Laser Based Alignment System (LBAS)

Position determination of fragile objects in nuclear physics experiments
Outline

• NSCL transfer reaction experiments
  – Inverse kinematics
• Experimental setup – things to be measured
• Requirement for position measurements
• Laser Based Alignment System (LBAS)
• Using LBAS on an experiment
• Details of the measurements
  – HiRA
  – Micro-Channel Plate Detector
  – Target
  – S800 Spectrometer
• Conclusion
NSCL Experiments – Transfer reactions

Inverse kinematics at 35 MeV/A

1. \(^{46}\text{Ar}(p,d)\) & \(^{34}\text{Ar}(p,d)\) - Oct 19, 07’

2. \(^{56}\text{Ni}(p,d)\) & \(^{56}\text{Ni}(d,^3\text{He})\) - Nov 29, 07’/08’
Experimental setup

Need sub-mm accuracy in position!
Requirement for position measurements

• Must be non-contact
  – Mechanical measurements may alter the configuration of our setup (HiRA, target, MCP, etc) and damage our detectors and target foils
Requirement for position measurements

- Accurate (sub-millimeter) position measurements
  - e.g. to resolve nucleus of different excited states

Kinematics of $p^{(86\text{Kr},d)^{85}\text{Kr}}$ @ 35 MeV/A

1$^{\text{st}}$ excited state
(0.305 MeV)

Ground state

Simulations by Jenny Lee
Laser Based Alignment System (LBAS)

- Small and portable
- Measure \((r, \theta, \varphi)\) of a point in space
  - Converted to \((x, y, z)\) afterwards
- Use triangulation to measure distance
  - Range: 25.4 cm – 40.6 cm
  - Resolution: 45.6 μm
- 2 rotary stages provides angles \(\theta\) and \(\varphi\)
  - Capable of measuring 360°
  - Resolution: less than 0.006°
Using LBAS on an experiment

- LBAS laser
- Experimenter (Sun)
- Detector (HiRA)
- Target Mask
- MCP Mask
- Reference objects (posts)
Using LBAS on an experiment

- Measure edges of the apparatus relative to the laser
- Determine the position of the apparatus relative to the laser

- Make measurements at different laser positions
  - due to limitation in its range
  - need to know the laser positions relative to each other

- Measure **reference objects** with different positions of lasers
- Match all the positions into a global laboratory coordinate system
Limitations of LBAS

• Laser measurement
  – LBAS works best on determination of sharp edges
  – Objects with simple shapes are preferred
  – The size of the object should be large enough

• Data analysis
  – More accurate to analyze measurements on a plane (for plane fitting)
  – Should incorporate as much information as possible in analysis (e.g. dimensions of the object from mechanical drawings)

• These considerations should be taken into account in the design of reference posts
Different laser positions - Top view

Laser Position 0

C1B C2B
C1F C2F

Laser Position 1

C3B C4B
C3F C4F

Laser Position 2

C5B C6B
C5F C6F

Laser Position 1

C7B C8B
C7F C8F

Problems with post measurements:
to be discussed later

Corners determined from least square fitting

(Measure MCP 0 and Target Mask)

(Measure HiRA)

(Measure MCP 1)

Schematic drawing –
Diagram not drawn to scale
Transforming different laser positions

- Measure 5 edges of each post (3 scans are made on each edge)
- Determine 3 planes by plane fitting
  - Fit the planes individually, or
  - Require that the planes are mutually perpendicular
- Determine the corner from the intersection of the 3 planes
- Deduce other corners and ball positions (to match global laser measurements) using the planes determined
- Now we have the positions of the same corners with respect to different lasers (or laser positions)
Transforming different laser positions

- Transformation between different laser positions:
  \[ \mathbf{x}_a = \mathbf{R}\mathbf{x}_b + \mathbf{d} \]
  where \( \mathbf{x}_a \) and \( \mathbf{x}_b \) are the same point in space relative to different laser positions

- Rotation Matrix (\( \mathbf{R} \))
  - Characterized by 3 Euler angles: \( \theta_x \), \( \theta_y \) and \( \theta_z \)
    \[ \mathbf{R} = \mathbf{R}(\theta_x)\mathbf{R}(\theta_y)\mathbf{R}(\theta_z) \]

- Translation vector (\( \mathbf{d} \))
  - Characterized by 3 vector components \( d_x \), \( d_y \), and \( d_z \)
    \[ \mathbf{d} = (d_x, d_y, d_z) \]

- Altogether 6 parameters to be determined
Transforming different laser positions

• Results: Laser 0 → Laser 2
  – Rotation: \((\theta_x, \theta_y, \theta_z) = (-0.16^\circ, -0.30^\circ, -0.00^\circ)\)
  – Translation: \((d_x, d_y, d_z) = (-401.59\text{ mm}, 0.58\text{ mm}, -1.17\text{ mm})\)

We moved the laser ~ 40 cm along beam direction from laser 0 to laser 2

The aluminum plate is not flat!

