y	Z	Radius
	mm	mm	mm	
Center	0.04	-380.61	-0.53	47.65

Upstream Beampipe CYL Cardinal Points

Point Name	X	Y	Z	Diameter
	mm	mm	mm	mm
Begin	0.62	-259.96	0.11	
Center	0.33	-303.85	0.19	61.24
End	0.04	-347.74	0.27	

LiF - Downstream Flange CIR Cardinal Points

Point Name	X	Y	Z	Radius
	mm	mm	mm	mm
Center	-0.85	-235.13	0.76	47.61

Table 1. Proton Beamline and LiF Target.

Collimator

The upstream and downstream holes were measured as circles. The measured diameter of the collimator hole is 6.33 mm. The circle centers were used to define the coordinate system as shown in Figure 13. The distance between the hole centers is 377.72 mm.

SiDet - Silicon Detector

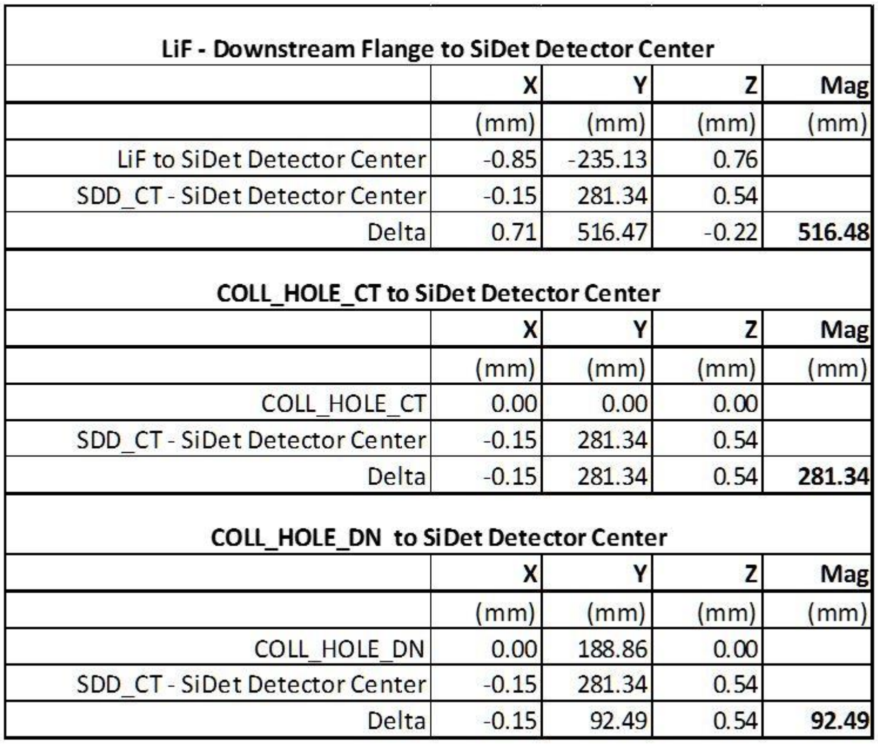
The SiDet was aligned to the downstream hole of the collimator. The top part of the detector was measured as a circle and the detector bottom section or tube in Figure 5b was measured as a cylinder. The surface of base plate below the detector was measured and these measurements were fitted to a plane. A point was constructed by intersecting the line connecting the centers of the tube cylinder with the base plate plane. Table 1 shows the center of the SiDet detector and the height of the detector above the base plate.

Point Name	X	Y	Z	Mag
	mm	mm	mm	(mm)
SDD_CT - SiDet Detector Center	-0.15	281.34	0.54	
SiDet Tube - Baseplate Intersection	3.88	277.85	-134.00	
Delta	4.03	-3.49	-134.54	134.65

Table 3. SiDet detector center and height.

Distances to SiDet

The geometric parameter, *l*, the distance from *LiF* to SiDet center was computed as shown in Table 4. Several other distances from the SiDet center were also computed and shown in Table 4. The distance *l* is 516.48 mm.



LiF - Downstream Flange to SiDet Detector Center

	X	Y	Z	Mag
	(mm)	(mm)	(mm)	(mm)
LiF to SiDet Detector Center	-0.85	-235.13	0.76	
SDD_CT - SiDet Detector Center	-0.15	281.34	0.54	
Delta	0.71	516.47	-0.22	**516.48**

COLL_HOLE_CT to SiDet Detector Center

	X	Y	Z	Mag
	(mm)	(mm)	(mm)	(mm)
COLL_HOLE_CT	0.00	0.00	0.00	
SDD_CT - SiDet Detector Center	-0.15	281.34	0.54	
Delta	-0.15	281.34	0.54	**281.34**

COLL_HOLE_DN to SiDet Detector Center

	X	Y	Z	Mag
	(mm)	(mm)	(mm)	(mm)
COLL_HOLE_DN	0.00	188.86	0.00	
SDD_CT - SiDet Detector Center	-0.15	281.34	0.54	
Delta	-0.15	92.49	0.54	**92.49**

Table 4. Distances to SiDet detector center.

