Gamma-ray energy tracking array: GRETINA

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Abstract. A Gamma-ray energy tracking array can provide higher efficiency, better peak-to-total ratio and higher position resolution than the current generation of detector arrays. Particularly, the capability of reconstructing the position of the interaction with millimetre resolution is needed to fully exploit the physics opportunities provided by current and next generation radioactive beam facilities. This paper presents the basic concepts of energy tracking, examples of physics opportunities, and the status of the GRETINA/GRETA project.

1. Introduction
Because of the high detection efficiency and good energy resolution of gamma ray detectors, gamma-ray spectroscopy has developed into one of the most powerful tools to study the structure of excited nuclear states. Each major advance in gamma detection has resulted in significant new insights into the structure of nuclei. Currently, one of the frontiers of nuclear studies is at the stability limits of the nuclei. To produce nuclei far from the stability line, new accelerators for radioactive beams have been built and more powerful ones are being planned and constructed. Experimental conditions with radioactive beams are more demanding than those of stable beam experiments, and existing gamma-ray detector technology will not be able to meet many of the new challenges. In the last decade, worldwide R&D efforts have achieved a number of technical advances which make it possible to construct a more powerful gamma-ray detector using the new idea of gamma-ray energy tracking. These are: the fabrication of highly segmented Ge detectors, fast digital electronics, and fast signal analysis algorithms, coupled with increased computing power. The tracking detector arrays can meet the challenges of radioactive beam experiments. For example, their higher efficiency will overcome the low intensity of the exotic radioactive beams and will extend the range of study to more neutron-rich and proton-rich nuclei; the higher background due to the decay of the radioactive beams and beam impurities can be better handled by the high count rate capability. More importantly, the radioactive beams produced from fragmentation reactions have relativistic velocities, and high position resolution provided by the tracking detectors is crucial for recovering the intrinsic resolution of a Ge detector by accurately correcting the Doppler shift. Two “demonstrator” arrays, AGATA [1] in Europe and GRETINA in the US, have been completed recently and in spite of their limited solid angle coverage (~1π) compelling physics programs have been started.

2. Principle of gamma-ray tracking
A tracking array covers the source of gamma rays with highly segmented Ge detectors [2, 3]. Detailed pulse shape information from each of the segments is obtained by fast signal digitizers, and this information is used to resolve the energy and three-dimensional positions of all gamma-ray
interactions [4, 5]. Once the location of interaction points is determined, they are used together with the characteristics of Compton scattering and pair-production processes, to determine (track) the scattering sequences of the gamma rays [6]. This provides high efficiency (50% for 1 MeV gamma rays) by adding back gamma-ray interactions scattered across crystals, excellent peak-to-total ratio (0.6) by rejection Compton scattered events from tracking, and accurate position resolution (2mm). In addition, it provides polarization measurement and higher counting rate capability. Such an array will increase the detection sensitivity by factors of several hundred compared to current arrays. In addition to nuclear physics research, tracking detectors have broad applications in medical imaging, homeland security, and environmental monitoring.

3. Status of GRETINA/GRETA

GRETINA uses coaxial Ge crystals with tapered hexagonal shapes. It consists of seven modules each of which containing four 36-fold segmented crystals. The 28 crystals cover a quarter of the total $4\pi$ solid angle. GRETINA is funded by US DOE, and its construction began in 2007 with LBNL being the lead laboratory. A number of US Universities and National Laboratories are involved in this collaborative effort: Argonne National Laboratory (trigger electronics, and data analysis/monitoring software), Michigan State University (detector testing and characterization), Oak Ridge National Laboratory (liquid nitrogen system and signal analysis software), and Washington University (target chamber).

The central part of GRETINA is the Ge detector modules, one of which is shown in Figure 1. These modules have been under extensive performance tests, including energy, time and position resolution measurements, as well as pulse rise time and cross talk properties. The position resolutions, as measured using collimated sources and data analyzed with the latest signal decomposition and tracking algorithms, are about 1-2 mm RMS depending on location of the interaction point in the crystal. The detector support consists of a 50-inch diameter spherical structure in two parts that can position detectors within a tolerance of 0.4 mm, and mechanisms for translation and rotation the two parts.

**Figure 1.** Left panel shows a GRETINA detector module being tested at LBNL. Right panel shows the four 36-fold segmented crystals in the cryostat.

The data acquisition system includes 100MHz 14-bit digitizer modules [7] and trigger modules [8]. There are more than 1000 channels of digitizers to record the detailed shapes of all the segments and central contacts signals. To locate interaction points in the crystal, a library of simulated signals (basis signals) are generated. This library consists of a grid of $(x, y, z)$ positions in the crystal and for each position the induced signal on the 36 segments and the central contact of the detector is calculated. Through source measurements, these signals are then corrected for the preamplifier response as well as integral and differential cross-talk between segments. As it is likely that multiple interactions occur within a crystal, linear combinations of basis signals are fitted to the measured traces in a process called signal decomposition. The best-fit solution determines the number, position, and energy...
deposition of the interaction points. These points are then used to track the scattering sequences of the gamma rays. The Linux-based computer cluster to perform signal decomposition and tracking has about 60 nodes each with 8 cores.