• Laser 1 → Laser 2 cannot be determined from fitting as the data is insufficient
  – Only the translation vector is calculated (by subtracting the two laser measurements on the same point)
  – Translation: \((d_x, d_y, d_z) = (123.15\text{ mm}, -0.84\text{ mm}, 0.15\text{ mm})\)
Transforming into global coordinates

- Matching LBAS measurements with global measurements (by Dave Sanderson’s laser), using its **ball measurements**
- We can then know the position of our apparatus relative to the entire laboratory – important to relate our apparatus to the magnetic elements of the S800 spectrometer for beam tracking.

Origin of the global laser

We are here! Distance scale $\sim 0.5$ m
Transforming into global coordinates

• Same procedure as transforming different laser positions

• Results: Dave $\rightarrow$ Laser 0
  
  – Rotation: $(\theta_x, \theta_y, \theta_z) = (0.21^\circ, 0.01^\circ, 5.68^\circ)$
  
  – Translation: $(d_x, d_y, d_z) = (-74728.3 \text{ mm}, -14487.8 \text{ mm}, 5585.4 \text{ mm})$

• Results: Dave $\rightarrow$ Laser 2
  
  – Rotation: $(\theta_x, \theta_y, \theta_z) = (0.01^\circ, -0.06^\circ, 5.47^\circ)$
  
  – Translation: $(d_x, d_y, d_z) = (-75191.7 \text{ mm}, -14193.2 \text{ mm}, 5512.7 \text{ mm})$

• S800 beam line angle (Dave) : $5.46^\circ$
  
  – Laser 2 measurements show a better agreement with Dave’s results
Problems with reference measurements

• Post measurements: **not enough or too many errors!**
  - 1 (out of 2) corner determination of laser 1 has to be discarded
  - 1 (out of 3) corner determination of laser 2 has problems in raw data
  - Global laser measurements on post 2 (both post and ball) are problematic

• The balls and corners are **too far apart**
  - Larger error introduced when deducing ball positions from corner positions

• All posts at the **same height**
  - The fitting would be too sensitive to errors in vertical direction

Corners determined from least square fitting:
- **Laser Position 0** (Measure MCP 0 and Target Mask)
- **Laser Position 1** (Measure MCP 1)
- **Laser Position 2** (Measure HiRA)
S800 Spectrograph

- Separate the residue from beam
- Measure residue properties (e.g. momentum)
- Beam tracking (to determine beam angle and position at the time of collision) requires the knowledge of the S800 magnetic elements including their position relative to the target.

The S800 is a large-acceptance, high-resolution spectrograph designed for experiments with fast radioactive beams produced via projectile fragmentation.

Magnetic dipoles (to bend the beam)

Magnetic quadrupoles (to refocus the beam)
Target

- \((\text{CH}_2)_n\) target of different thickness
- Large target to accommodate large beam spot
- During experiment, the target can be changed using a target ladder
- Center of the target is found using a target mask, which has 5 holes on it
- Need to determine the center of each hole
- Center of the target = position of center hole

A hole on the target mask

Hole size: 2 mm
Target

- 2 scans on each hole, giving 4 edge points each
- Plane fitting to find the plane for all edge points
- Obtain a first-order estimate of the centers by averaging the scanned edge points
- Use fitting to find a better estimate, requiring
  - All centers lie on the plane determined
  - Distance between centers fixed
  - Right angle at 4 corners

Constrains imposed in fitting:
- Edge points measured by laser
- Center to be determined
Target

• Results
  – 1~2 data points (among 20) found to be problematic from plane fitting
  – Target mask tilted by 0.7° with respect to the beam
  – Small discrepancy (< 0.2 mm) between first-order estimate and refined estimate

• Problems in determining the radius of the hole
  – The holes appeared to be elliptic instead of circular
  – May due to the distance from laser to target mask (~ 36 cm apart)
  – Asymmetric shape of the finite-size laser beam spot?
HiRA Detectors

• The **High Resolution Array**

• Detect the light particles (deuteron, proton, $^3$He etc.) produced in the reaction.