Neutron Detector – Scintillator Bars

In order to obtain the geometric parameters (*r, θ)* for the Antonella experiment, it was very important to determine the geometric center of each scintillator bar. Six points were measured with the I-360 probe on all the four sides of each scintillator bar. A total of 504 points were measured for all the 21 scintillator bars. Figure 15 shows the measurements for the first bar, BAR1. A plane was fitted to the six points on each side of the bar get BAR1_1, BAR1_2, BAR1_3, and BAR1_4 planes as shown in Figure 16. A mid-plane was constructed from BAR1_1 and BAR1_3 planes and another mid-plane from BAR1_2 and BAR1_4 planes. A line, $\text{Line}_{\mathbf{BAR1}}$, was constructed by intersecting the two mid-planes using the plane-plane intersection function of the Spatial Analyzer$^{\text{TM}}$ software. This line defined the geometric center of bar BAR1. A point, BAR1, was constructed on this line by intersecting the X = 0, YZ plane along the beamline with $\text{Line}_{\mathbf{BAR1}}$. The geometric parameters, *r* and θ were computed from the coordinates of center of SiDet and the coordinates of point BAR1. Similar calculations were done for bars BAR2 through BAR21 (Figure 14). Table 5 show the summary of all the 21 scintillator bar points and Table 6 shows the summary of the geometric parameters, *r* and θ.

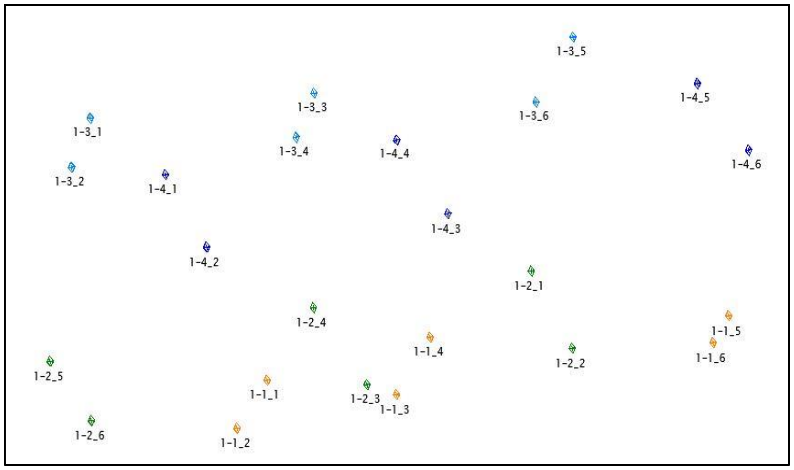


Figure 15. Scintillator bar measurements.

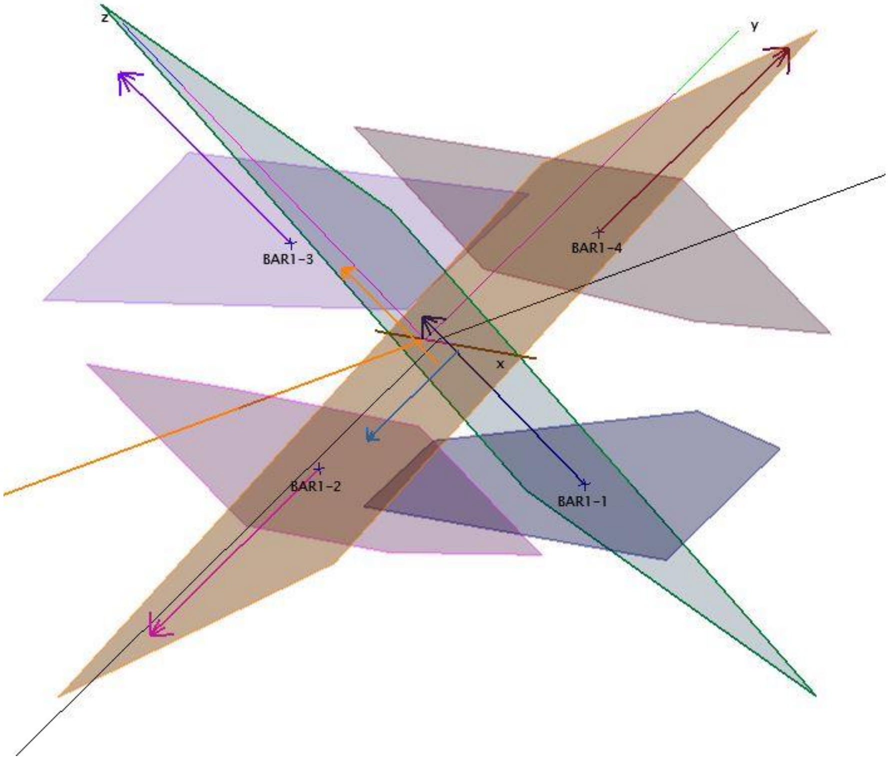
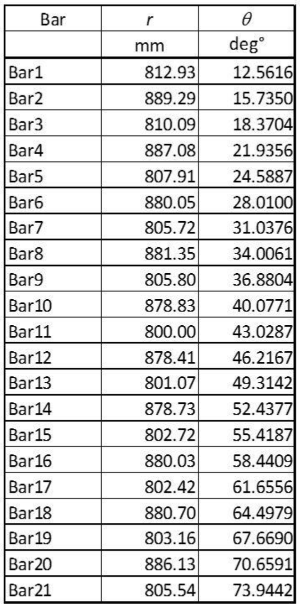


