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A POSITION SENSITIVE HIGH-EFFICIENCY NaI(Tl) PHOTON-DETECTION SYSTEM FOR USE WITH INTERMEDIATE ENERGY RADIOACTIVE ION BEAMS

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We have built an array of position-sensitive NaI(Tl) photon detectors for use in radioactive beam experiments at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. The array consists of 38 cylindrical NaI(Tl) detectors oriented co-axially in three concentric rings around the particle-beam axis. Each crystal has a diameter of 5.75 cm, is 18 cm long and is read out by two photomultiplier tubes, one at each end of the crystal. Because of the position-dependent attenuation of the scintillation light in the crystal it is possible to determine both the photon energy and the interaction point of the photon in the detector. This photon detection system is very well suited for the investigation of exotic nuclei which, at the NSCL, are produced in fragmentation reactions. Exotic beams produced by this method have high velocities and potentially low particle rates. Both of these properties are addressed in the described setup. The Doppler shift due to the large beam velocities is corrected on an event-by-event basis using the known interaction positions of the photons in the detector. Low particle rates can be accommodated with particle-γ coincidence measurements and the high efficiency of the array.

1 Introduction

The construction of the A1200 fragment separator at the National Superconducting Cyclotron Laboratory [1] made the production of radioactive nuclear beams (RNBs) through projectile fragmentation possible at this facility. This opened up the possibility to perform extensive nuclear structure studies of many unstable, so far inaccessible, nuclei. One well established method to study especially the collective character of nuclei is Coulomb excitation. Here one nucleus is excited in the Coulomb field of the other and the de-exciting γ ray is detected in a suitable detector. The measured γ-ray energy readily reveals information about the level spacing in the nucleus and the γ-ray yields can be used to extract excitation cross sections which are directly related to nuclear matrix elements.

Although commercially available high purity Germanium (HPGe) detectors have an extremely good energy resolution, RNBs produced by projectile fragmentation reactions have certain properties which make this resolution difficult to realize in practice.[2] These beams have high velocities, at the NSCL typically 30% of the speed of light, and potentially low particle rates. Due to the high beam velocities the energy of the γ ray is Doppler shifted, depending on the emission angle with respect to the velocity of the γ-emitting particle,

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[2] Presently under development are highly segmented HPGe detectors which will change this picture in the near future.

according to:

$$E_{cm} = E_{lab} \frac{(1 - \beta \cos(\theta_{lab}))}{\sqrt{1 - \beta^2}} \tag{1}$$

Assuming an opening angle of the photon detector of $\Delta\theta_{lab} = 20°$ (a 7 cm diameter HPGe detector at 20 cm), $\theta_{lab} = 90°$, $\beta = 0.3$, and using

$$\Delta E_{lab} = E_{lab} \frac{\beta \sin(\theta_{lab})}{1 - \beta \cos(\theta_{lab})} \Delta\theta \tag{2}$$

we obtain at best an energy resolution of 10% (compared to the intrinsic resolution of about 0.1%). This could be improved by moving the detector to a larger distance resulting in considerably lower γ-detection efficiency. However, a high photon detection efficiency is particularly important because of the low beam particle rate. Therefore the high intrinsic resolution of these detectors can, at this point, not be utilized.

Here we report on the construction of a high efficiency position sensitive NaI(Tl)-based photon detection system. The granularity of the detector does not significantly increase the energy resolution due to Doppler broadening.

2 Mechanical Setup and Principles of Operation

Each NaI(Tl) crystal is cylindrical, about 18 cm long and 5.75 cm in diameter and encapsulated in a 0.45 mm thick aluminum shield. A quartz window, about 1 cm thick, is attached at either end. A 5 cm diameter photomultiplier tube (PMT) is optically coupled to each window. For mechanical stability the aluminum shield of the NaI(Tl) crystal is rigidly connected (epoxied) to a second aluminum pipe which holds the PMT and the connectors for high voltage (HV) input and signal output. A total of 38 detectors are arranged in an aluminum frame in 3 concentric rings, of 11 (inner), 17 (middle) and 10 (outer) detectors, oriented co-axially to the particle beam axis around a 150 mm diameter beam pipe (see figure 1). The radii of the three detector rings are 10.8 cm, 16.9 cm and 21.8 cm.