• 16 telescopes, all ~35 cm away from the target and facing target
  
  – Each telescope contains 2 Silicon detectors plus 4 CsI.
  
  – E (middle) detector has 32 strips arranged **vertically** and **horizontally**, forming $32 \times 32 = 1024$ pixels, each with size $\sim 2 \text{ mm} \times 2 \text{ mm}$

• Need to know the position of every pixel relative to the target, in order to determine the scattering angle
LBAS measurements of HiRA Detectors

- Measure the frame of each telescope (3 scans on each side of the frame)
- Determine the 4 corners by fitting
- Require the 4 corners to form a square
  - Lying on the same plane
  - Equal side length
  - Right angles at each corner
- Deduce the pixel positions using mechanical drawings
- Transform the pixels into the target frame
- Compare with design
HiRA Detectors

• Results: comparison with design
  – Most of them in good agreement
  – Some of the telescopes are off by 1 to 2 strips

  – Distance from center of telescope (Si face) to target: 35.97 cm (discrepancy less than 0.12 cm; 35.5 cm by design)

  – Telescopes do not face the target exactly; tilt < 2.6°

  – Systematic discrepancies – distortion in mounting structure
Micro-Channel Plate (MCP) Detector

- Provide position and timing information of an ion traversing the target
- The beam position can be calibrated using an MCP mask
- The 6 larger holes of the MCP mask are measured with laser

Larger holes (5 mm spacing between holes)
Micro-Channel Plate (MCP) Detector

Calibration of MCP

- Need to convert the coordinates (used in analysis) here into global coordinates for beam tracking
  - To determine the exact position, angle where the beam hits the target
  - Especially important when the beam size is large (~ 2-3 cm in diameter for radioactive beam such as $^{56}$Ni)

Results from Alisher
Micro-Channel Plate (MCP) Detector

• Same method as the target
  – Data: 4 edges points on each hole
  – Analysis: Plane fitting $\rightarrow$ estimate center $\rightarrow$ refine estimate by fitting with constrain

Configuration of the larger holes:

• Results
  – Angle between MCP and beam: $58.46^\circ$ for MCP 0, $59.79^\circ$ for MCP 1
  – $\sim 1.5$ mm off in height between target and MCP 0
  – $\sim 0.7$ mm off in height between target and MCP 1
  – The radius of the holes are better determined compared with target mask
Conclusion

• LBAS measurements can achieve ~ 0.3 mm accuracy, using the analysis method mentioned here
• The approach used here is systematic and general, and can be applied to other experiments
• Problematic measurements:
  – Global laser measurements: 1 post (out of 4)
  – Post measurements (LBAS):
    • Position 1: 1 post (out of 2)
    • Position 2: 1 post (out of 3)
  – Target measurements: ~ 10%
  – HiRA measurements: ~ 5%
  – MCP measurements: ~ 0% (!)
Experimental setup

Average telescope-target distance: 359.7 mm
(Distance from every pixel to target is known)
Discrepancy: < 1.2 mm

Distance along beam direction: 98.4 mm
Discrepancy from target height: 0.7 mm

Distance along beam direction: 596.6 mm
Discrepancy from target height: 1.5 mm

Facing target up to 2.6° (or even smaller)

Tilted by 0.74°
Tilted by 59.79°
Tilted by 58.46°
Suggestions

• Study the performance of LBAS laser in more detail
  – Off points are frequently encountered on scans across smooth surfaces
  – The accuracy of the laser varies with range

• Data analysis of LBAS should be done promptly after measurements

• The reference objects should be redesigned
  – Should accommodate corner measurement (for LBAS) and ball measurement (for global laser)
  – Design posts with different heights

• Cross-checking for the laser offset correction

• New Excel fitting package available!
**Measurement Method (Z-Offset)**

- **Laser Offsets:** Align laser with Θ-Stage axis.
- **Θ-Offsets:** Align Θ-Stage assembly with Φ-Stage axis.

Number from laser menu; we should measure it ourselves and check how accurate it is!

\[
z\text{LaserOffset} = 4.896 + \frac{32.5}{25.4} - (5.8825 + 0.59) = 7.5431\text{mm}
\]
~ The End ~
Transforming different laser positions

- The parameters of transformation are determined from least square fitting
  - Minimizing the discrepancy

\[ \chi^2 = \sum \| x_{ai} - Rx_{bi} - d \|^2 \]

where \( x_{ai} \) and \( x_{bi} \) are measurements of a point \( i \) relative to different laser positions
Actually…the MCPs are tilted the other way! (but I found it hard to draw that way…)

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Remark