Experiments with segmented Germanium Detectors for Nuclear Structure Studies

By

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Abstract:

The National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University has developed the SeGA. An array of 32-fold segmented high-purity Germanium detectors optimized for in-beam gamma-ray spectroscopy with beams of fast ($v = 0.3c-0.5c$) exotic nuclei. The SeGA array consists of 18 separate detectors. Each cylindrical crystal is 8 cm long and 7 cm in diameter and made of n-type high-purity germanium. The outer p-type ion-implanted contact of the crystal is vertically segmented into four longitudinal segments and horizontally segmented into eight transverse segments (Figure 1). The detectors are placed “side-on” to the gamma-ray source (target) and the transverse segments provide the angular resolution for Doppler correction. The supple design of the array was optimized for fast beam experiments. The detectors can be arranged in several configurations with distances to the target varying from 10 cm to 100 cm.

![Figure 1](image_url)
Introduction:

At the NSCL scientists are interested in high-resolution gamma-ray spectroscopy with fast beams. The beam begins at the ion source where electrons are removed, to make the atoms electrically charged, so that we can use electromagnetic fields to accelerate the element. The beam is then injected into and accelerated by the K500 cyclotron to 15 percent of the speed of light. It is then sent to the K1200 cyclotron. The already fast-moving ions are sent through a thin carbon foil near the center of the K1200. The foil rips off more electrons as the ions run through it, producing more-highly charged ions. They are then accelerated to half the speed of light. Now scientists have an intense beam of a stable isotope at a very high speed. To produce a beam of a new unstable isotope, the beam of a stable isotope is sent down another vacuum tube to the A1900 fragment separator. Just before the A1900, the beam collides with a piece of metal so that it breaks into pieces. Some of these pieces are the desired rare unstable isotopes. The A1900, in effect, picks the specific exotic isotope out of the fragments after the collision. Now that a beam of a specific isotope is made, it speeds through a vacuum pipe to the experimental vault. There it hits a target and we use gamma-ray spectrometers (SeGA) to learn what happens in this reaction.

Atomic nuclei can emit light called gamma rays when they are excited. Gamma rays have a much higher energy than can be seen by human eyes. Special equipment called a gamma-ray spectrometer allows study of these rays and peering into the internal structure of the nucleus. Studying gamma rays reveals what makes each nucleus special [1]. By electronically partitioning each germanium crystal, in the array, into 32
segments one can measure the energy and interaction points of gamma rays emitted by these fast-moving rare isotopes.

**Gamma-ray Spectrometers:**

In order to understand our world in more detail certain measures must be taken. The goal is to thoroughly understand the internal structure of atomic nuclei and the laws that govern their interaction. There are many ways to study nuclei to try and answer fundamental questions. One of the most popular methods to study these rare and short-lived species is to excite them by bombarding them with another nucleus. After the nucleus is excited, it will often de-excite by emitting energy in the form of high-energy photons—gamma rays. With arrays of gamma-ray spectrometers, this light can be detected to learn about the properties of that rare nucleus. The Study of high-energy photons is a valuable means to understand the internal structure of these nuclei.

Modern high-resolution gamma-ray detectors (Figure 2) consist of a reversed-bias diode made by applying electrical contacts to a high-purity germanium crystal. The germanium in the detector acts as an insulator. In other words, essentially no current flows through the germanium when a voltage is applied. When a gamma ray hits the germanium detector, a small current is made. This current can thus be detected with sensitive electronics equipment.
SeGA Technical Information:

The SeGA is utilized to determine the angle of the emitted gamma ray and thus the energy of the gamma ray in the rest frame of the particle of interest (Equation 1). The segmentation of the germanium crystal allows for a measurement of the opening angle to within 1 centimeter of the interaction position of a gamma ray [2]. The central contact energy resolution varies between 2.5 keV and 2.8 keV. The average resolution of the 32 side channels is 2.5 keV for all but the four segments at the front where the average resolution is 3.3 keV (all resolutions were measured at 1332 keV).

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E_{\gamma}^{\text{pro}} = \frac{E_{\gamma}^{\text{lab}}(1 - \beta \cos \theta_{\text{lab}})}{(1 - \beta^2)^{1/2}}, \quad \beta = \frac{v_{\text{lab}}}{c}
\]

Equation 1  Gamma rays produced in experiments with high velocity beams are considerably Doppler shifted. While the energy of the photon in the laboratory frame \(E_{\gamma}^{\text{lab}}\) is measured, the quantity of interest is the energy of the photon in the rest frame of the projectile nucleus \(E_{\gamma}^{\text{pro}}\). The energy of the emitted photon in the rest frame of the projectile can be reconstructed from the energy of the photon observed if the laboratory angle of photon emission \(\theta_{\text{lab}}\) and the velocity of the projectile in the laboratory frame \(v_{\text{lab}}\) are known [2].