Figure 16. Scintillator bar planes and mid-planes.

Point	X	Y	Z
	mm	mm	mm
BAR1	0.00	1074.67	176.91
BAR2	0.00	1137.20	241.24
BAR3	0.00	1050.07	255.28
BAR4	0.00	1104.15	331.52
BAR5	0.00	1015.96	336.36
BAR6	0.00	1058.14	413.47
BAR7	0.00	971.59	415.65
BAR8	0.00	1011.98	493.14
BAR9	0.00	925.87	483.90
BAR10	0.00	953.76	566.11
BAR11	0.00	866.14	546.22
BAR12	0.00	889.18	634.53
BAR13	0.00	803.56	607.82
BAR14	0.00	817.05	696.97
BAR15	0.00	736.96	661.36
BAR16	0.00	741.95	750.34
BAR17	0.00	662.31	706.71
BAR18	0.00	660.53	795.41
BAR19	0.00	586.51	743.47
BAR20	0.00	574.81	836.70
BAR21	0.00	504.13	774.70

Table 5. Scintillator bar points in X = 0, YZ-plane.



Bar	r	θ
	mm	deg°
Bar1	812.93	12.5616
Bar2	889.29	15.7350
Bar3	810.09	18.3704
Bar4	887.08	21.9356
Bar5	807.91	24.5887
Bar6	880.05	28.0100
Bar7	805.72	31.0376
Bar8	881.35	34.0061
Bar9	805.80	36.8804
Bar10	878.83	40.0771
Bar11	800.00	43.0287
Bar12	878.41	46.2167
Bar13	801.07	49.3142
Bar14	878.73	52.4377
Bar15	802.72	55.4187
Bar16	880.03	58.4409
Bar17	802.42	61.6556
Bar18	880.70	64.4979
Bar19	803.16	67.6690
Bar20	886.13	70.6591
Bar21	805.54	73.9442

Table 6. Geometric parameters r and θ to Scintillator bar points.

CONCLUSION

The geometric parameters of the Antonella experiment - l, r and θ - were surveyed at the University of Notre Dame, Indiana. The high accuracy of the survey was critical to reducing the systematic uncertainties of the ionization efficiency measurement. The fact that these uncertainties were minimized as was done in [1], made the contribution of the Antonella experiment relevant and competitive. The results were sent to the physicist, Federico Izraelevitch, to be used for his analysis. His physics analysis and conclusion are written up in [1].

ACKNOWLEGEMENT

We would like thank Charles Wilson and Michael O'Boyle of the Alignment and Metrology Department of Fermilab for all the help with measurements and calculations.

REFERENCES

[1] F. Izraelevitch et al., *Antonella: A nuclear-recoil ionization-efficiency measurement in silicon at low energies*. Paper in preparation 2016

[2] F. Izraelevitch, *Antonella: A nuclear-recoil ionization-efficiency measurement in silicon at low energies*. FCPA Seminar, July 20, 2015

[3] L. Lamm, *FN Tandem Van de Graaff Accelerator at Notre Dame*, June, 2009. http://www.jinaweb.org/outreach/PIXE-PAN09/docs/Accelerator%20Presentation_June2009.pdf

[4] http://apitechnical.com/Downloads/2012/Radain-Specifications-Sheet.pdf

[5] http://pdf.directindustry.com/pdf/api-automated-precision-europe-gmbh/intelliprobe-360-wireless-specifications/15655-405673.html