When a γ ray interacts with the crystal a certain number of scintillation photons, proportional to the deposited energy, are produced and about half propagate to either end of the crystal. Assuming an exponential attenuation, the light output on each side is described by the following formulas:

$$E_1 \propto E e^{-\mu\left(\frac{L}{2}+x\right)} \quad \text{and} \quad E_2 \propto E e^{-\mu\left(\frac{L}{2}-x\right)} \tag{3}$$

where x is the distance of the interaction point from the center of the crystal, L is its total length, μ describes the attenuation of the light, E is the total energy deposited, and $E_{1,2}$ are the measured signals. It follows that we can recover the total energy and the interaction position through:

$$E \propto \sqrt{E_1 E_2} \quad \text{and} \quad x \propto \log(E_1/E_2) \tag{4}$$

For a more detailed derivation including the errors on these quantities see [2,3].

3 Electronics

The standard electronics setup to process the signals from the NaI(Tl) array is shown in figure 3. A multi-channel high voltage (HV) power supply (LeCroy System 1440) provides typically +1400 V to each PMT. Signals from the PMTs are fed into a fast amplifier (custom built at NSCL/MSU) and then split into two streams which are used for discrimination and energy measurement. One stream is fed into a constant fraction discriminator (LeCroy MSU 1806 CFD, LeCroy 3420) whose output signal is used for the generation of an event trigger, a scaler signal, and timing signal. The event trigger usually requires, in addition to a γ signal, a beam particle signal in timed coincidence. After a trigger signal has been generated, all PMTs that belong to a NaI(Tl) in which at least one PMT fired (according to the bit register, LeCroy 4448) will be read out. The energy is obtained by feeding the PMT signal directly into a shaping amplifier with a shaping time of about 5μs. These shapers are 16-channel single width CAMAC modules built by PICO systems. The resulting signals are digitized by 16-channel peak sensing ADCs (Philips Scientific 7164H). The trigger, whose signal is correlated in time with the beam particle signal, initiates a start signal for all time to digital converters (TDCs) (Philips Scientific 7186) which are stopped by individual PMT signals and therefore measure the time between detection of the photon and the beam particle. The TDC range is set to 200ns, which corresponds to the length of the coincidence window between photons and beam particles. The time spectra help to distinguish between photons emitted from the target and photons emitted by particles stopping in the zero degree detector. The event read-out time is about 300 μs.

4 Calibration and gain matching

Before and/or after each experiment a position, energy, and efficiency calibration of the NSCL NaI(Tl) array is performed. For the position calibration we constructed a collimated γ-ray source consisting of two tungsten cylinders each 7.6 cm long and 14 cm in diameter arranged co-axially with a 4.6 mm gap in between. A 0.5 MBq ^{60}Co source is centered between the two cylinders. The whole collimator can be inserted into the beam pipe allowing simultaneous position calibration of the entire array.

In order to gain match the detectors the collimated source is positioned in the middle of the array and a first coarse gain adjustment is performed by tuning the PMT HV through a visual inspection of the PMT signal amplitudes. Afterwards the shaper gains are adjusted to the desired dynamic range, depending on the expected maximum γ-ray energy, while, at the same time, keeping the total gain of two signal processing chains, belonging to the same detector, matched by centering the peak of the reconstructed position (as defined by equation 4) around zero, from which follows that $E_1 = E_2$. This procedure is carried out by remotely adjusting the gains of each shaping amplifier channel, while looking at online spectra.