The germanium crystal is a solid high purity semiconductor (diode). The passage of ionizing radiation creates electron-hole pairs, which are then collected by an electric field. The semiconductor must be operated at liquid nitrogen temperatures (77 K) because of a need for large resistance within the crystal. The reversed bias junction, in effect, enlarges the depletion zone and thus the sensitive volume for radiation detection – the higher the external voltage, the wider the depletion zone. The higher external voltage
will also provide a more efficient charge collection. The resistance of the semiconductor, however, limits the maximum voltage that can be applied. At some point, the junction will break down and begin conducting [3]. Germanium detectors must always be operated at low temperatures otherwise the high leakage current will cause irreversible damage to the crystal. Since the detectors must be operated at liquid nitrogen temperatures it requires mounting the crystal in a rigid cryostat with an accompanying dewar for the liquid nitrogen. These detectors will be operated perpendicular to the target (Figure 3). So that the cryostat of each counter doesn't interfere with other detectors the dewar is mounted at a 45 degree angle with respect to the crystal axis. In figure 2 the small cylinder at the bottom is where the germanium crystal is housed. As one can see the dewar at the top contains most of the volume of the detector. This of course puts several constraints on the experimental geometries that can be used (Figure 5).

At the National Superconducting Cyclotron Laboratory the SeGA is used in coincidence with the S800 spectrograph (figure 4). The S800 is a high-resolution, large-acceptance spectrograph used in experiments where projectile fragmentation is produced. The S800 consists of two parts: the analysis line and the spectrograph. The analysis line is everything in figure 4 up to the target, as the beam travels from left to right. This part of the S800 is used for different purposes, fine-tuning the beam onto the reaction target, implementing various optical modes as well as measuring the characteristics of the incoming particles. The spectrograph part of the S800 runs from the target to the focal plane, this is the large-acceptance part, large-acceptance in both solid angle (20 msr) and momentum (5%) [1].
The high resolution of the S800 enables it to distinguish between two particles of slightly different energies. The S800 spectrograph is equipped with sensitive detectors that measure the positions and angles of particles deflected by the magnetic fields. Analysis software is then used to deduce the characteristics of the particles before and after the reaction. The SeGA is located around the target area of the S800 to get a more complete picture of what is happening in the reaction.

Figure 3 One plane (φ=0º) of six of the segmented germanium detectors. There are 2 detectors per theta angle (29º, 78º and 127º) with respect to the beam.
Spectroscopy with Germanium Detectors:

At this time germanium detectors have the highest resolution available for gamma rays. The energy resolution and signal to noise ratio are of utmost importance for precision spectrum measurements. Attention is also paid to count rates, in order to avoid a pile-up effect and dead time which can alter the spectrum. Source-detector geometry is another factor that needs to be accounted for. Calibration using a known gamma ray energy source, with a mounted distance, that is reproducible is used.

For signal isolation purposes, the bias voltage is supplied through a series resistor rather than directly. The bias voltage determines the thickness of the depletion layer in the crystal. The higher the voltage thus reduces the noise by increasing the depletion thickness. However, the higher the voltage the greater is the risk of breakdown incurred. In germanium typical voltages are as high as 3800-4800 V. When applying the bias voltage one should take care to do it slowly raising the voltage a few hundred volts at a time and allowing the detector to “settle” for a few seconds after each time. This will help to insure breakdown does not occur.

The S800

Figure 4
To collect the charge signal from the detector a charge-sensitive preamplifier is used. Since this signal is at a low-level, the preamplifier must have low-noise characteristics. The basic function of the preamplifier is to amplify weak signals from the detector and to drive it through the cable that connects it to the main amplifier.

The main amplifier has two main purposes: amplify the signal from the preamplifier, and shape it to a convenient form for further processing. For spectroscopy one of the most important factors is the pulse-shaping characteristic. Pulse shaping helps improve the signal-to-noise ratio by limiting the bandwidth, and shortens the tail to avoid pile-up [3]. After the amplified and shaped pulse leaves the main amplifier it goes through more electronics (ADC, MCA, QDGG, CAMAC, CFD, TDA) where the pulse has other stipulations put on it. Then it is sent to computers with a data acquisition system. There the pulse information is recorded for analysis.

![Figure 5](image)

**Figure 5** Entire SeGA array, in the beam direction, with eighteen detectors at nine different theta angles with respect to the beam axis.
Conclusion:

Nuclear structure studies utilizing gamma-ray spectroscopy is a valuable tool in understanding the building blocks of our universe. Continued study is an effective means to understand the internal structure of these nuclei. Not only does nuclear study help us grasp what is happening in our universe, but we also reap benefit with more applicable devices such as medical scanners, for example, PET and MRI apparatuses. Progress is being made in developing new systems and ways of doing experiments. A good deal of effort has been put forth in nuclear studies, especially in gamma ray spectroscopy. A search for a new high-Z semiconductor, which can be operated at room temperature and be fabricated inexpensively, is one of the next stepping-stones in gamma-ray spectroscopy [3].
References:


[4] Figure 3 and Figure 5 taken from Heather Olliver, National Superconducting Cyclotron Laboratory Proposal for Experiment 02009

[5] Figure 1 taken from http://groups.nscl.msu.edu/gamma/, 32-fold Segmented Germanium Detector Array