The Measurement and Analysis of Coulomb Excitation

By: Eric Brownson

Benedictine College

Abstract

Coulomb excitation is one of the probes that are being used at the major nuclear research laboratories. The following is intended to be a basic overview of Coulomb excitation, and an introduction to the experimental detectors that are use at the NSCL.

Introduction to the theory behind Coulomb excitation:

Before I give a synopsis of all of the experimental hardware that I was privileged to be able to work with as part of my REU experience at the NSCL I must give a brief description of what the group I was working with was trying to see.

Coulomb excitation is one of the few areas in science where the nomenclature used accurately depicts what is actually going on. Most simply Coulomb excitation is exciting atomic nuclei via a Coulomb interaction between two nuclei. The two nuclei that are used are the nuclei of the target and the nuclei of a beam of particles provided by the coupled cyclotron at the NSCL. For all of the experiments that were performed during the summer of 2001 a gold foil target was used. The cyclotron staff provided several distinct beams to us for our experiments. They ranged in energy from around 60 MeV/nucleon to about 140 MeV/nucleon. Intermediate energies are considered to be between 50 MeV/nucleon and 200 MeV/nucleon [1]. Each beam provided us with nuclei containing the same charge to mass ratio. This will be expanded upon more later when the Zero degree detector (ZDD) is discussed.

Coulomb excitation is used as a probe to test different theories concerning the internal structure of atomic nuclei. One of the most prevalent of which is the shell model. This of course could be the subject of many more pages, but as it is only indirectly related to the work that I performed, I will discuss it no further then to say that it predicts the energy levels of the excited states of the nuclei [2].

Coulomb excitation can be an elastic or inelastic reaction between the two nuclei. Of course any time that you throw two nuclei together with a velocity difference of up to a half the speed of light there is a chance for the two nuclei to overcome the Coulomb barrier and form fragmentation products. Fortunately the beam atoms involved in nuclear reactions tend to be deflected more strongly then the Coulomb excited atoms [3]. So if a detector is placed downstream of the target the ratio of nuclear reactions to Coulomb excitations can be controlled by having a certain acceptance angle for the zero degree detector. A diagram of the experimental setup can be found in Figure 1 with the ZDD labeled.

Any time you deal with relativistic particles such as the beam particles you are forced to deal with multiple reference frames. Both the target's and beam's particles will become Coulomb excited. Both of which will emit a photon when they return to their ground state. The gold target's emitted photons can be observed in the laboratory frame. The beam's emitted photons must be Doppler corrected for a peak to be seen. This Doppler correction requires knowledge of the beams velocity and, the angle of the emitted photon compared to the beam. The first is known from the set up of the A-1900, which separates the particles of interest from the particles that we don't want coming from the cyclotrons. The angle of the emitted photon to the beam can be computed from the photon´s detection position, the placement of the target, and the course of the beam. To a first order approximation the course of the beam is known to several degrees. This is because the beam is tuned to hit the center of the target, and the acceptance angle of the zero degree is limited, figure 2. For better knowledge of the beam's course a pair of PPACs are used. The PPACs are a set of x-y position sensitive parallel-plate detectors [4]. The position of the photon's detection is known because both types of gamma ray detectors, the Ge and APEX detectors, are position sensitive. They to will be discussed further later. The emission of the original gamma ray is assumed to take place at the target [5].

Fundamentals of the APEX array:

One of the two detectors used to measure the energy of the emitted gamma rays is the APEX array. The placement of the APEX array can be found in Figure 1. The APEX array is an array of twenty-four NaI scintillating crystals with a photo multiplier-tube at the end of each crystal. Each crystal was placed parallel to the beam line in such a way as to form a cylinder around the beam line.

