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A non-contact laser-based alignment system (LBAS) for nuclear-physics experiments

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ABSTRACT

High-resolution reconstruction of reaction dynamics in nuclear-physics experiments with radioactive beams requires accurate knowledge of the beam-particle trajectories and the precise alignment of detectors with respect to the reaction target. In many cases, sub-millimeter position measurements of fragile beam-tracking and particle–detector systems are essential. We have constructed a laser-based alignment system (LBAS) which is a non-contact, high-precision alignment tool designed for applications where excellent spatial positioning must be achieved. The working principles and performance of the laser-based alignment system are presented.

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1. Introduction

Present and future facilities for accelerated beams of rare isotopes open up new opportunities to study exotic nuclei far from stability [1]. Many laboratories around the world (e.g. NSCL, GSI, RIKEN, and GANIL) produce rare-isotope beams through fast-projectile fragmentation of a primary beam combined with direct in-flight separation techniques. While allowing access to many unexplored nuclei, the radioactive beams, when compared to stable beams, suffer from low intensities and large emittance inherent in the fragmentation process. These conditions present a unique set of experimental challenges and, consequently, new detector systems have been developed for studies of radioactive-beam experiments. The availability of radioactive beams also facilitates experiments performed in inverse kinematics, where particles are emitted in collisions of heavy projectiles on light targets such as protons or deuterons.

The need for precise position determination of the detector systems can be illustrated through direct transfer reactions carried out in inverse kinematics. As an example, consider the $p(^{46}\mathrm{Ar},d)^{45}\mathrm{Ar}$ transfer reaction at a beam energy of 33 MeV/nucleon [2]. The calculated kinematics of the scattered deuteron in the laboratory frame for the ground state and first few excited states up to 2.510 MeV are shown in Fig. 1. At large scattering angles in the lab, the kinematic broadening ($dE/d\theta$) increases since for a given angular interval a larger range of energies is covered. Consequently, small uncertainties in the scattering angle lead to large uncertainties in the kinematics. For $\theta_{\mathrm{lab}} > 36^{\circ}$ the kinematic broadening can become greater than 2 MeV/degree, making neighboring states difficult to resolve. This effect is particularly troublesome for states with large angular momentum, e.g. the $f_{7/2}$ ground states of ^{56}Ni and ^{46}Ar nuclei, where important kinematic information is contained at large scattering angles in the laboratory.

Fig. 2 shows the simulated energy spectra for deuterons emitted from the $p(^{46}\mathrm{Ar},d)^{45}\mathrm{Ar}$ reaction over an angular range of $35.0^{\circ} < \theta_{\mathrm{lab}} < 35.3^{\circ}$. The GEANT4 [3] simulation is constructed to model the high resolution array (HiRA), an array of silicon-strip detectors developed for measurements in rare-isotope beam experiments, including transfer reactions [4]. The left panel of Fig. 2 is the resulting energy spectrum for the ground state and first excited state (0.5421 MeV) of ^{45}Ar where there is no uncertainty in the interaction position at the target. In this case both the ground state and excited state are cleanly separated with a peak resolution of 0.560 MeV FWHM. The resolution is limited by the target thickness of 2.5 mg/cm^2 used in the simulation. In the right panel, however, we include an uncertainty of 8 mm FWHM in the interaction position. Here, the peak resolution worsens to 1.660 MeV and the states in ^{45}Ar can no longer be resolved. Similar resolution issues arise from the uncertainties associated with the detector positions themselves.

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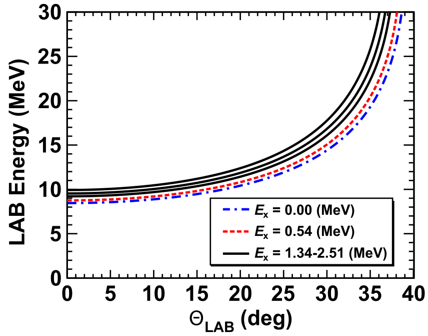

Fig. 1. Laboratory energy as a function of emitted deuteron laboratory angles from the $p(^{46}Ar,d)^{45}Ar$ transfer reaction at 33 MeV/nucleon in inverse kinematics. Significant kinematic broadening can be observed in regions at laboratory scattering angles $>30^\circ$.