The construction of GRETINA was completed in March 2011. Since then, a number of engineering runs have been carried out at the 88-Inch Cyclotron of LBNL to test the system under various realistic experimental conditions, to improve its performance, and to further characterize its properties. These conditions included high spin, delayed coincidence, external detectors, high counting rate, high-energy gamma ray, and measurements of linear polarization. In one of the experiments the reaction $^{122}\text{Sn} + ^{40}\text{Ar}$ (170 MeV) was used to produce high spin states in Er isotopes. Figure 2 shows the interaction points determined from the signal decomposition algorithm and the actual detector modules. Figure 3 shows a gated spectrum of $^{156}\text{Er}$ from gamma-gamma coincidences analysis. These data were used to understand and optimize the tracking algorithm under high gamma-ray multiplicity conditions.

![Figure 2](image1.png)

**Figure 2.** Left panel shows the interaction points determined from the signal decomposition algorithm. Right panel show the actual detector modules.

![Figure 3](image2.png)

**Figure 3.** Sum of coincidence spectra of $^{156}\text{Er}$ from the $^{112}\text{Sn}(^{40}\text{Ar},6\text{n})$ reaction. Energy gates were placed on the $2^+$, $4^+... 12^+$ states of the ground state band.

In the fall of 2011, GRETINA was moved and installed at the target position of the Berkeley Gas-filled Separator (BGS) [9] for a series of commissioning runs aimed at probing the structure of heavy nuclei near $^{254}\text{No}$. This collaboration is coordinated by Rod Clark (LBL) and Teng Lek Khoo (ANL). Before starting the low cross-section heavy nuclei experiments, the reaction $^{144}\text{Sm} + ^{36}\text{Ar}$ was used to...
produce $^{176}$Pt as a test case for the GRETINA-BGS coincidence setup where the compound residues were detected at the focal plane of BGS. A spectrum from this run is shown in Figure 4. Using these data, the analysis including signal decomposition and tracking was optimized for the anticipated low energy gamma rays from the heavy elements. The data on $^{254}$No were taken at a high rate of $>30$ kHz per crystal. A degradation of energy resolution due to the non-linearity of the digitizers was observed. Subsequently the non-linearity of all the digitizers was measured and a correction algorithm was implemented. Data analysis is still on going.

![Figure 4. Sum of gamma-gamma coincidence spectra of $^{176}$Pt produced in the $^{144}$Sm + $^{36}$Ar reaction from a GRETINA-BGS coincidence experiment.](image)

In April 2012 GRETINA was moved to Michigan State University for a fast beams campaign at the S800 spectrograph [10]. Currently, there are 24 approved experiments for a total of 3351 hours of beam time. Commissioning experiments were scheduled in July and physics runs will start in August. In 2013 GRETINA will relocate to ANL for studies of exotic nuclei using stable beams and neutron-rich beams from CARIBU [11]. These science campaigns take advantage of the unique capabilities available at these facilities and will provide opportunities to advance studies in nuclear structure, nuclear reactions, and fundamental symmetries.

It is the intention of the US nuclear physics community to build the $4\pi$ tracking array GRETA. A plan has been developed to complete GRETA for “day one” experiments at FRIB. Prior to FRIB operations, GRETA will enable forefront experiments at existing stable and radioactive beam facilities with its scientific reach increasing significantly as more detectors are added to GRETINA. The GRETINA Physics Working Group developed a White Paper [12] which documented the most exciting physics cases, and then was submitted as part of the 2007 US DOE/NSF NSAC Long Range Planning activities. This was well received and GRETA obtained a strong endorsement in the final Long Range Plan document.

4. Physics opportunities

The unprecedented capabilities of a tracking detector array will extend the science reach of existing and future accelerator facilities such as FRIB in the US. These facilities will produce nuclei with extreme proton-to-neutron asymmetries, and they are expected to have a wide range of interesting nuclear properties. Of particular interest is the emergence of new shell structures and collectivities, effects of weak binding and coupling to the continuum. Obviously, the properties of neutron-rich and heavy nuclei are crucial for an accurate understanding of the origin of the elements in the cosmos as well as the nuclear reactions that drive the stellar evolution and explosions. In the following I will give a few examples of physics opportunities which could be advanced by a tracking array.
Nuclear shell structure and magic numbers are well established for nuclei near the line of stability. However, recent studies of light neutron-rich nuclei indicate that the magic numbers could be different at extreme ratios of neutron to proton number. For the study of the most exotic nuclei located near the nucleon drip lines and produced by in-beam fragmentation at NSCL and FRIB, GRETINA will give a factor of 10 increase of the resolving power over the existing arrays such as SeGA [13], and GRETA can give a gain in resolving power of up to 10-100 over GRETINA. For example, GRETA will enable the study of the alteration of shell structure and the emergence of new collective phenomena at the two extremes of a proton-magic isotopic chain with fast beams from $^{48}$Ni to $^{80}$Ni at FRIB using nucleon knock out reactions as well as Coulomb excitation reactions.

To study the underlying single-particle levels, transfer reactions such as (d,p) or (d,$^3$He) are best suited for determining the excitation energy and strength of the single particle excitations. For example, experiments [14] in the region near $^{132}$Sn have been carried out at HRIBF ORNL using the array CLARION. These studies use lower-energy (re-)accelerated radioactive beams, e.g. at ANL and NSCL today, and FRIB in the future, in inverse kinematics, and thus have the conditions of large recoil velocity, low beam intensity, and high background. The higher efficiency, higher peak-to-total ratio, and better position resolution of the tracking detector would extend these studies to more exotic nuclei toward the driplines. A 4π tracking array could study nuclei produced with ~50 times weaker intensity than using current gamma ray detector arrays.

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