When a gamma ray enters one of the crystals it excites the crystal in proportion to the amount of energy in the original gamma ray. The crystal then settles to its ground state, when it does it must emit photons. The photons then travel to the PMTs at each end of the crystal. As the photons move thru the crystal some of them are absorbed, so the signal is absorbed by the crystal in an exponential fashion [6]. Figure 3 demonstrates this graphically. The amount of light that reaches each phototube is proportional to the original gamma ray energy and inversely proportional to the exponential of the distance from the interaction point to the individual phototube. From the information from each phototube the gamma ray's interaction point and energy can be found. This is worked out mathematically in the caption underneath figure 3.

As with all PMTs when they are placed into a magnetic field their efficiency is decreased. Since the experimental setup is placed near the output of the A-1900 fragment separator stray magnetic field lines cross the experimental setup. To combat this affect the PMTs were specially chosen for their resistance to magnetic fields. They use a fine mesh dynode structure and they have a small distance between the photo cathode and the first dynode [7].

Segmented Ge Detectors:

Before I discuss the segmentation of the Ge detectors I will explain the physical basis for how the detector detects. The Ge detector has a highly pure Ge crystal encapsulated in a cryostat. The crystal links two contacts that are separated by high voltage. When the gamma ray enters the crystal it excites electrons from the valence band into the conduction band. This causes a decrease in resistivity in the crystal, and current is allowed to flow from one contact to another. The amount of excited electrons is dependant on the gamma ray's energy. According to Ohm's Law the amount of current flowing is inversely proportional to the resistance between the two voltages. So the amount of current that is allowed to flow depends on the original gamma ray energy. The current can then be amplified and read out into a computer. [8]

When we receive a signal from the detector we find the energy of the gamma ray, but we still need to know where in the detector the gamma ray hit. To better determine where the gamma ray hit the crystal the crystal is segmented. The Ge detector's segments share a common central contact that is held at a high voltage. Each Ge detector has 32 segments. The crystal is divided into four 90 degree arcs. The crystal is also divided into eight cylinders. A diagram of this can be seen in figure 4. So the position of the gamma ray striking the crystal can be found by measuring the current in each segment. [9, 10, 11]

One of the concerns with highly pure Ge crystals is that they remain highly pure. To do this the crystals are placed in a vacuum. The Ge detectors used were kept at around ten to the minus sixth torr. If the vacuum was ever found to be bad then the detector was removed from the setup and a leak check was performed. After a leak is sealed the detector needs to be annealed [12]. Annealing is a process of heating the crystal to boil off any impurities. Annealing was performed with the vacuum being held by means of a turbo pump so that all of the boiled off impurities were removed from the system.

Zero Degree Detector:

The zero degree detector is a PMT with a pair of plastic cylinders glued to the front. The two plastic cylinders and the PMT were positioned in such a way that the beam would enter the first plastic cylinder and then move into the second plastic cylinder. The beam would be entirely stopped by the second plastic cylinder. Each time a particle entered a plastic cylinder it would take some energy out of the beam particle and produce photons. These photons would then be measured by the PMT. The two plastics had a different sensitivity to charge and different response time in producing the light that could be read out by the PMT. So the amount of light produced by each plastic would be dependant on the charge of the beam particle. The light from the upstream plastic would reach the PMT before the light from the second plastic. So the leading edge of the light pulse compared to the rest of the signal would give you an estimate for the ratio of the light produced in each plastic. The beam is made up of nuclei with the same charge to mass ratio so the different nuclei could be differentiated by the different ratios of light produced in each plastic. The cyclotron operators provided us with the relative amounts of different nuclei that make up the beam. So the relative number of particles with the different ratios of light produced in each plastic would tell us which particles were which. The data is recorded on an event-by-event basis so the recorded data can be gated on the isotope that you want to observe.

Conclusion and Acknowledgements:

Gamma rays take a certain amount of time to travel from the target to the gamma ray detector. So when the data is analyzed the gamma rays that take a different amount of time can be discarded to further get rid of background gamma rays.