Having matched all detectors the collimator is moved in steps (typically every 1–2 cm) to different positions and the data is recorded to tape. Figure 2 shows the reconstructed position versus the true position. We see that in the central region of the detector the correlation is linear, while at the edges the assumption of equations 3 are no longer valid and the curve flattens. The data points can be fitted very well with a third order polynomial, which includes the turnover of the curve close to the edges of the detector.

Since the re-constructed energy is not completely independent of position, a position dependent energy calibration must be performed by applying position cuts to the energy spectra (typically 10 to 20 cuts per detector). The detectors have on average a position resolution of about 2 cm and an energy resolution of about 8% at 662 keV. The 2 cm position resolution translates into a contribution to the energy resolution, due to the Doppler effect, of 5% for the inner 11 detectors, whereas without the position information the energy resolution is much worse. This is illustrated in figure 4. The top panel shows an energy spectrum without Doppler corrections from a recently performed Coulomb excitation experiment [4]. We can see one peak at 547.5 keV, which corresponds to a transition in ^{197}Au, which served as the (stationary) target nucleus. Also visible is a 'bump' around 900 keV. The bottom panel shows the same spectrum, but each event has been Doppler corrected using the known photon interaction position in the NaI(Tl) detectors. Now we can clearly see a peak centered at 891 keV which corresponds to the γ decay of the first excited state in the radioactive isotope ^{40}S, which was the RNB produced by the A1200 fragment separator. The measured resolution is 8.7% and only slightly larger than the resolution obtained from a stationary source.

The photo-peak efficiency for the inner 11 detectors, depending on the actual target position, is about 10% at 890 keV and scales roughly with inverse energy in the region between 0.7 and 2 MeV. This high efficiency enables us to do experiments with beam particle rates as low as 10 particles/s [5].

5 Conclusions

We have built a high efficiency photon detection system for nuclear structure studies using intermediate energy (E/A = 30-70 MeV) RNBs. The array consists of cylindrical NaI(Tl) detectors which are position sensitive in the longitudinal direction and therefore allow for the correction of the considerable Doppler shift in RNB experiments. The usefulness of the detector has been demonstrated in a number of experiments, see e.g. [4–6].

We thank Professor Lee Sobotka (Department of Chemistry, Washington University, St. Louis, Missouri) for saving the NaI(Tl) detectors and making them available to us.

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Fig. 1. Arrangement of the position sensitive NaI(Tl) detectors. The array is surrounded by a 17 cm thick layer of lead to shield from background radiation.

Fig. 2. Position calculated from the two PMT signals over the actual position of the collimated source. The open circles show a sample position spectrum with the source located at 8 cm. The dotted lines are cubic and gaussian fits to the calibration curve and the position spectrum, respectively. The inset shows an energy spectrum using the collimated ^{60}Co source at the same position. The line is an double gaussian fit with quadratic background.

Fig. 3. Schematic drawing of the electronics for the NSCL-NaI(Tl) array: The master trigger is usually defined as a coincidence between a NaI(Tl) and a beam particle signal.

Fig. 4. Typical spectrum illustrating the correction for the Doppler shift. The top panel shows the raw γ-ray spectrum, while the bottom panel shows the same spectrum corrected for the Doppler shift using the position information of the NaI(Tl) detectors (see text).