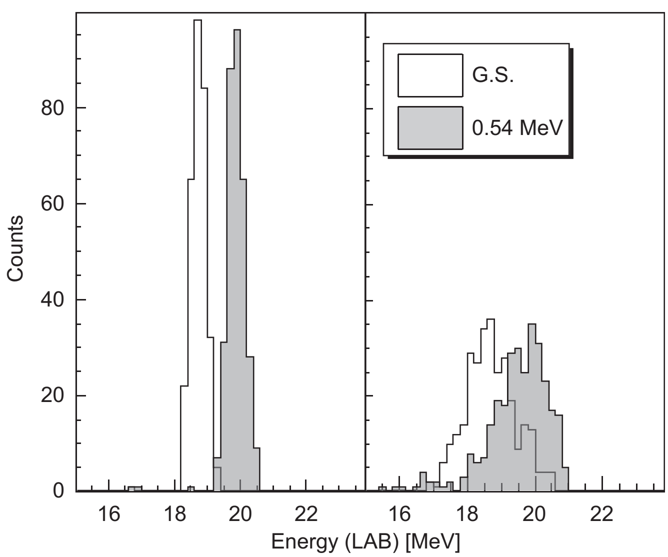

Fig. 2. GEANT4 simulation illustrating the effects of position uncertainty on the deuteron spectra from the $p(^{46}Ar,d)^{45}Ar$ reaction at $35.0^\circ < \theta_{ab} < 35.3^\circ$ in HiRA. Typical detector resolutions as well as the finite coverage of the silicon strips are taken into account. (Left) Energy spectrum assuming no uncertainty in the interaction position and (right) a position uncertainty of 8 mm FWHM.

High-resolution measurements require precise knowledge of detector positions with respect to the point of interaction at the reaction target. Any high-granularity detector with significant uncertainty in its position will therefore be no better than a perfectly aligned low-granularity detector. Ideally, position measurements should be accomplished without coming into physical contact with the target, detectors, delicate foils, or other equipment since they may be easily distorted or broken. In the case of thin foils, mechanical contact may tear the foil. For targets mounted on movable ladders with long lever arms, mechanical contact may alter the target alignment. Therefore, the device used for position measurement should not influence the devices being measured.

2. LBAS components and principles of operation

The LBAS system consists of a laser–displacement sensor, two rotary-stage stepping motors driven by individual controllers, and three terminal servers used for LAN/serial communication. The laser sensor is mounted to the rotary stages as shown in Fig. 3 and provides a precise measurement of the distance to a surface. Each rotary stage gives an angular measurement thereby providing, when combined with the measured distance, a unique position measurement. We refer to the vertically and horizontally mounted rotary stages as the Θ stage and Φ stage, respectively, since they define a spherical coordinate system where $\theta = 0^\circ$ corresponds to the laser beam pointing in the upward vertical direction.

A schematic diagram of the LBAS layout is shown in Fig. 4. The RS-232 serial I/O of the laser and rotary-stage controllers are each connected to LANTRONIX UDS10 terminal servers. Each terminal server is connected via ethernet connection to a standard network switch and is assigned a unique, fixed IP address. A PC connected to the network switch is used to communicate with each device through a TCP/IP socket connection to their IP address. In addition, a JAVA-based interface allows the user to issue device commands, collect position data, and control the LBAS system.

2.1. Laser sensor

The laser–displacement sensor by Schmitt Measuring Systems, Inc (Model no: Acuity AR600) [5] provides a non-contact distance measurement through a diffuse–reflection laser-triangulation technique. The main sensor components consist of a class-II 650 nm laser, a CCD digital line-scan camera, and a microprocessor. All components are contained within a housing box, as shown in Fig. 3, of dimensions 3.50 in. × 1.10 in. × 7.38 in. ($L \times W \times H$).

The basic operating principle is illustrated in Fig. 5. Laser light is projected through an aperture located at the bottom of the housing, illuminating the target surface, where it is focused to

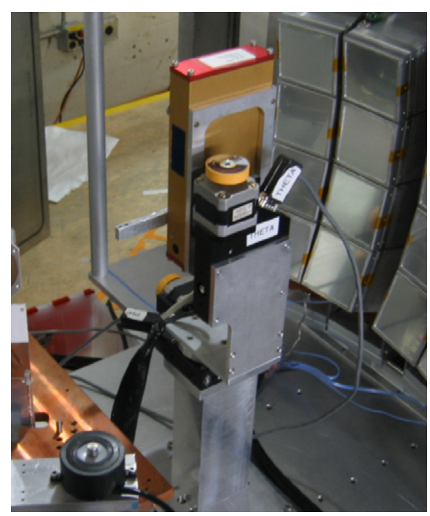

Fig. 3. Photograph of LBAS device showing the laser–displacement sensor mounted to two rotary stages.

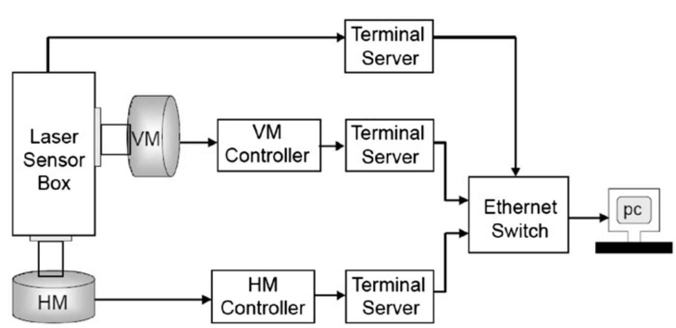

Fig. 4. Schematic layout of the components of LBAS. The two rotary stages are driven by individual motor controllers. Communication for both the laser–displacement sensor and the stepping motors is accomplished through three terminal servers with fixed IP addresses connected to a LAN and accessible through commands sent from a computer.