After the recorded data is gated on the isotope of interest and a Doppler correction is made the result is the spectra of the Coulomb excited nuclei. I would like to thank the National Science Foundation (NSF) for funding my summer REU at the NSCL at Michigan State University under contract PHY 9912212. I would also like to thank Thomas Glasmacher and the members of his research group for their indispensable guidance throughout the summer.

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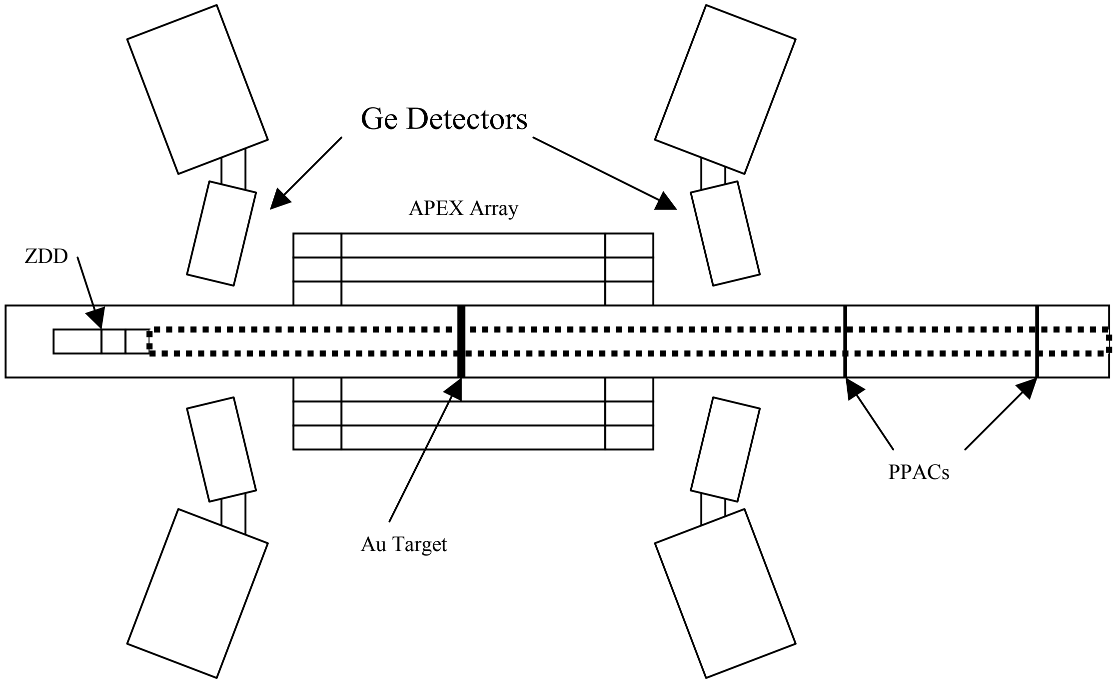

Figure 1:

Figure 1 is a depiction of the experimental setup. This is a cross section of the experiment. The APEX array forms a cylinder around the beam line. The Ge crystals are the rectangles closest to the beam line where the Ge detector label is pointing. The larger rectangle is a large Dewier that is filled with liquid nitrogen. The dotted line down the center of the diagram is the path of the beam. The beam would travel from right to left.

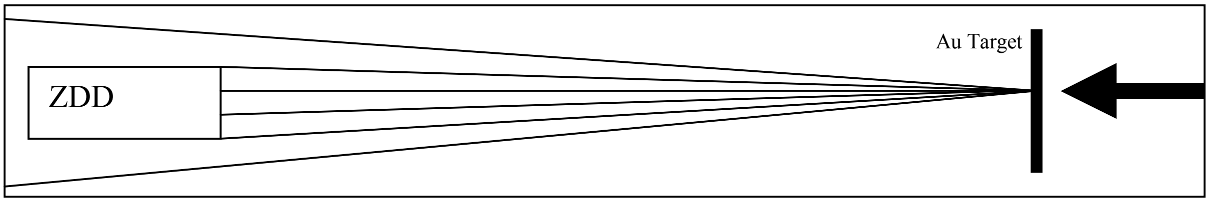

Figure 2

Figure 2 demonstrates the acceptance angle for the ZDD. The bold arrow on the right is meant to represent the beam before it strikes the target. The lines to the left of the target are some of the possible paths the deflected nuclei can take. Only the nuclei that are deflected at small angles are recorded by the ZDD.