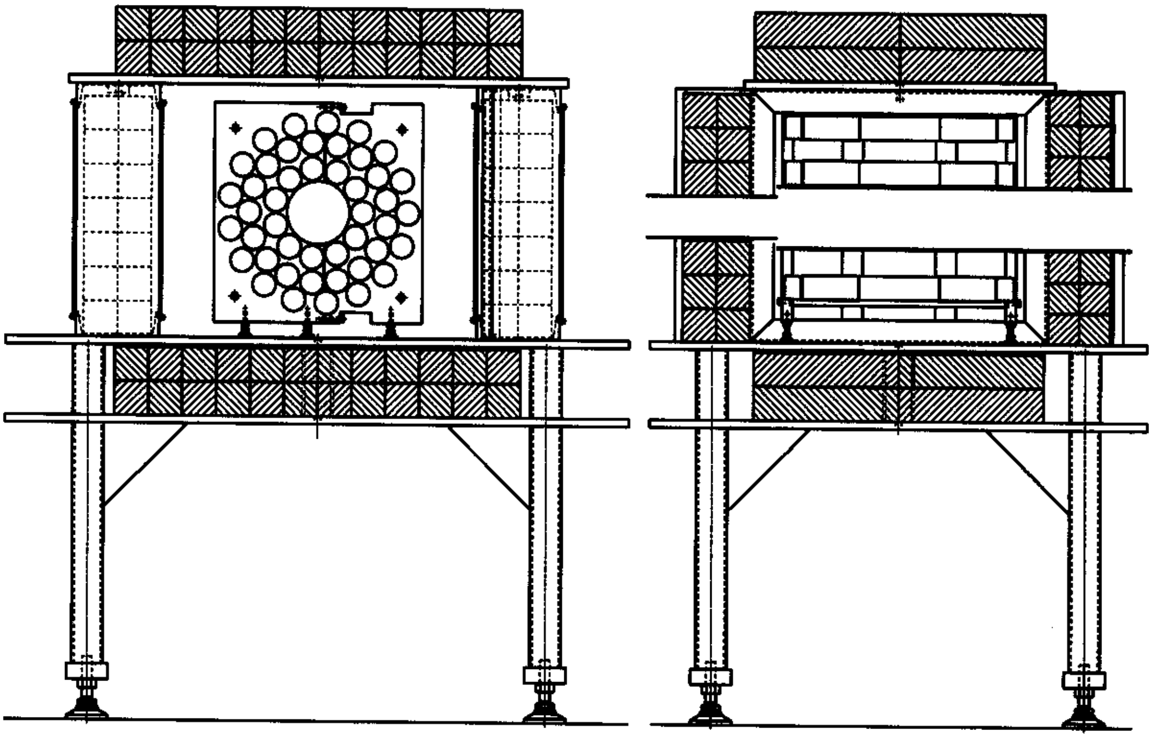

FIGURE 1

mech_setup.eps