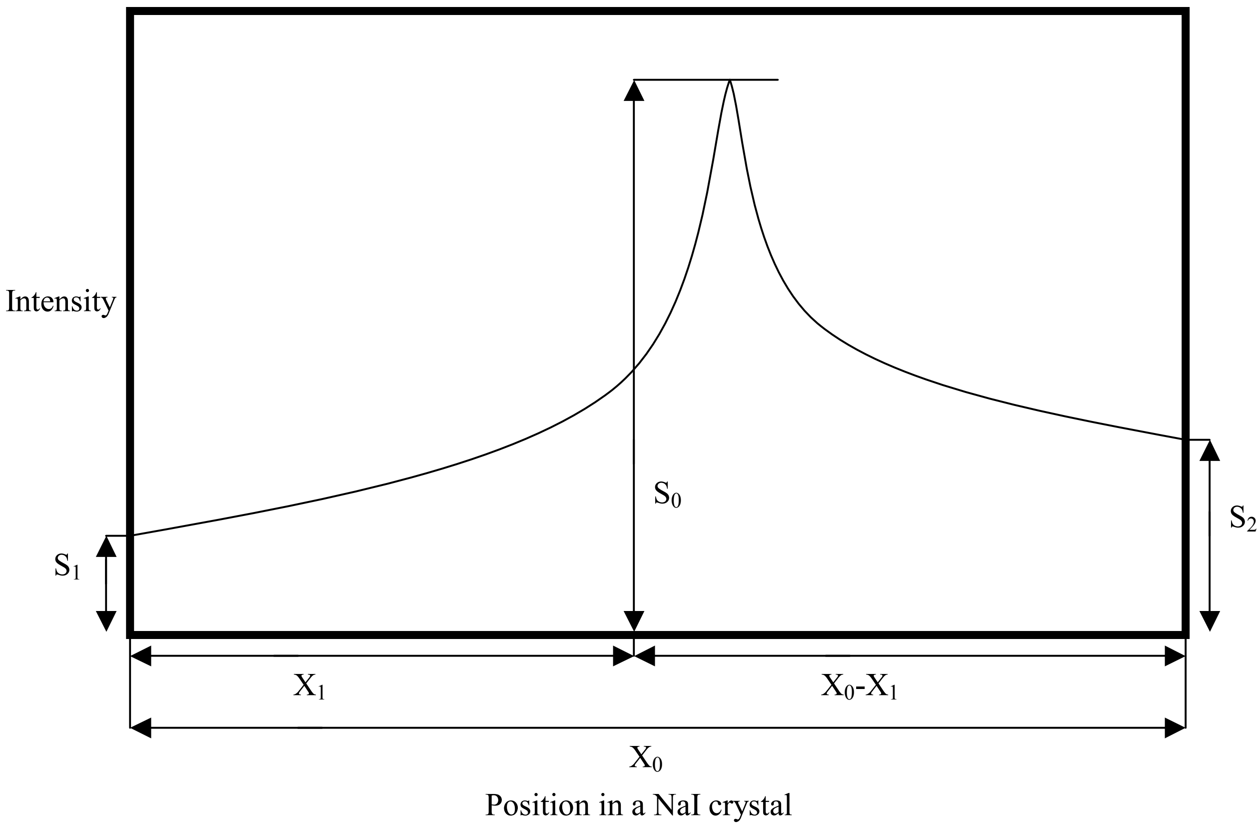

Figure 3

Figure 3 is an exaggerated graphical representation of the light absorption in the NaI crystal. It also has the intensities and positions labeled for the derivation of the inversion of the two PMT readings into the gamma ray's position and energy in the laboratory frame.

Assuming exponential decay of the form,

$S_1=S_0*exp[-\mu X_1]$ and, $S_2=S_0*exp[-\mu(X_0-X_1)]$

you can obtain,

$S_1*S_2=[S_0*exp[-\mu X_1)]]*[S_0*exp[-\mu(X_0-X_1)]]$ or,

$S_1*S_2=S_0^2*exp[-\mu X_0]$ which can be solved for S_0,

$S_0=(\text{constant})*(S_1*S_2)$

Which is the original gamma ray energy in terms of constants and measurable quantities.

You can also obtain,

$S_1/S_2=[S_0*exp[-\mu X_1]]/[S_0*exp[-\mu(X_0-X_1)]]$ or,

$S_1/S_2=exp[\mu X_0-2\mu X_1]$ which can be solved for X_1,

$X_1=[Ln[S_1/S_2]-\mu X_0]/[-2\mu]$

Which is the gamma ray's position in terms of constants and measurable quantities.

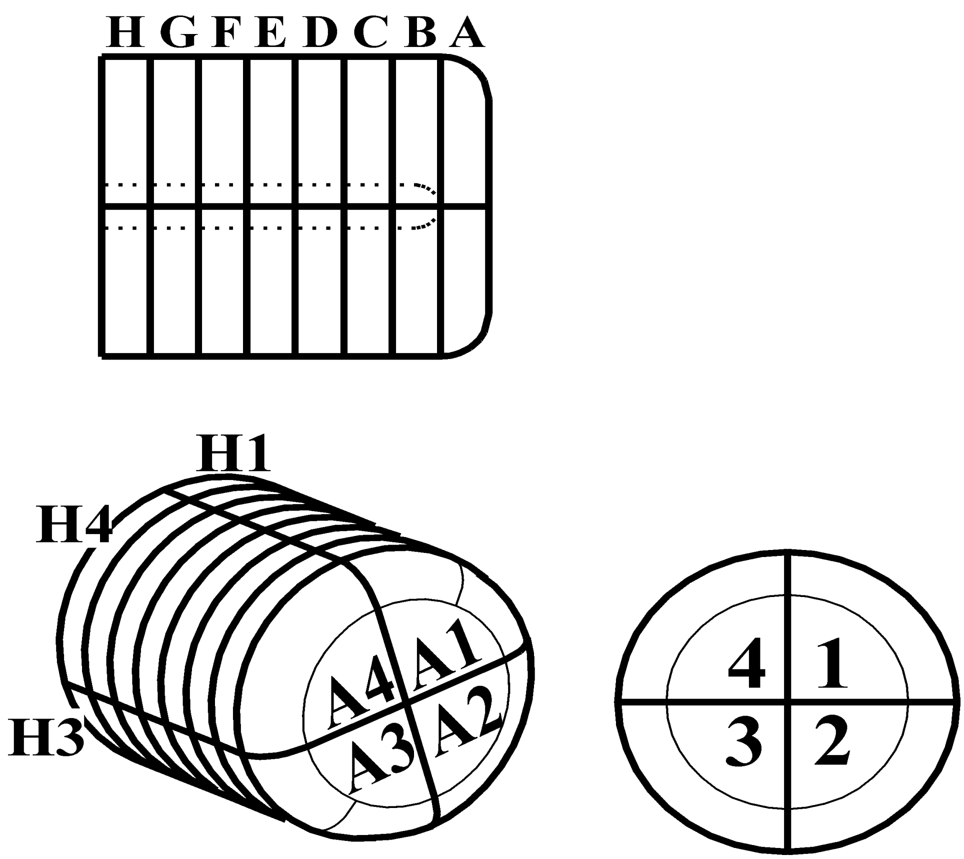

Figure 4

Figure four show both the division of the Ge crystals and the naming system used to refer to the different segments.