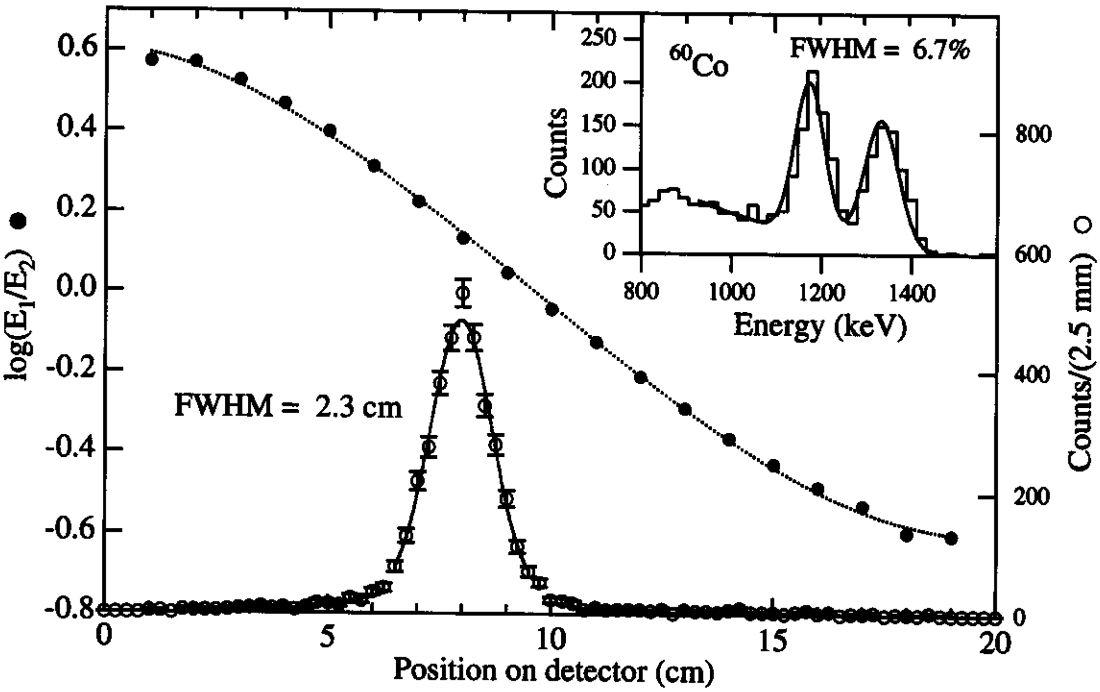

FIGURE 2

pos_cal.eps

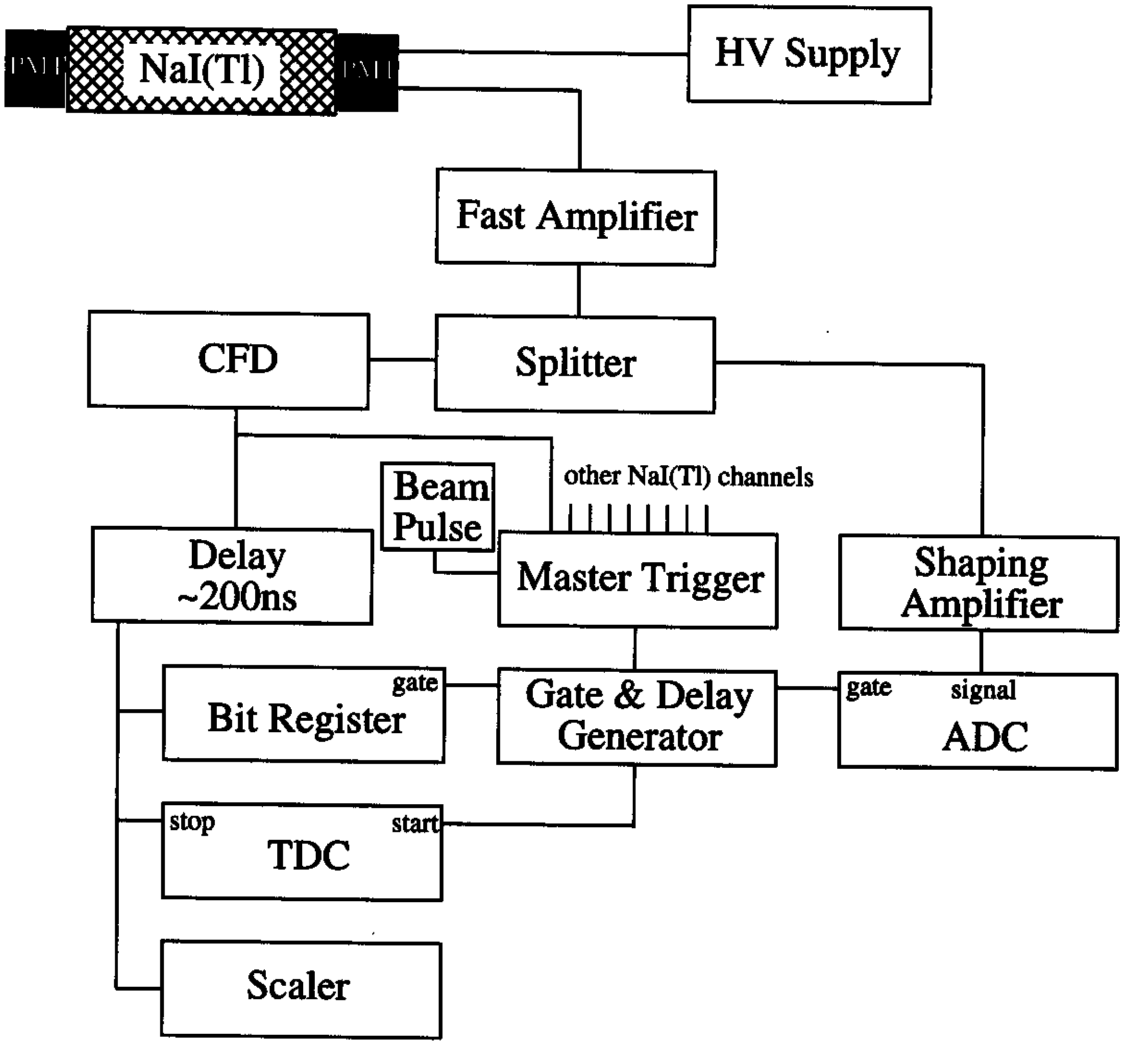

FIGURE 3

elec_setup.eps

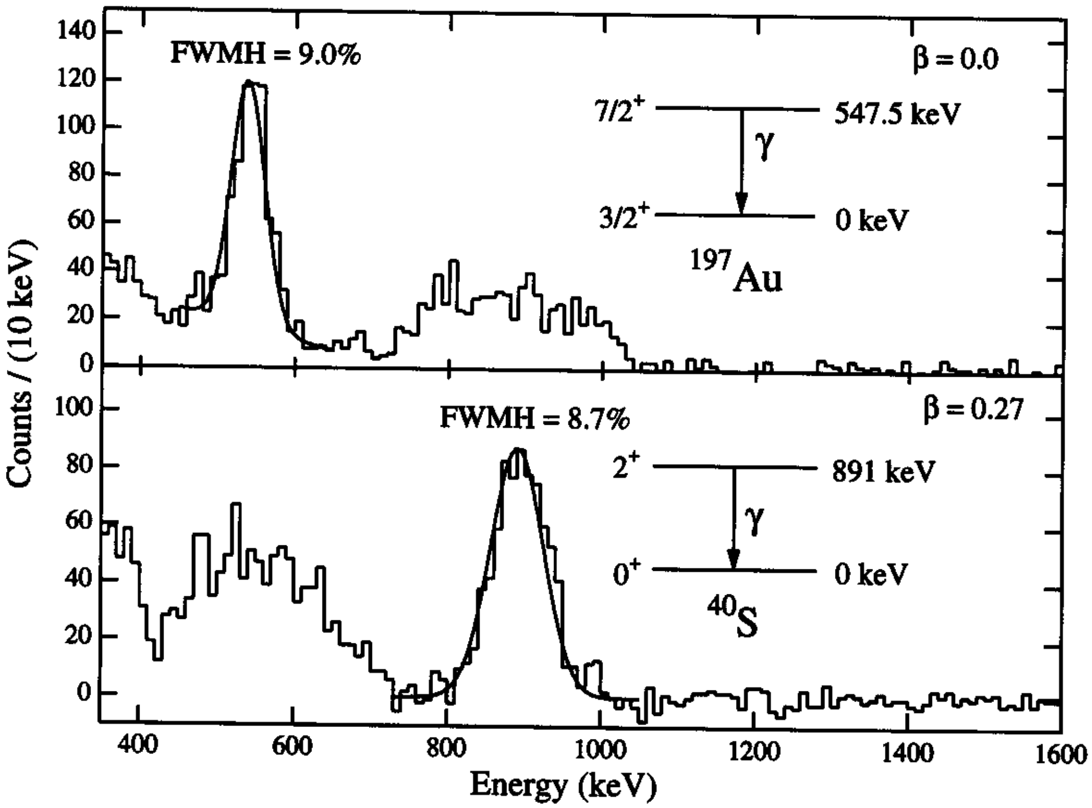

FIGURE 4

40s.eps